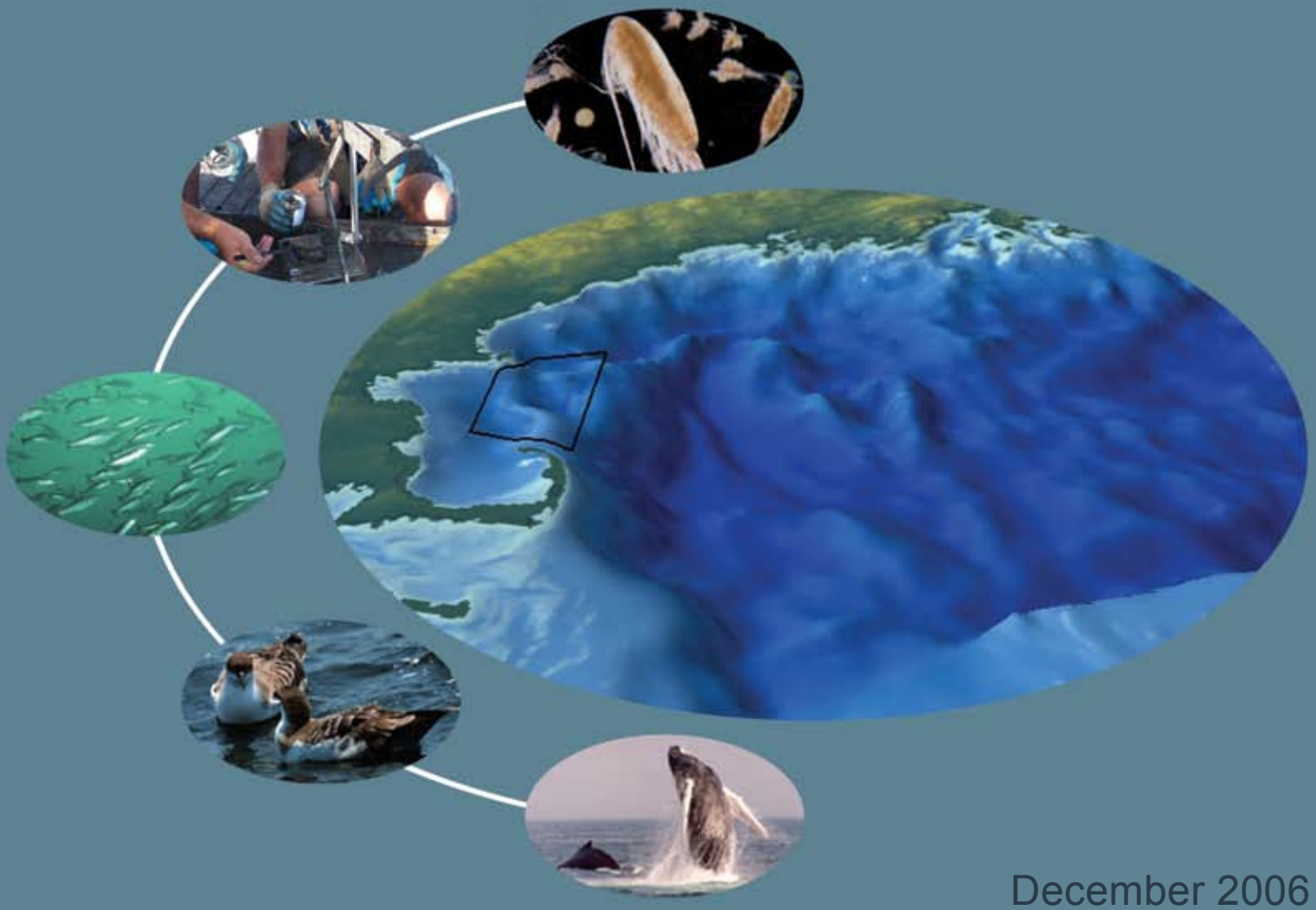
An Ecological Characterization of the Stellwagen Bank National Marine Sanctuary Region

Oceanographic, Biogeographic, and Contaminants Assessment



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NOAA Technical Memorandum NCCOS 45

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ABOUT THIS DOCUMENT

This ecological characterization represents the continuation of an ongoing partnership between the National Marine Sanctuary Program (NMSP) and the National Centers for Coastal Ocean Science (NCCOS), Center for Coastal Monitoring and Assessment (CCMA). The purpose of this collaboration is to apply a biogeographical approach to the management of marine resources within the National Marine Sanctuaries. This particular work, conducted in collaboration with the Stellwagen Bank National Marine Sanctuary (SBNMS) and scientists conducting research within the Gulf of Maine region, builds on and advances biogeographic techniques developed by CCMA's Biogeography Team for other National Marine Sanctuaries including Channel Islands, Cordell Bank, Gulf of Farallones, Monterey Bay, and Gray's Reef. At the onset of the project, CCMA, SBNMS, and NMSP staff identified a set of targeted research topics to fill existing gaps in baseline environmental data, and enhance the understanding of key ecological patterns and processes to support the Management Plan Review process. Four objectives were addressed in the ecological characterization of SBNMS: 1) conduct analysis of geospatial distributions of selected fishes, seabirds, marine mammals, and contaminants within the Sanctuary and Gulf of Maine region, 2) identify biological and physical datasets that can be used to augment existing Sanctuary data for a comprehensive biogeographic assessment in a GIS environment, 3) identify ecologically important areas within the Sanctuary and surrounding region, and 4) model the physical and biological dependencies that may explain the temporal and spatial dynamics of the ecosystem represented within the Sanctuary and Gulf of Maine region.

The ecological characterization consists of three complementary components: a text report; a suite of quantitative spatial and statistical analyses that characterize physical, contaminant, and biological patterns of the Stellwagen Bank NMS region; and an extensive geodatabase of all spatial, temporal, derived, and primary datasets acquired, assimilated, and analyzed to conduct the characterization. The ecological characterization report provides essential information on the distribution of modeled and observed species needed to support the development of monitoring and scientific studies, the development of educational material, and support of other spatially-explicit management decisions. The results of this ecological characterization are available via hard copy and website. For more information on this effort please visit the NCCOS Biogeography Team webpage dedicated to this project at http://ccma.nos.noaa.gov/ecosystems/sanctuaries/stellwagen_nms.html or direct questions and comments to:

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EXECUTIVE SUMMARY

The mission of NOAA's National Marine Sanctuary Program (NMSP) is to serve as the trustee for a system of marine protected areas, to conserve, protect, and enhance their biodiversity, ecological integrity, and cultural legacy while facilitating compatible uses. Since 1972, thirteen National Marine Sanctuaries, representing a wide variety of ocean environments, have been established, each with management goals tuned to their unique diversity. Extending from Cape Ann to Cape Cod across the mouth of Massachusetts Bay, Stellwagen Bank National Marine Sanctuary (NMS) encompasses 2,181 km^2 of highly productive, diverse, and culturally unique Federal waters (Figure 1). As a result of its varied seafloor topography, oceanographic conditions, and high primary productivity, Stellwagen Bank NMS is utilized by diverse assemblages of seabirds, marine mammals, invertebrates, and fish species, as well as containing a number of maritime heritage resources. Furthermore, it is a region of cultural significance, highlighted by the recent discovery of several historic shipwrecks. Officially designated in 1992, Stellwagen Bank became the Nation's twelfth National Marine Sanctuary in order to protect these and other unique biological, geological, oceanographic, and cultural features of the region.

The Stellwagen Bank NMS is in the midst of its first management plan review since designation. The management plan review process, required by law, is designed to evaluate, enhance, and guide the development of future research efforts, education and outreach, and the management approaches used by Sanctuaries. Given the ecological and physical complexity of Stellwagen Bank NMS, burgeoning anthropogenic impacts to the region, and competing human and biological uses, the review process was challenged to assimilate and analyze the wealth of existing scientific knowledge in a framework which could enhance management decision-making. Unquestionably, the Gulf of Maine, Massachusetts Bay, and Stellwagen Bank-proper are extremely well studied systems, and in many regards, the scientific information available greatly exceeds that which is available for other Sanctuaries. However, the propensity of scientific information reinforces the need to utilize a comprehensive analytical approach to synthesize and explore linkages between disparate information on physical, biological, and chemical processes, while identifying topics needing further study. Given this requirement, a partnership was established between NOAA's National Marine Sanctuary Program (NMSP) and the National Centers for Coastal Ocean Science (NCCOS) so as to leverage existing NOAA technical expertise to assist the Sanctuary in developing additional ecological assessment products which would benefit the management plan review process.

CCMA's Biogeography Team, recognized leaders in the field of ecological assessments, had the capability to provide the necessary analytical tools and skills to support the Stellwagen Bank NMS requirements. At the initiation of the project, CCMA met repeatedly with Sanctuary staff to discuss Sanctuary scientific needs and define a collaborative project commensurate with the scope, duration, and support of the partnership effort. As prescribed in the NMSP/NCCOS partnership agreement, CCMA staff worked closely with Sanctuary staff to plan the analytical approach, conduct the ecological characterization, interpret the results, and compile the findings into a report (Kendall and Monaco, 2003).

The Purpose

> *"Most reserve locations and boundaries were drawn by a political process that focused on economics, logistics, or public acceptance, while largely overlooking or ignoring how the complex ecology and biology of an area might be affected by reserve protection."* (Halpern and Warner, 2003).

Ensuring that National Marine Sanctuaries are an effective tool for conservation and management requires that the Sanctuary location and size adequately incorporates relevant marine ecology, oceanographic conditions, and anthropogenic impacts (Browman and Stergiou, 2004). NCCOS and the NMSP have committed to evaluating Sanctuary marine resources using biologically-based regional distribution patterns as part of the Sanctuary management plan review process. In the case of several existing Sanctuaries, this includes evaluating boundary modification as part of the management plan review.

The two fundamental principles implemented as part of the Biogeography Team's commitment to conducting an ecological characterization of Stellwagen Bank NMS included: 1) evaluating marine resource distribution patterns and trends based on an integrated biogeographic approach and 2) conducting the biogeographic assessment at a regional spatial scale relevant to the conditions being characterized.

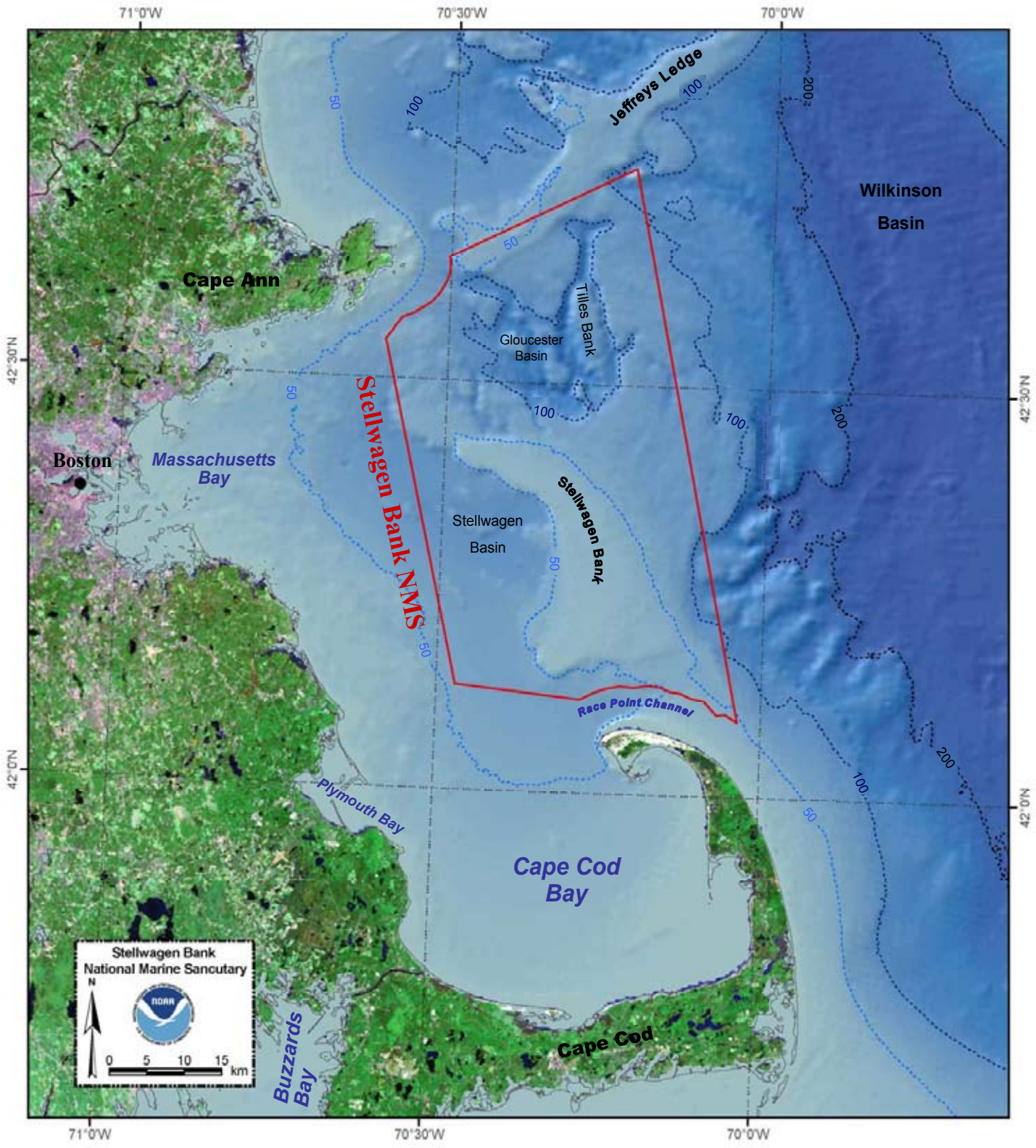

Figure 1. Boundary of Stellwagen Bank National Marine Sanctuary.

Biogeographic Analysis

Biogeographic analysis is an ideal tool for scientists and Sanctuary managers to evaluate biodiversity conservation and ecosystem integrity across the continuum of spatial and temporal scales. Completing a biogeographic assessment of the distribution of such resources within, across, and beyond the Sanctuary boundary is critical for understanding the Sanctuary within the wider ecological context and understanding how the ecosystem composition changes through time. Using the biogeographic approach, managers can explore potential changes in resource distribution that result from alternative management practices. For example, in Stellwagen Bank NMS this includes considering a relocation of the Boston Harbor shipping channel to reduce marine mammal vessel strikes, expansion of the Sanctuary boundary to encompass additional biological hotspots, and the refinement of monitoring efforts to overcome existing gaps in understanding and data coverage.

The biogeographic process is organized around the development of geospatial data layers, integrated analyses, and specific quantitative products to aid in resource management (Figure 2). Biogeographic data assembled and compiled for this product were derived from a wide range of sources including academia, Federal/State government, and data housed within the Stellwagen Bank NMS and Biogeography Program. Many of the data utilized for this project were compiled to explicitly address previous data gaps in understanding and coverage. For instance, remote sensing and GIS technologies were utilized to provide a comprehensive data set on oceanographic conditions (i.e. internal waves, water stratification, thermal fronts, and circulation patterns). Additionally, analyses on the distribution of several marine resources (i.e. seabirds, cetaceans, zooplankton and icthyoplankton) were made possible through extensive efforts to compile, integrate, effort-correct, and spatially enable previously disparate datasets gathered by various universities, NGOs, and Federal/State agencies.

The biogeographic data utilized for this project encompass, as completely as possible, the distribution of ecologically and economically important species and physical, biological, and chemical habitat variables influencing their distribution. All of these data were integrated into a GIS geodatabase using a common spatial framework at biologically-relevant spatial scales. The GIS geodatabase enables visualization of species' and community spatial and temporal patterns, and facilitates statistical manipulation and combination of information to produce relevant geospatial products. The production of spatially-explicit biogeographic analyses such as "hotspot" identification, mapping of community metrics, and development of spatial predictive species models are made possible only through the integration of statistics and GIS.

Regional Context

Due to the high mobility, temporal fluctuation, and dynamic nature of many of the biological and physical conditions within the Stellwagen Bank NMS, analysis of distribution patterns and ecological linkages must be conducted at a spatial scale which extends beyond the Sanctuary boundary. Ecologically meaningful patterns within Stellwagen Bank NMS are a subset of patterns that are largely determined by and extend throughout the Gulf of Maine. For example, research has shown that individuals of several protected species found within the Stellwagen Bank move extensively throughout the Gulf of Maine (Baumgartner and Mate, 2005). Therefore, evaluating the efficacy and effectiveness of management strategies and the relative importance of ecological hotspots within the Sanctuary is predicated on understanding the condition of resources and the broader spatial and temporal movements of animals throughout the region as a whole. This report considers the physical and biological phenomena at a scale including, but extending beyond the Sanctuary boundary, and then evaluates the results so as to explain conditions occurring within the Sanctuary.

When embracing ecosystem management practices, it is incumbent that management jurisdictions and regulatory policy must fully consider, encompass, and represent the ecosystem characteristics of the biogeographic region. The Gulf of Maine, a 93,239 km^2 semi-enclosed sea in the Northwest Atlantic Ocean, is a distinct biogeographical region (Figure 3) from surrounding Scotian Shelf, Georges Bank, and Southern New England regions based on oceanographic and ecological characteristics (e.g. water masses, patterns of primary production, geographic patterns of species assemblages) (Cook and Auster, 2006). There are four hydrographically distinct sub-regions in the Gulf of Maine each having unique physical, hydrographic, and oceanographic conditions: estuarine areas, coastal regions, the central Gulf, and shallow offshore Banks. Stellwagen Bank NMS is centrally located within the generally well-mixed coastal Gulf of Maine biogeographic region, but species abundance,

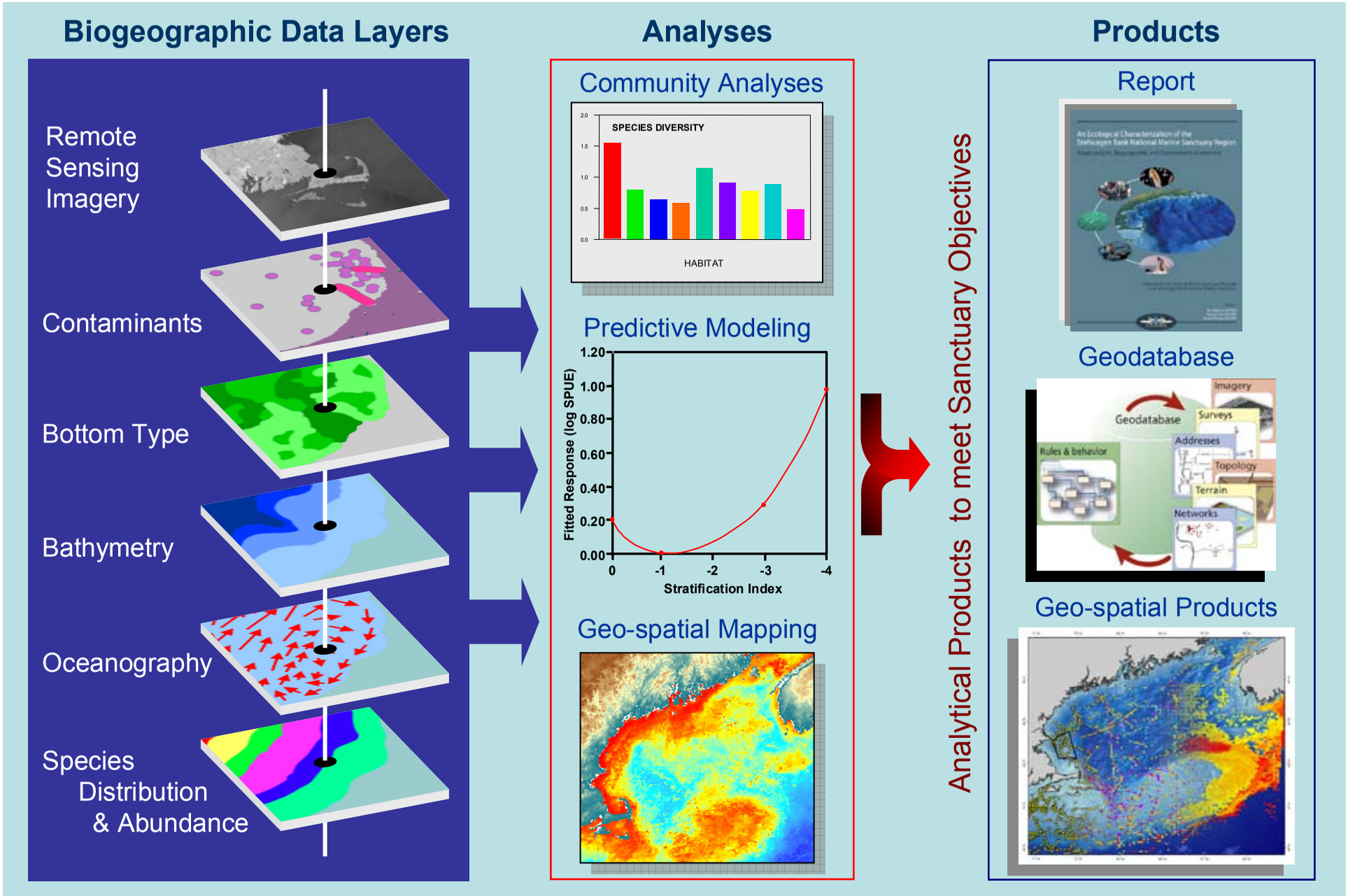

Figure 2. Generalized biogeographic approach used to study Stellwagen Bank National Marine Sanctuary.

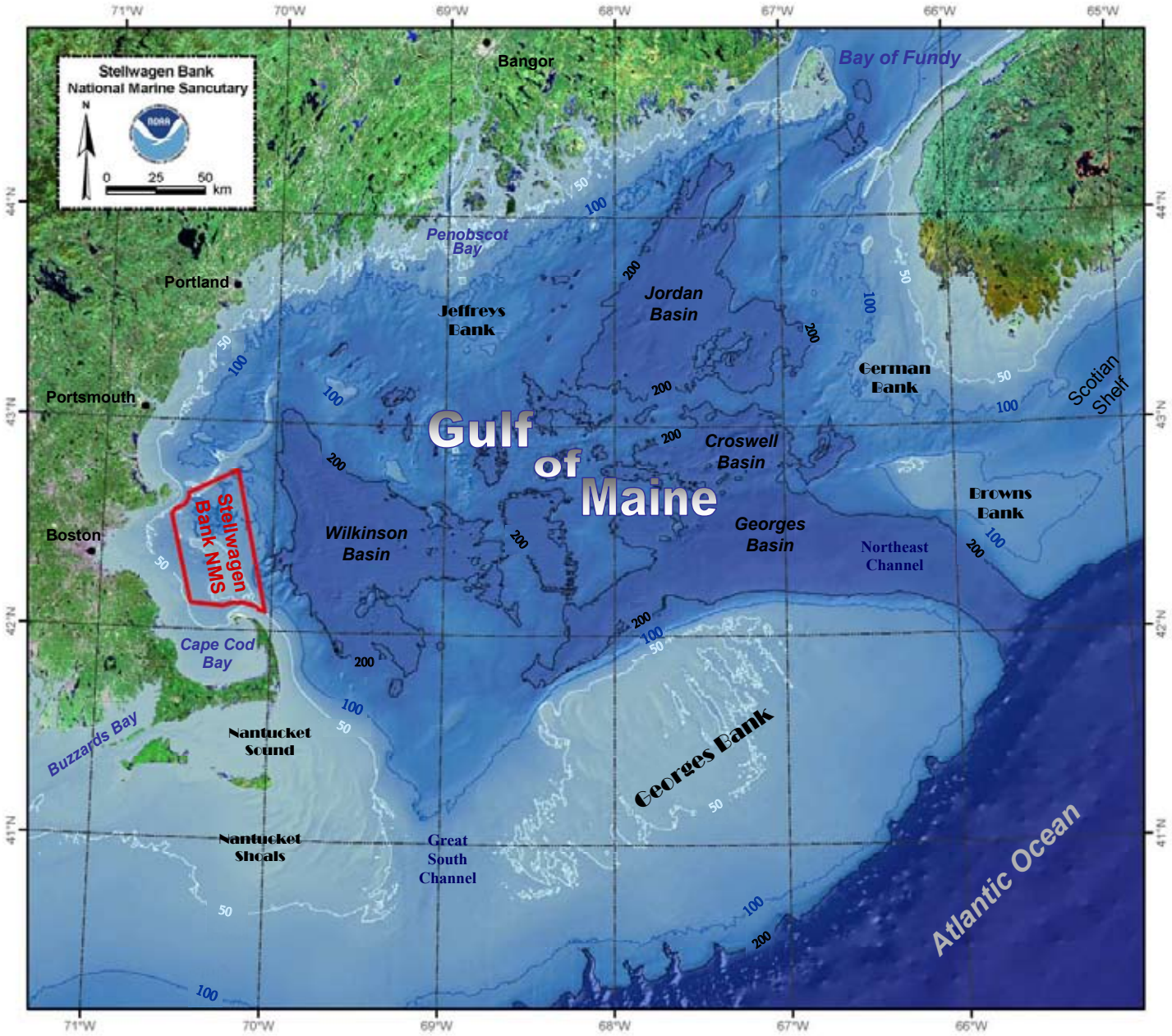

Figure 3. Gulf of Maine study region.

distribution, and population dynamics are strongly influenced by large spatial and temporal variability of physical conditions of the three other regions (Greene et al., 2004).

The success of exploring species spatial and temporal distribution, population shifts, and understanding physical oceanographic phenomena is largely determined by the quality of data being analyzed. Limitations of data within Stellwagen Bank NMS therefore needed to capture dynamics throughout the entire Gulf of Maine to develop environmental linkages which could then be used to explain the broad-scale patterns Gulf of Maine-wide and trends occurring with the Sanctuary proper. For instance, traditionally, cetacean and seabird sightings data have been represented as digital and non-digital distribution maps (atlases) using spatially aggregated observations, mean monthly density in large spatial grids, or summarized data represented as contours of relative abundance. While the “atlas” approach has made a valuable contribution to the understanding of broad-scale spatial patterns of seabirds, few studies have attempted to link the spatial and temporal patterns of seabirds and cetaceans to the surrounding environment at each location. Furthermore, the spatial resolution of these types of maps is coarse, and predictions are usually discontinuous due to limited sampling effort.

Natural and anthropogenically induced variability in environmental condition is an important component in determining the resilience and productivity of marine ecosystems. Long-term re-structuring of species assemblages are controlled by broad scale trends in environmental condition occurring at decadal or greater temporal scales (e.g. water stratification, North Atlantic Oscillation), whereas high amplitude shorter frequency variations (e.g. food availability, recruitment) induce local instabilities or distribution shifts of biological components (Sissenwine and Murawski, 2004). Understanding how well Stellwagen Bank NMS represent the diversity of species present within and among the Gulf of Maine biogeographic region is critical for assessing the conservation value of marine resources and identifying gaps in the protection of biological diversity (Auster and Shackell, 2000). Through the development of sophisticated modeling techniques, it is now possible to link the distribution and abundance of biota quantitatively and temporally with the multi-dimensional environment at specific locations. This approach has the additional desired benefit of being able to analyze natural and anthropogenic changes occurring outside Stellwagen Bank NMS which will ultimately affect distributions found within the Sanctuary.

This Document

The scientific team for this project represents an unparalleled depth and breadth of expertise. CCMA's collaboration with Stellwagen Bank NMS and academic experts offered a previously uncapitalized opportunity to integrate a wide range of expertise both within the Center, as well as outside experts. The project provided an opportunity to integrate the capabilities of CCMA's Biogeography an Coastal and Oceanographic Assessment Status and Trends teams into a unified, interdisciplinary product. The extent of the teaming approach is reflected in the diversity of topics, size, and scope of the products. The report, map products, and geodatabase provide managers and scientists with a suite of analyses and information that, when coupled with pre-existing Sanctuary geospatial information, enables improved research, monitoring, and analysis activities within the Stellwagen Bank NMS region.

This report provides a series of science-based ecological studies that together offer a regional characterization of the Gulf of Maine based on the coupling of physical-chemical-biological processes. The modeling of ecological linkages implemented for this project has been demonstrated to be a valuable tool in advancing our knowledge and identifying the gaps in understanding of the many complex processes that dictate the overall ecosystem dynamics of the Gulf of Maine. This product would not have been possible without the critical step of peer review and contributions from a number of experts.

The following is an abbreviated executive summary of each of the five detailed chapters contained in the Ecological Characterization of Stellwagen Bank National Marine Sanctuary region:

Physical and Oceanographic Setting

Stellwagen Bank is a partial boundary between Massachusetts Bay and the Gulf of Maine. As such it affects the conditions within Massachusetts Bay, and to a lesser extent, conditions in adjacent waters in the Gulf of Maine. The water properties in the vicinity of Stellwagen Bank are determined in part by the large scale counter-clockwise circulation pattern and seasonal density layers within the Gulf of Maine. Oceanographic features on the Bank itself are primarily related to the strong tidal currents driven by an approximately three meter tidal range. These tidal currents interact directly with the sediments on the Bank, limiting accumulation of fine sediments. Tidal flows over the shallow Bank generate relatively large currents and during stratified periods internal waves (both stationary lee waves and propagating waves) result from these currents. All of these physical phenomena have the potential to enhance the flux of nutrients into the upper layer during periods of stratification, and thereby contribute to the high levels of productivity found in the region of the Bank. Additional nutrients may be supplied to the surface layers in the vicinity of the Bank by the tidal flow of water up the slopes of the Bank. In conjunction with the shallow depth, these currents may generate sufficient turbulence to mix nutrient rich water into the surface layer. The water column is generally stratified during the period from late spring through early fall, when light is maximum. Seasonal stratification suppresses water column mixing, contributing to the depletion of nutrients in the upper layer of the water column. Energetic tidal currents at the Bank overcome stratification, and thus lead to enhanced productivity. Strong primary productivity during the spring and fall promote rich secondary production which in turn fuels the ecologically diverse pelagic and benthic ecosystems. From a management and ecological perspective, it is necessary to understand the large-scale oceanographic patterns and how they influence the smaller-scale management unit of the Sanctuary. The Physical and Oceanographic Setting chapter contained

within this report synthesizes and summarizes the wealth of scientific information for the large-scale ecosystem and its implications to the oceanographic patterns observed within the Sanctuary.

Characterization of Chemical Contaminants

The status and trends of trace elements and organic contaminants in Massachusetts Bay as whole were assessed with the objective of investigating export of contaminants to the system. The foregoing assessment was conducted using contaminant concentrations in both sediment and tissue (mussels and fish). The current status of chemical contaminants in the shallow portions of Stellwagen Bank is significantly lower than those of the other region of Massachusetts Bay including Cape Cod Bay. Boston Harbor is the most polluted zone of the Massachusetts Bay/Cape Cod system. Sediments in the deep areas in Stellwagen Basin are accumulating contaminants from a variety of sources. The temporal assessment revealed no statistically significant trends for trace metals and PAHs, while banned, but persistent organic contaminants (DDTs and chlordanes) show very slow decreasing trends over the monitoring years. The persistence of some organic compounds at relatively high concentrations in Boston Harbor, implies that the Harbor may be a continuing source of contaminants to other areas of Massachusetts Bay. However, data in the current study indicates that pollution impacts in the Stellwagen Bank National Marine Sanctuary appear minimal. There is no indication that relocation of the Publicly Owned Treatment Works (POTW) effluent has had short term consequences on the magnitude of export of contaminants from Boston to Stellwagen Bank NMS. That is not to say that contaminant export from Boston is not occurring, only that it does not appear to have accelerated. Discharge reductions from improved sewage treatment efficiencies implemented by the Massachusetts Water Resources Authority have definitely aided in this regard.

Marine Fishes

The Gulf of Maine has 652 documented species. The large diversity of marine fishes is attributed to the proximity of the region situated between the Acadian and Virginian biogeographic regions. Seasonal shifts in temperature and productivity facilitate the mixing of northern and southern migrants, as well as on-shelf movements of slope and deep sea species. Stellwagen Bank NMS (and the Gulf of Maine) is dominated by resident species and species composition is seasonally affected. Additionally, a wide diversity of habitats and oceanographic conditions promote a diverse assemblage of species within the Sanctuary. Species diversity metrics were highly variable throughout the region and show that areas of ecological significance are not consistent spatially and/or temporally and are indicative of dynamic continental shelf fish communities. The Sanctuary's high productivity is depicted as an area of high larval fish abundance, which is directly influenced by the oceanography of the region which facilitates high primary productivity. The wide diversity of habitats supports many species within a variety of trophic guilds of commercial or recreational relevance, such as cod and haddock. Several species within the Sanctuary are listed as a species of concern under the Endangered Species Act. Lastly, several species are abundant within the Sanctuary, but have limited distribution within the Gulf of Maine, (i.e. alligatorfish and snake blenny). The Sanctuary is also an important spawning ground for sand lance, an important prey item for many bird and mammals species.

Seabirds Distribution and Diversity

Seabirds form an important ecological component of the Gulf of Maine ecosystem and their broad-ranging movements, longevity and sensitive dependence on fish prey make them useful bioindicators of ecosystem condition and change. The Gulf of Maine region including Stellwagen Bank has been recognized locally and internationally as an important area for seabirds, some of which have traveled many thousands of kilometers to utilize the rich food resources of the region. Areas with a high abundance and richness of seabirds are often considered of special interest in marine resource management strategies and in the design of marine protected areas (MPAs) or networks of MPAs. Determining which areas of the open ocean are most important to seabirds requires quantitative information on the spatial and temporal distribution of seabird species. This report describes the summer and winter distributions of several seabird species across the Gulf of Maine, with special emphasis on Stellwagen Bank. Novel regression tree techniques were applied to develop predictive spatial models and to quantitatively link the presence of seabirds with their environment, including data on sea surface conditions and bathymetry. We produced both effort-corrected presence maps and predictive maps of species occurrence for selected seabird species. Of the birds included in this study, sightings data indicated that non-breeding summer migrants (Greater Shearwater and Wilson's Storm-petrel) were most prevalent within Sanctuary waters. At the scale of the Gulf of Maine, bathymetric features such as the coastline, the nearshore slopes along the northern sections of the Gulf of Maine, as well as bathymetric features such as Georges Bank, the Great South Channel, the Northeast Channel, and the waters offshore from the southern tip of Nova Scotia appear to represent distinct

features supporting a high diversity and abundance of seabirds. Overall, depth and sea surface temperature were the most important predictors. This information can be used to identify potential ecological hotspots and coldspots of occurrence both inside and outside the Sanctuary for both summer months and winter months.

Cetacean Distribution and Diversity

The southern Gulf of Maine provides essential resources for approximately 13 species of whale and dolphin, several of which are endangered species. Stellwagen Bank represents a high-use area for many of the endangered large whales, yet relatively few studies have attempted to explain quantitatively the spatial and temporal distribution patterns for these populations over such a broad geographical area. For this report we first quantified and described seasonal spatial patterns of relative abundance for individual species of cetaceans, and for all large whales combined and all dolphins/porpoises combined. We then developed a spatially-explicit modeling approach for exploring cetacean-environment linkages using a wide range of environmental data with varying spatio-temporal resolutions. We incorporated both relatively static features, such as derivatives of bathymetric structure and relatively dynamic variables, such as prey abundance, sea surface conditions and water column structure (stratification).

Patterns of abundance revealed that some geographic areas consistently exhibited high abundance of multiple cetacean species, but that individual species exhibited distinctive spatio-temporal patterns across seasons. Our methods allowed us to rank the importance of individual environmental variables and in general, we found that static features, most notably the 100 m isobath, were better predictors of cetacean distribution patterns than were dynamic features, such as sea surface temperature and chlorophyll a concentration. The shoals and slope waters adjacent to the 100 m isobath including Stellwagen Bank and Jeffreys Ledge were identified as key high-use areas for all abundant cetacean species in the southern Gulf of Maine. Information on the specific environmental characteristics of high-use areas combined with maps of relative abundance provide useful ecological insights and essential baseline information to support individual species management and ecosystem-based management.

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CHAPTER 1 - PHYSICAL AND OCEANOGRAPHIC SETTING

Randy Clark, Jim Manning, Bryan Costa, and Arthur Desch

1.1 INTRODUCTION

The Gulf of Maine is a partly enclosed sea, located along northeastern North America from Cape Cod, Massachusetts, north to the Bay of Fundy, and east to Cape Sable, Nova Scotia (Figure 1.1.1). The Gulf of Maine spans 90,700 km^2 and has an average depth of 150 m (Conklin, 1995). The geology of the Gulf of Maine has been shaped by glaciation, volcanism, erosion, subsidence, and sea level rise and features prominent banks, basins and channels. The most notable seafloor features include: Georges Bank, Browns Bank, Georges Basin, and the Northeast Channel to the east; Stellwagen Bank, Cashes Ledge and Wilkinson Basin to the west; the Great South Channel to the south and Jordan Basin to the north. The Gulf of Maine ecosystem is influenced by complex meteorology, bathymetry, and circulation driven by surface and subsurface currents that is highly productive and supports diverse biological communities.

Massachusetts Bay is a semi-enclosed embayment that opens into the Gulf of Maine at its eastern boundary. It is roughly 100 km long, 50 km wide, and has an average depth of 35 m. The Stellwagen Bank National Marine Sanctuary (NMS) resides on the eastern edge of the Bay where depths rise to 20 m on Stellwagen Bank (Figure 1.1.1). The Sanctuary is approximately 40 km east of Boston, and includes most of the waters between Cape

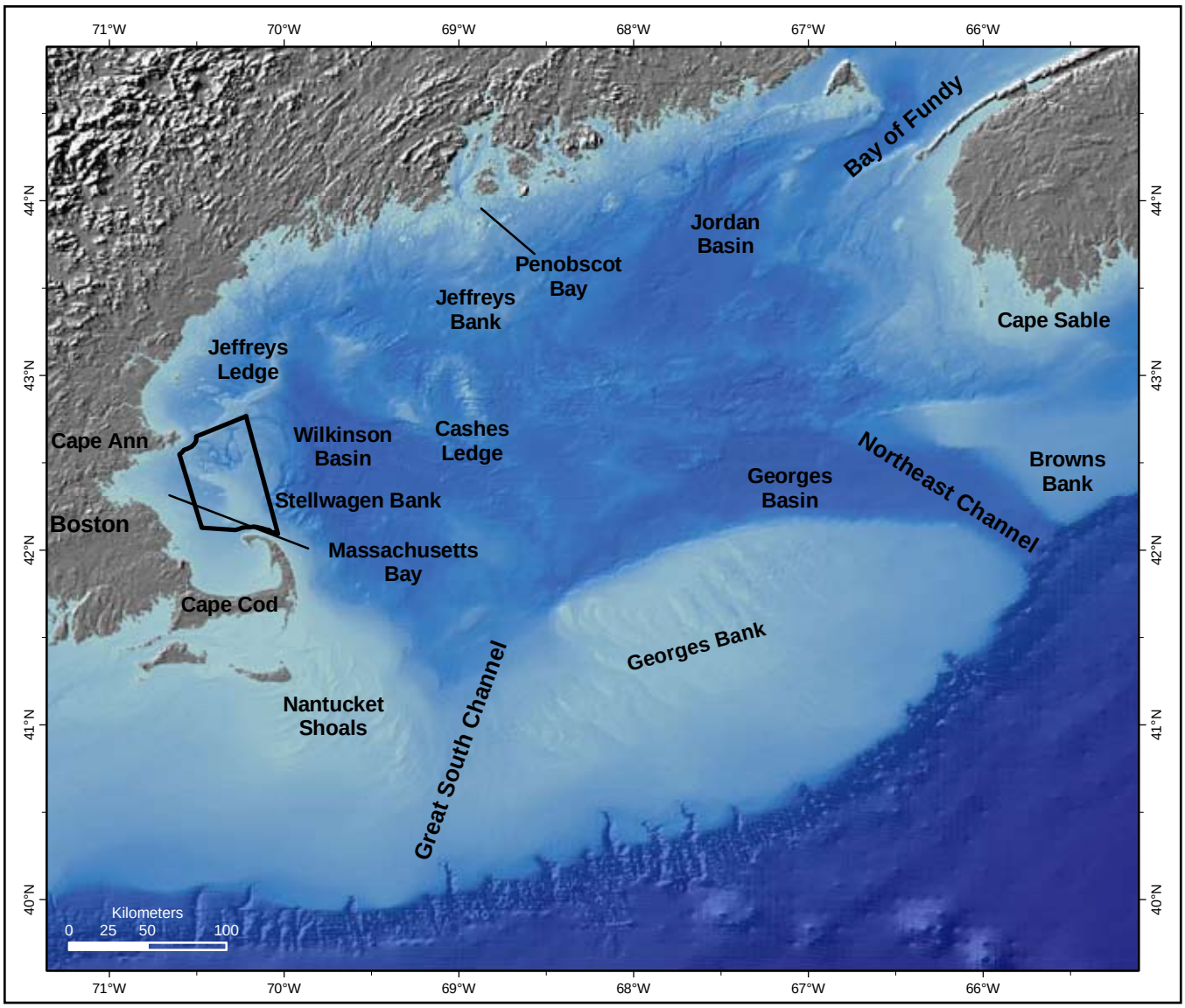

Figure 1.1.1. Major features within the Gulf of Maine.

Cod and Cape Ann (approximately 2,181 km^2). The Sanctuary is situated entirely within federal waters (> 3 miles offshore) and encompasses all of Stellwagen Bank and the southern portion of Jeffreys Ledge. The Sanctuary's complex geology influences the flow of seafloor currents and seasonal biological productivity. The seafloor topography is comprised of boulders, gravel, sand, and mud habitats which support rich invertebrate and fish assemblages.

The topography of the Sanctuary is complex with numerous banks and ridges and interconnecting, deeper water basins (Figure 1.1.2). Stellwagen Bank and surrounding areas provide one of the richest, most productive marine environments in the United States. The Stellwagen Bank area sustains a large diversity of marine mammals and fishery resources which constitute an important ecological and economic resource for the region. Due to its accessibility, the Bank is used extensively for whale watching, commercial and recreational fishing, and recreational boating.

Cold, nutrient-rich bottom water upwells to the top of Stellwagen Bank and mixes with sunlight, causing suitable conditions for plankton production. It is this plankton-rich water that attracts many species of animals to the Stellwagen Bank area.

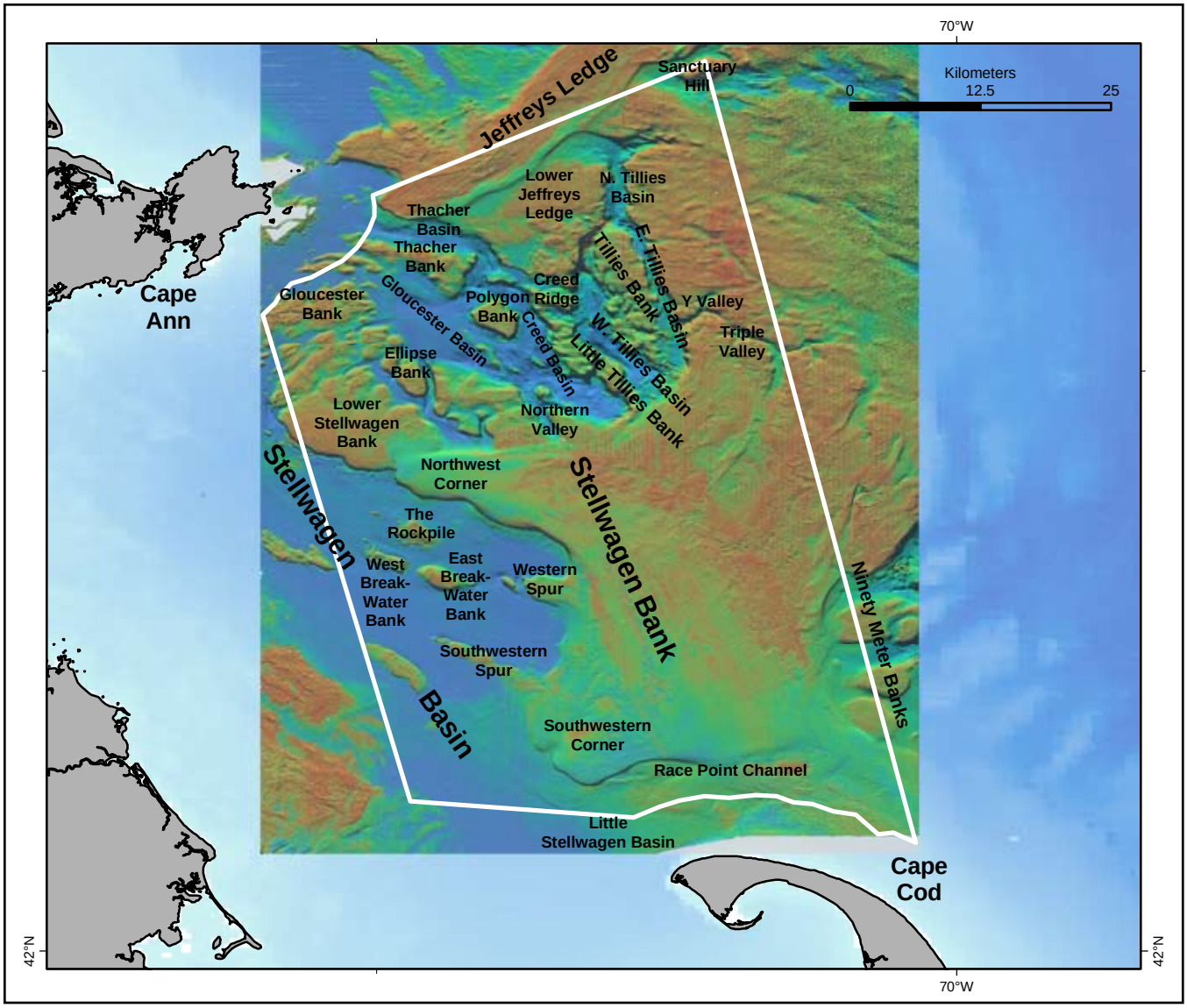

Figure 1.1.2. Geologic features within Stellwagen Bank National Marine Sanctuary. Source: USGS, 2000.

Stellwagen Bank is recognized as one of the most important areas in the North Atlantic for whales. The Sanctuary serves as an important feeding and nursery ground for many species of marine mammals including humpbacks, fins, minkes, northern rights, pilots, and orcas. Seasonal marine mammals include white-sided and white-beaked dolphins, harbor porpoises, and bottlenose, common, and striped dolphins. Harbor seals, gray seals, and leatherback sea turtles are infrequently found within the Sanctuary. Over 30 species of coastal and pelagic seabirds, from the common herring gull to the endangered roseate tern are also found at Stellwagen Bank.

The Gulf of Maine's physical oceanography is perhaps one of the best studied ecosystems in the world. The scientific literature is extensive and well documented. This chapter examines the large-scale oceanographic patterns within the Gulf and draws inferences as to how they influence the conditions within the Stellwagen Bank NMS. The physical processes active at the bank are largely responsible for the ecological productivity within the Sanctuary.

1.2 CLIMATE AND WEATHER

Five main phenomenon influence the weather and climate in the Gulf of Maine: 1) warm waters of the Gulf Stream; 2) cold water flowing southwest from the Scotian Shelf (i.e., the Nova Scotia Current); 3) cold air blown in from Central North America; 4) warm, moist air from the Gulf of Mexico; and 5) the predominantly westward-moving jet stream across eastern North America (Conklin, 1995; Sherman *et al.,* 1996). These factors, in conjunction with other continental and marine influences, classify the Gulf of Maine as a cold-type marine climate (Sherman *et al.,* 1996).

Air Temperature

The factors listed above interact to generate strong annual thermal cycles (Sherman *et al.,* 1996) and plentiful precipitation within the region. Maximum air temperatures typically reach 26°C while temperatures less than 0°C can persist over four months/year. Summer dew point temperatures above 15˚C are not common in the region, indicating humid conditions and weak transfers of latent heat between the ocean and the atmosphere. Winter temperatures, on the other hand, are usually at or near 0˚C, indicating little to no humidity and thus, large latent and sensible heat fluxes from the ocean into the atmosphere (Sherman *et al.,* 1996). In addition, local terrestrial topography, most notably the Appalachian Mountains, often trap cold air masses between the mountains and sea, enhancing land-sea thermal gradients (Sherman *et al.,* 1996).

Precipitation

The Gulf of Maine's climate is characterized by abundant (100-112 cm/year) and uniform precipitation throughout the year (Sherman *et al.,* 1996). Precipitation events are dominated by winter cyclones (i.e., areas of closed, low pressure circulation with counterclockwise rotating winds) followed secondarily by summer convection (Sherman *et al.,* 1996). The Gulf of Maine receives a significant amount of snow (i.e., 17+ days of greater than 2.5 mm water-equivalent) that greatly contributes to fresh water input into the Gulf of Maine during the spring and summer months (Babb and DeLuca, 1988; Sherman *et al.,* 1996).

Wind

Winds in the Gulf of Maine exhibit a mean flow of 3.75-4.5 m/s from the south/southwest between April and August, and a mean flow of 4.0-4.5 m/s from the northwest (occasionally northeast) between October and February. As a result of these patterns, most meteorological events that occur in the Gulf of Maine come from the southwest and northwest, and are steered by the general westerly flow in the middle and upper troposphere (Babb and DeLuca, 1988; Sherman *et al.,* 1996).

Storms and Hurricanes

Winter Storms

During the winter, the Gulf of Maine is surrounded between generally sub-freezing daily mean temperatures over land and greater than 20˚C temperatures over the Gulf Stream (Sherman *et al*, 1996). This temperature contrast creates a persistent baroclinic zone (i.e., a zone where surfaces of constant pressure intersect surfaces of constant density) in the lower half of the atmosphere between the northwestern wall of the Gulf Stream and the coastline (Sherman *et al*, 1996). Consequently, winter weather in this region largely depends on the interaction

of the baroclinic zone and the vorticity maxima (i.e., the location of the maximum rotation of a small air parcel) in the westerly jet stream to generate, intensify or dissipate cyclones (Sherman *et al*, 1996). When winter cyclones do form, they commonly follow two tracks: 1) along the coast and 2) along the Gulf Stream. Coastal-track storms, which are advected inshore and move along the coastline, produce clockwise wind turning in the shear zone associated with warm and cold waves. These storms are often disrupted by the Appalachian Mountains. The mountains usually stall cold fronts reducing their intensity, but storms generally redevelop and strengthen in the Gulf of Maine region (O'Handley, 1988). Gulf Stream track storms (more commonly known as nor'easters) travel along the Gulf Stream, and produce more gradual counterclockwise turning. Coastal storms enhance inertial wave generation more than by Gulf Stream storms (Sherman *et al*, 1996), and in general, winter storms create waves with longer periods and greater heights than summer storms (Babb and DeLuca, 1988).

Summer Storms

During the summer, cyclonic storms in the Gulf of Maine are less frequent and of lower intensity because the baroclinic zone, associated with the main jet stream, moves north (Sherman *et al*, 1996). Because of this northward movement, most of the strong winds and heavy precipitation events are locally generated and often short-lived. These squalls and strong events, however, may still cause noticeable changes in surface water properties of localized areas in the Gulf of Maine (Sherman *et al*, 1996).

Hurricanes

Hurricanes also occur, albeit infrequently, in the Gulf of Maine (Babb and DeLuca, 1988). Hurricanes that reach the Gulf of Maine, dissipate rapidly due to cool (<20˚C) Gulf water, and primarily affect water levels near coastal regions (Conklin, 1995; Sherman *et al*, 1996).

Long Term Climatic Phenomenon

The Gulf of Maine's climate results from a combination of continental and oceanic characteristics. The climate and marine ecosystem in this region are often affected by large-scale climatic patterns, such as the North Atlantic Oscillation (NAO). The NAO has a global impact as it affects sea surface temperatures, wind conditions, and water circulation throughout the northern Atlantic Ocean. The NAO is a product of the balance between the winter barometric pressure system over Iceland and the opposing high pressure system over the Azores (Wahle, 2000) and is a major source of inter-annual variability in atmospheric circulation over the North Atlantic (Hurrell, 1995). The severity of the NAO, which is measured using an index from +1 (strong/high) to -1 (weak/low), is determined by calculating the difference in sea-level pressure between winters. During strong NAO winters, there can be a considerable pressure gradient across the North Atlantic, and westerlies can be over 8 m/s stronger than in low NAO winters. Since 1980, NAO indices have been unprecedented positive, resulting in broad patterns of warming over the continents and cooling over the oceans (Hurrell, 1995). These changes in the mean circulation patterns over the North Atlantic have been accompanied by pronounced shifts in storm tracks and synoptic eddy activity. In turn, these shifts affect the transport of atmospheric moisture and thus, regional precipitation patterns (Hurrell, 1995). Prolonged periods of anomalous NAO circulation patterns are likely to affect the rate of deep water formation in the North Atlantic (Hurrell, 1995). Changes in these rates would greatly affect the Gulf of Maine as it is particularly susceptible to climate-driven changes in North Atlantic circulation patterns (Pershing *et al.,* 2003).

The NAO has a direct effect on the position and strength of important North Atlantic Ocean currents. The NAO significantly influences the latitude of the Gulf Stream Current and the interannual variability in the location of the current. The strength of the Gulf Stream and North Atlantic currents are also affected by the NAO. During negative NAO years, the Gulf Stream Current weakens and shifts southward. The location and strength of the Gulf Stream are an essential part of the North Atlantic climate system, moderating temperatures and weather from the U.S. to Great Britain and the Mediterranean.

The NAO has also been linked to the distribution of various trophic groups in the Gulf of Maine. Temporal and spatial patterns of *Calanus* copepods have been linked to the phases of the NAO (Fromentin and Planque, 1996; Stenseth *et al.,* 2002). Positive NAO periods have corresponded with increased abundance of copepods and decreased abundance was observed during negative NAO years (Conversi *et al.,* 2001; Greene and Pershing,

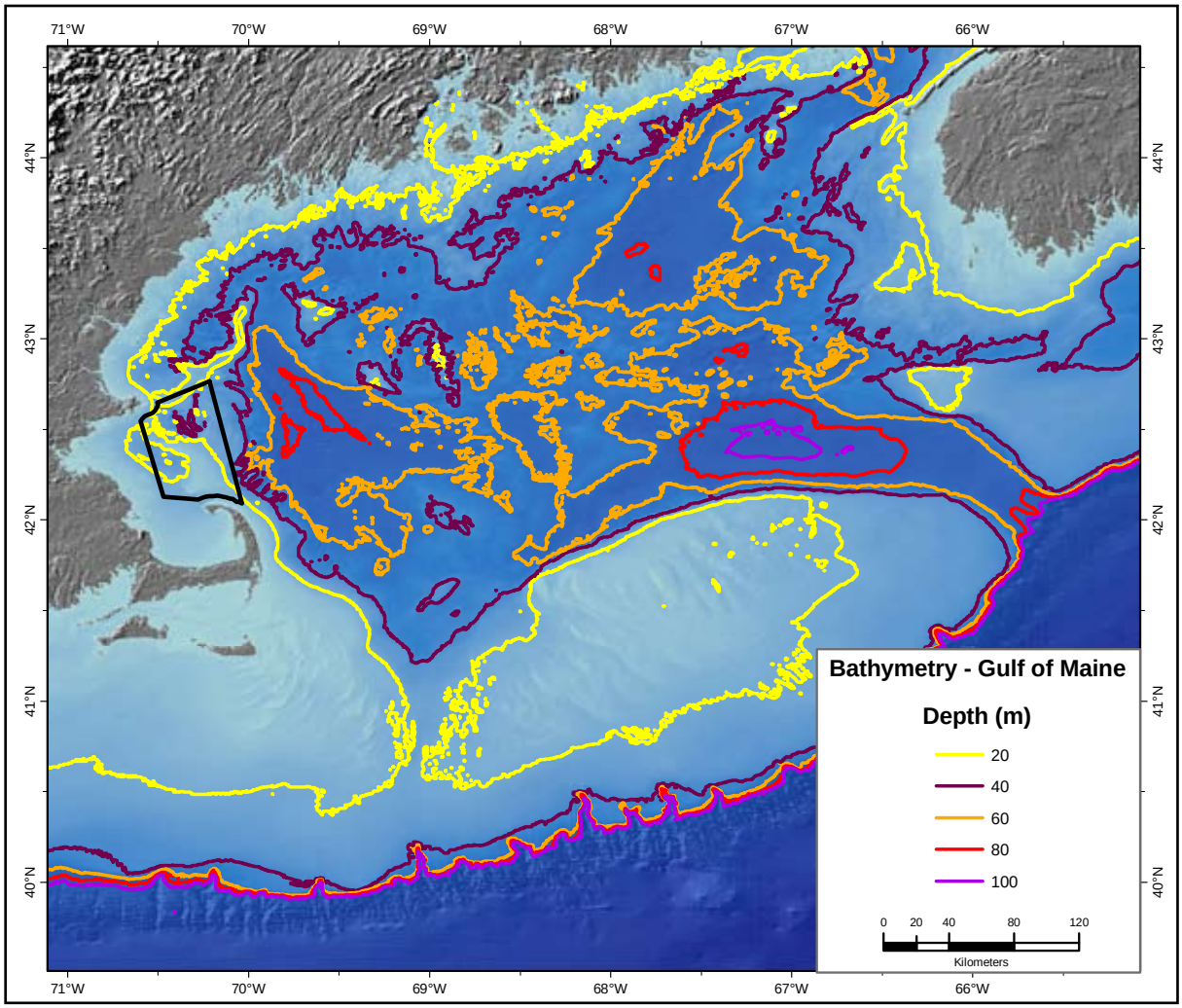

Figure 1.3.1. Gulf of Maine bathymetry with contour lines to 100 m.

2004). Direct links to NAO phase have also been observed with fish, marine mammals, and seabirds (Drinkwater *et al.,* 2003).

1.3 BATHYMETRY

The Gulf of Maine's bathymetry is complex and has a long history of data collection. The U.S. Geological Survey developed a digital bathymetric grid for the Gulf of Maine with 15-second (~400 m) resolution. The grid is a compilation of smaller digital datasets primarily from the National Ocean Service Hydrographic Data Base, Naval Oceanographic Office Digital Bathymetric Data Base, Bedford Institute of Oceanography, and Brookhaven National Laboratory (Roworth and Signell, 1998).

The Gulf of Maine contains several prominent banks and basins that are flanked by two deep channels leading into the Atlantic Ocean (Figure 1.3.1). The two most prominent banks, Georges Bank and Browns Bank, define the seaward edge of the Gulf of Maine. Georges Bank comprises an area of 38,458 km^2 that rises from a depth of 200 m and reaches its shallowest depth at approximately 40 m. Browns Bank is separated from Georges Bank by the Northeast Channel and comprises an area of approximately 1,781 km^2. Depth at Browns Bank ranges between 100-200 m.

Many large basins are found throughout the Gulf. Wilkinson Basin, which is approximately 105 km W-E and 165 km N-S at its widest points, has a maximum depth of around 280 m, and is situated between Cape Ann to the west and Cashes Ledge to the east. Jordan Basin, which is approximately 115 km W-E and 125 km N-S at its

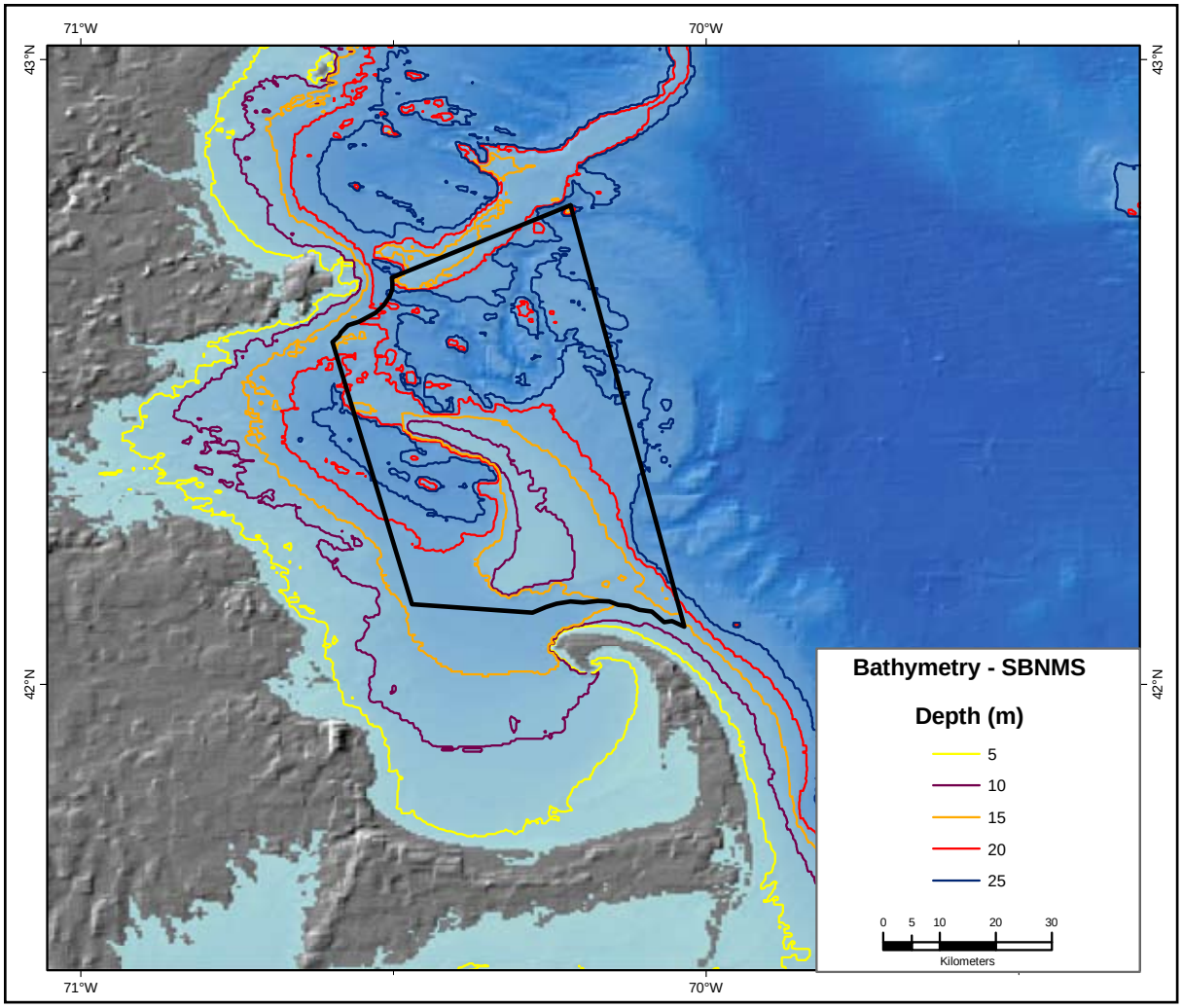

Figure 1.3.2. Bathymetry within Stellwagen Bank National Marine Sanctuary.

widest points, has a maximum depth of around 300 m, and is situated at the mouth of the Bay of Fundy. Georges Basin, which is approximately 90 km W-E and 30 km N-S at its widest points, has a maximum depth of approximately 377 m, and is located at the mouth of the Northeast Channel leading into the Gulf of Maine.

The major bathymetric features within Stellwagen Bank NMS include, Stellwagen Bank, Tillies Bank, Jeffrey's Ledge, Stellwagen Basin, and Gloucester Basin (Figure 1.3.2). Stellwagen Bank comprises most of the central and southeastern portion of the Sanctuary where depths range between 19-37 m. Waters adjacent to the west of the Sanctuary can be as deep as 100 m, and depths seaward of the continental shelf edge can surpass 200 m. Tillies Bank is located in the northern portion of the Sanctuary, surrounded by deep channels at approximately 50 m. Jeffrey's Ledge is a large ridge that extends approximately 53 km to the northeast with water depths ranging between 30-67 m. Only a small portion of the ledge is located in the northern portion of the Sanctuary. Stellwagen and Gloucester Basin's comprise approximately 25% of the Sanctuary and contain the deepest portions of the Sanctuary at approximately 60 m.

Bathymetric Complexity

Examining bathymetric complexity serves as a proxy for quantifying structure in the region (i.e. mesoscale rugosity). This analysis provides context to provide potential linkages to spatial patterns and observed biogeographic patterns described in subsequent chapters. For example, offshore circulation patterns in the region result, in part, from the interaction of large-scale ocean currents, local geography, and the unique basin and bank topography of the Gulf of Maine. These currents influence the distribution of marine organisms in the region. Additionally, areas of high structural complexity may exhibit high diversity per unit area (Hixon *et al.,* 1991; Hixon and Tissot, 1992;

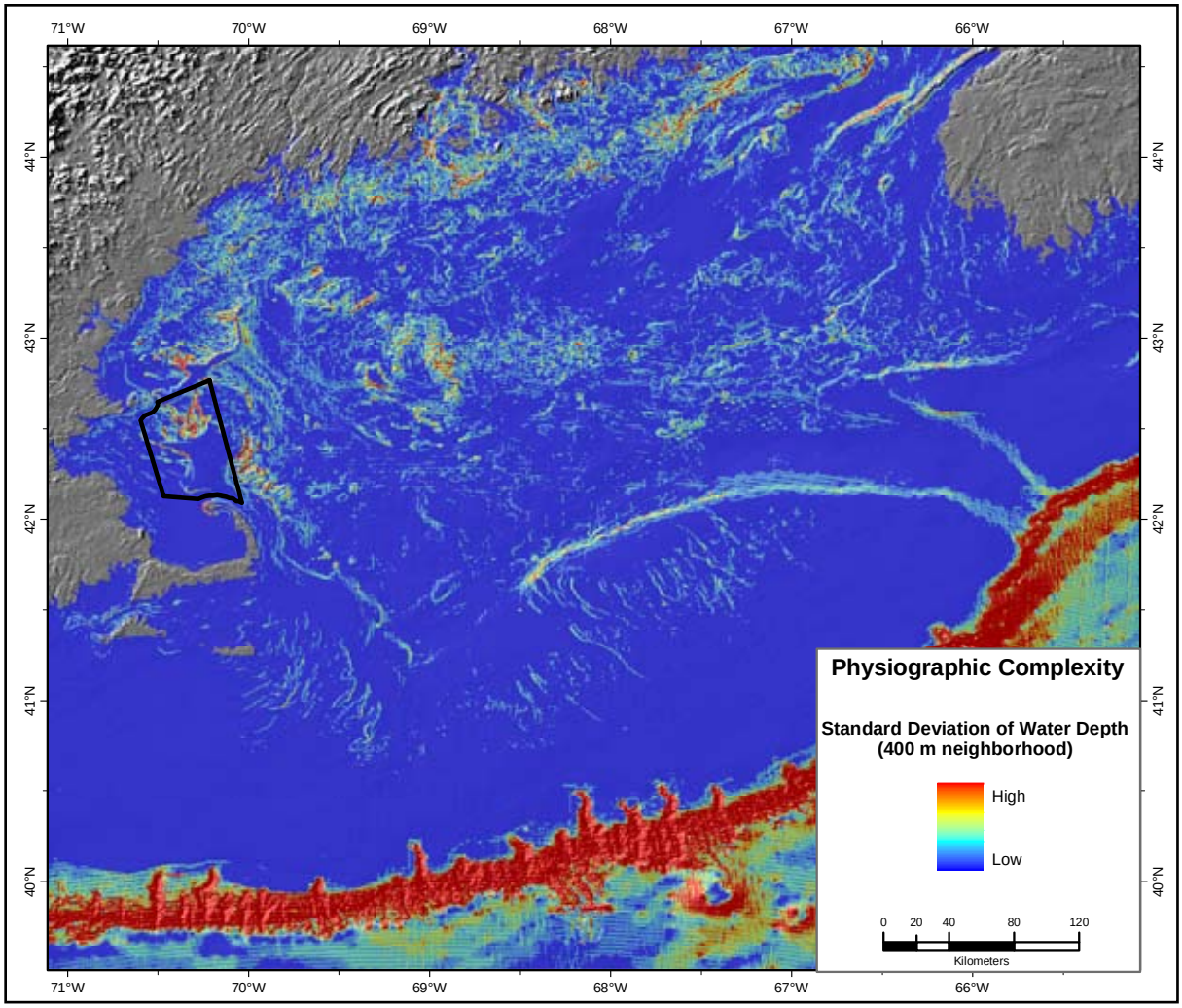

Figure 1.3.3. Bathymetric complexity within the Gulf of Maine.

Auster et al., 1998; Starr, 1998; Yoklavich *et al.,* 2000, 2002; Auster et al., 2001; Field *et al.,* 2002; Williams and Ralston, 2002; Auster and Lindholm, 2005).

Bathymetric complexity was calculated using the USGS 15-second bathymetry grid using a neighborhood statistical function in ArcMap 9 (GIS), that depicts the degree of variation in water depth within a prescribed (and constant) area for the entire seascape. A standard deviation of water depth was calculated within a 400 m radius "moving window". The calculated standard deviation was then assigned to the centroid of that neighborhood. This analysis was performed by centering the moving window on each bathymetric grid cell in the source data, and resulted in an estimate of the standard deviation of bathymetry at a scale of 400 m for the entire region (Figure 1.3.3). Areas of high complexity are highlighted by warm colors (red, orange, yellow) and indicate where complexity is greater than 2 standard deviations above the mean. The most notable area of high complexity is observed where the continental shelf drops rapidly. The continental slope drops sharply from the edge of the continental shelf (~100 m) to depths greater than 2000 m. This analysis also highlights the many submarine canyons and seamounts at the shelf/slope interface. Areas of high complexity are numerous on the shelf, most notably along the northern fringe of the Gulf adjacent to the shorelines of Maine, New Hampshire, and Massachusetts. High complexity is observed on the northern edge of Georges Bank and the southwestern edge of Browns Bank that form the corridor of the Northeast Channel. Approximately 18% of the area within the Sanctuary (398 km^2) is characterized by high complexity. These areas are located around Stellwagen and Tillies Banks and Lower Jeffreys Ledge, as well as smaller features in the northern portion of the Sanctuary; Ellipse, Polygon, and Thacher Banks (Figure 1.3.4).

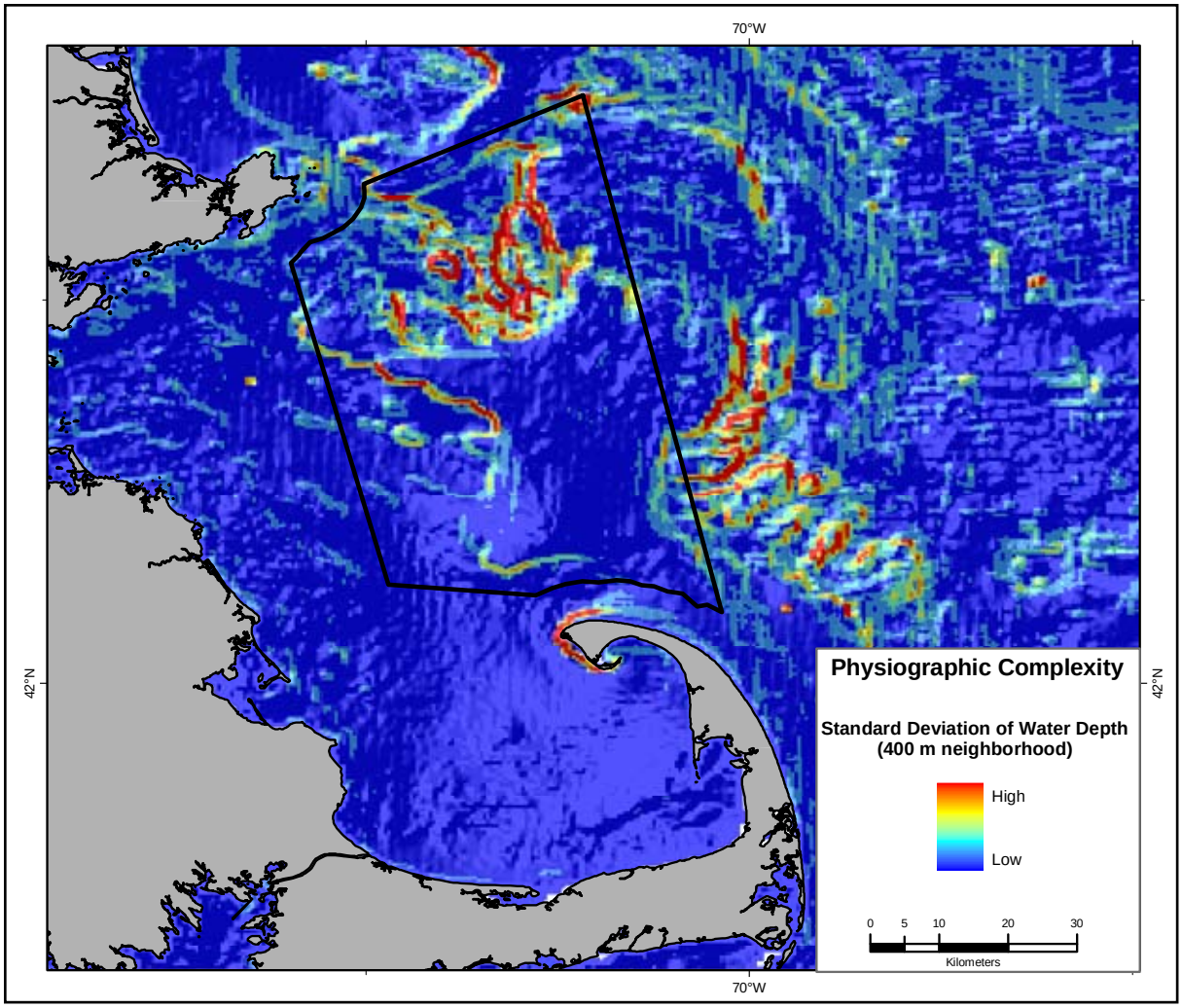

Figure 1.3.4. Bathymetric complexity within the Stellwagen Bank National Marine Sanctuary.

1.4 BENTHIC SUBSTRATE

Geologic History

Throughout time the Gulf of Maine has been shaped by fluvial and glacial erosion (Emery *et al.,* 1965; Ziegler *et al.,* 1965). Approximately 20,000 years ago, the Gulf of Maine was covered with glacier ice. Several thousand years later the ice retreated and the Gulf was exposed as dry land, allowing it to be eroded by newly-formed streams (Belknap *et al.,* 1988). Such dominant topographic features, like the Northeast Channel, may have been carved out by this riverine system (Conklin, 1995). As the glacier retreated, it scoured the Gulf basin, further excavating valleys previously created by stream erosion. These excavated valleys became what are now known as the Jordan, Georges and Wilkinson Basins (Babb and DeLuca, 1988; Conklin, 1995). At the same time, rising seas began to flood the Gulf of Maine basin, as the glacial ice continued to melt (Conklin, 1995). This trend was subsequently reversed when glacioisostatic rebound began, continuing in the region until around 9,500 years ago (Babb and DeLuca, 1988). The oscillatory rise and fall of the shoreline and sea levels through out the region's geologic history played a major part in developing the general distributions of sediments that exist today (Wahle, 2000).

Sediments

The uneven topography and mixture of sediment types in the Gulf of Maine promote diverse and heterogeneous benthic habitats. Within the Gulf there are three major sediment environments: rocky ledge, sandy nearshore ramp, and basin (Belknap *et al.,* 1988). Rocky ledges are spread throughout the Gulf (Conklin, 1995), such as Jeffreys Ledge (Figure 1.4.1), and are generally clear of sediments. Rocky ledges are typically colonized by di-

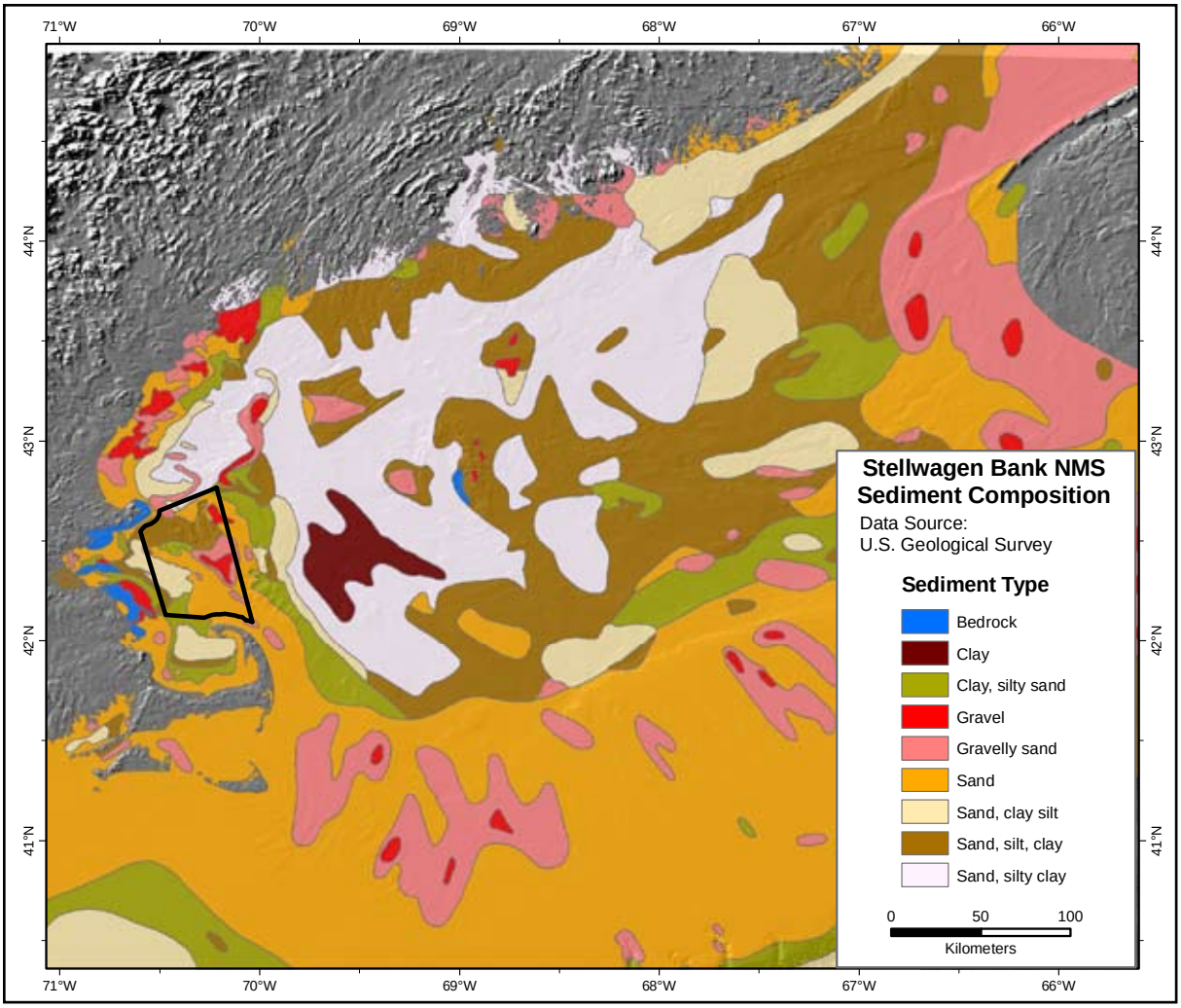

Figure 1.4.1. Broad-scale sediment composition with the Gulf of Maine.

verse assemblages of algae and sessile invertebrates (Sebens *et al.,* 1988; Vadas and Steneck, 1988). Ledges vary in size but generally change with depth into a shell-hash, gravelly apron and tapering into sand or mud. Sand ramps are remnants of reworked river deltas or beach deposits with banding, ripples, and waves which are influenced by currents and wave activity. Basins are the result of former estuaries during periods of lower sea-levels. They are typically comprised of organic-rich muds and are extensively bioturbated.

Since 1962, the U.S. Geological Survey and the Woods Hole Oceanographic Institution have been collecting continental shelf sediment information off the eastern United States. Thousands of sediment samples have been collected and interpreted (USGS, 2000) to provide a comprehensive map of benthic substrate from Connecticut through Maine and extending offshore to the continental shelf-slope interface (Figure 1.4.1). The sediment data is categorized into nine sediment types based on grain size analysis: bedrock, gravel, gravel-sand, sand, clay-silt/sand, sand-silt/clay, sand-clay/silt, and clay (Table 1.4.1). Mud is a common sediment component in the deep water basins and is represented in these data by the sand-silt/clay and sand-clay/silt categories.

The Gulf of Maine is mostly covered by sand and mud, comprising nearly 83% of the total bottom area. Sediments of larger grain size, such as bedrock and gravel, comprise approximately 16% of the benthic sediment cover within the Gulf.

Sediment distribution within the Stellwagen Bank NMS is proportionally similar compared to the Gulf of Maine. Similar proportions of large grained sediments, sand, and mud are found within the Sanctuary, however, these data indicate that there are no areas of exposed bedrock or clay within the Sanctuary (Table 1.4.2).

A cooperative effort involving the USGS, NOAA, the University of New Brunswick and the Canadian Hydrographic Service developed a higher resolution benthic substrate map for the Stellwagen Bank Sanctuary (USGS, 2000). Multibeam echo sounder surveys were conducted between Fall 1994 and Fall 1996 resulting in 18 quadrangles within and adjacent to the Stellwagen Bank NMS. The maps revealed for the first time the high variability in sediment texture and seafloor morphology over small spatial scales. The images depict high resolution benthic substrate composition in terms of hardness in contrast to the more broad-scale map of interpolated sediment cores. Figure 1.4.2 displays multibeam backscatter intensity as a measure of benthic substrate composition within the Sanctuary with hard or coarse grained sediments (rocky outcrops, boulders, gravel) in orange; less coarse sediments (large grained sands) as green; and, soft sediments (fine grain sand and mud) as blue. In general, the basins (colored blue) within the Sanctuary (Stellwagen Basin in the southeastern portion of the Sanctuary, Gloucester Basin in the northwest) are composed of mud and fine sand. Overall, the soft sediment type comprises approximately 617 km^2 of the Sanctuary. The larger sediment types (colored in orange) typically occur on the surface of banks and ridges and are primarily composed of exposed rock, boulders, and gravel. Within the Sanctuary these sediments cover approximately 822 km^2. Medium sized sand sediments (colored in green) can also occur on bank and ridge surfaces, but are the dominant sediment types along the slopes of bank and ridge features that lead to the deeper basins. These sediments account for approximately 749 km^2 of the Sanctuary's total area (Figure 1.4.3).

Table 1.4.1. Benthic sediment type in the Gulf of Maine. Source: Brown et al., 1989; USGS, 1995.

Sediment Type	Grain Size (mm)	Relative Cohesiveness	Area (km^2)	Area (%)
Bedrock	N/A	Not Cohesive	527	0.24
Gravel	>2		2,866	1.32
Gravelly Sand	0.25-2		30,543	14.09
Sand	0.125-1		73,339	33.83
Sand & Clay Silt	0.002-1		26,905	12.41
Sand, Silt & Clay	0.002-1		31,494	13.12
Sand & Silty Clay	0.002-1		28,438	14.53
Clay & Silty Sand	0.002-0.25		21,101	9.73
Clay	0.0005-0.002	Cohesive	1,587	0.73

Table 1.4.2. Benthic sediment type within Stellwagen Bank NMS. Source: Brown et al., 1989; USGS, 1995.

Sediment Type	Grain Size (mm)	Relative Cohesiveness	Area (km^2)	Area (%)
Bedrock	N/A	Not Cohesive	0	0
Gravel	>2		146	6.67
Gravelly Sand	0.25-2		243	11.09
Sand	0.125-1		823	37.52
Sand & Clay Silt	0.002-1		264	12.05
Sand, Silt & Clay	0.002-1		510	23.26
Sand & Silty Clay	0.002-1		33	1.52
Clay & Silty Sand	0.002-0.25		172	7.86
Clay	0.0005-0.002	Cohesive	0	0

Periodically, benthic sediments can be resuspended due to high surface wave energy. Typically, winter storms with strong winds from the northeast generate sufficient bottom currents to resuspend sediments at depths less than 50 m (Butman et al., in prep). Although less frequent, summer storms may have significant intensity to generate high surface wave energy. Within Massachusetts Bay, the western shoreline and the top of Stellwagen Bank are shallow enough to facilitate sediment resuspension due to strong surface wave energy. Within Stellwagen Bank NMS, approximately 25% (505.4 km^2) of the Sanctuary is less than 50 m, however, the majority of the sediment is large or moderate in grain size (Figure 1.4.2). Strong surface wave energy may exceed a threshold for sediment resuspenion at 30 m; 10% during the winter (thee days/month) and 4% (one day/month) during the summer. At 50 m, resuspension rates fall to 1.6% (.5 days/month) during winter and 0.2% (0.1 day/month) during the summer. Resuspension at depths greater than 85 m are almost negligible during both summer and winter (Butman et al., in prep).

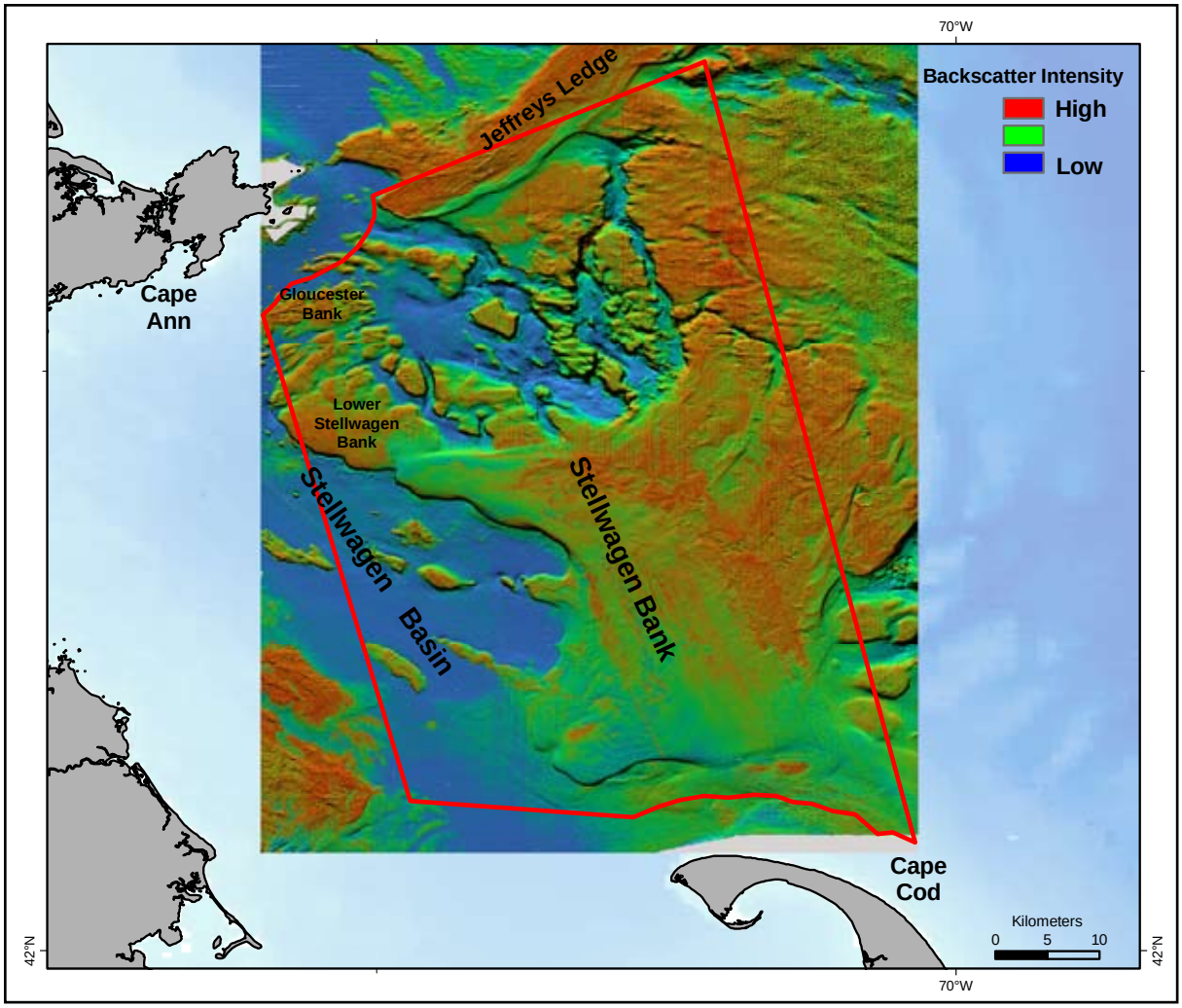

Figure 1.4.2. Backscatter intensity and shaded relief topography of Stellwagen Bank NMS. Red indicates high backscatter intensity material (gravel and rock); blue indicates low backscatter intensity material (fine sand and clay); green indcates medium backscatter intensity typical of coarse sand (USGS, 2000).

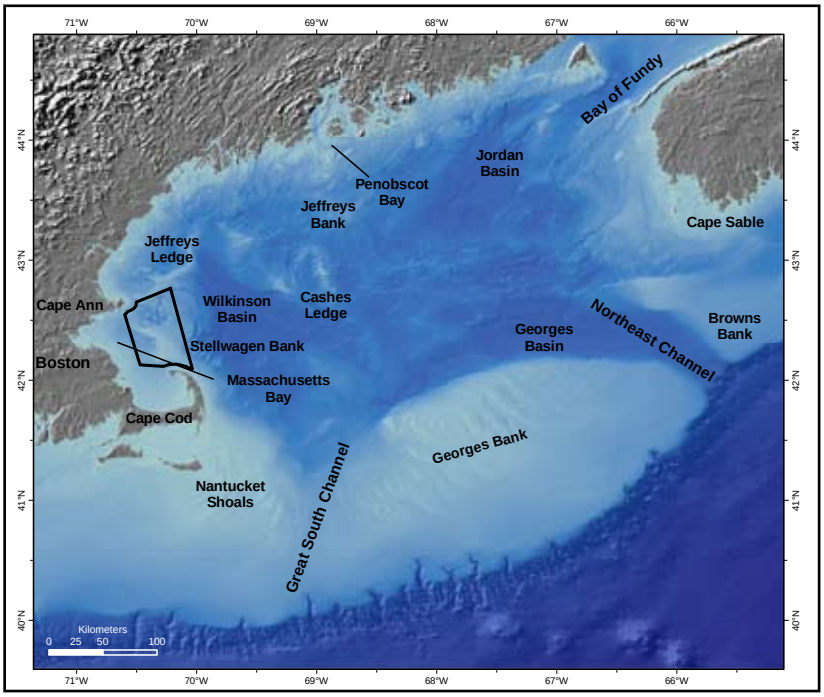

Figure 1.4.3. Percent area (km^2) of substrate composition within Stellwagen Bank NMS. Source: USGS, 2000.

Along the western shore of Massachusetts Bay, resuspended sediments are typically transported towards Cape Cod Bay and Stellwagen Basin and deposited (Butman and Bothner, 1997) and this mechanism has been hypothesized to be correlated with elevated levels of contaminants from Boston Harbor (Ravizza and Bothner, 1996).

The distribution of benthic fishes and invertebrates are strongly related to bottom type (Watling *et al.,* 1988; Langton and Uzmann, 1989; Langton and Robinson, 1990). Accordingly, the wide variety of bottom types within the Gulf of Maine and the Stellwagen Bank NMS support a diversity of habitats for fish and invertebrate communities (Mountain and Jessen, 1987; Auster et al., 2001).

1.5 SEA SURFACE TEMPERATURE

The waters within the Gulf of Maine and the northern Atlantic Ocean undergo a significant annual temperature cycle. The region from the Mid-Atlantic Bight to the Grand Banks exhibits the highest interannual variability in sea surface temperature anywhere in the North Atlantic Ocean (Petrie and Drinkwater, 1993). Variability in sea surface temperature is a reflection of circulation and climate changes that may occur at episodic, seasonal and inter-annual time scales. In summary, relatively cold and low salinity water from the Scotian Shelf enters the Gulf in the surface layers around Cape Sable. Relatively warm, saline water from the offshore slope enters at depth through the Northeast Channel. These inflows progressively mix as they move counterclockwise around the Gulf of Maine. Characterizing the distribution and variability of sea surface temperature is fundamental to understanding the environmental conditions influencing the variability of the coastal and estuarine ecosystems in marine sanctuaries and larger ecosystems. The variability in water quality conditions over time can be linked to changes observed in established surveys of living marine resources, including distributions of seabirds, fish, and marine mammals. This section examines sea surface temperature patterns and frontal boundaries within the Gulf of Maine and provides context for subsequent biological analyses.

Quantifying sea surface temperature variability over a large area is difficult to characterize from shipboard or moored measurements, but can be assessed from long-term, well-calibrated satellite data. Sea surface temperature (SST) data were received from the NASA Pathfinder Version 5.0 dataset. This dataset derives a climatological grade sea surface temperature product from Advanced Very High Resolution Radiometer (AVHRR) imagery, which was generated from several NOAA Polar-orbiting Environmental Satellites (POES) between 1985-2004. The Pathfinder dataset consists of seventeen years (1985 to 2001) of daily (excepting clouds) and monthly mean, climatological-grade georeferenced sea surface temperature data for coastal U.S. waters. Interim data of the same quality was available for 2002 to 2004 from the National Oceanographic Data Center at NOAA. The Pathfinder dataset was calibrated for inter-comparison of the temperature data across the entire period, facilitating climate and other studies (NASA, 2004; NASA, 2005). Spatial resolution of the Pathfinder data varies slightly with latitude, with a horizontal resolution of about 4 km at 35 degrees of latitude. Pathfinder is distributed along a 0.04 degree grid in Cartesian coordinates. The original 4 km data were resampled to 1.1 km to match the spatial resolution of the SeaWiFS dataset and to create subsets of the same region as the chlorophyll and turbidity images (Section 1.7). Monthly images were produced from daily images. The majority of the products were obtained as monthly means and then binned to seasonal and inter-annual monthly means. Seasonal images were created from the monthly mean images using the following seasonal breakdown:

Fall-September, October, November
Winter-December, January, February
Spring-March, April, May
Summer-June, July, August

All image data was subset to the specified region of interest and reprojected into Albers Conical Equal Area projection using the North American Datum 1983 with Geodetic Reference System 80 ellipsoid.

In addition, monthly, seasonal, and annual sea surface temperature data were extracted for the area within Stellwagen Bank NMS to examine spatial and temporal patterns. These data may be useful to further understand oceanographic dynamics, as well as examine any possible correlations with biological resources.

Sea surface temperature within the Gulf of Maine (Figures 1.5.1 and 1.5.2) exhibit significant seasonal patterns where warmest values were observed during the summer, transitions during spring and fall, and lowest during the winter. The influx of cooler waters from the Scotian Shelf are most obvious dung the spring and winter. During the spring and summer cooler waters were observed entering the Gulf from the Bay of Fundy and Penobscot Bay as a result of tidal mixing and runoff from spring rainfall. During the summer, the majority of the central Gulf is stratified and sea surface temperature is generally homogeneous. Cooler waters are also observed around Georges Bank during the summer as a result of vertical current mixing (Brown *et al.,* 1989; Sherman *et al*, 1996).

These trends are more apparent when examining mean monthly sea surface temperature maps (Appendix 1). Cooler waters associated with the Maine Coastal Current are also evident during late summer and fall (June-October).

Sea surface temperature patterns within Stellwagen Bank NMS exhibited similar monthly and seasonal patterns as that observed for the Gulf (Figure 1.5.3). Data were not available between Feb-June 1995. Spring temperatures were typically the coolest ranging between 12-13.8°C. Mean temperature was greater than average during 1998-2002. Summer temperatures ranged from 19-21.8° C. Fall temperatures exhibited slightly more variability than spring

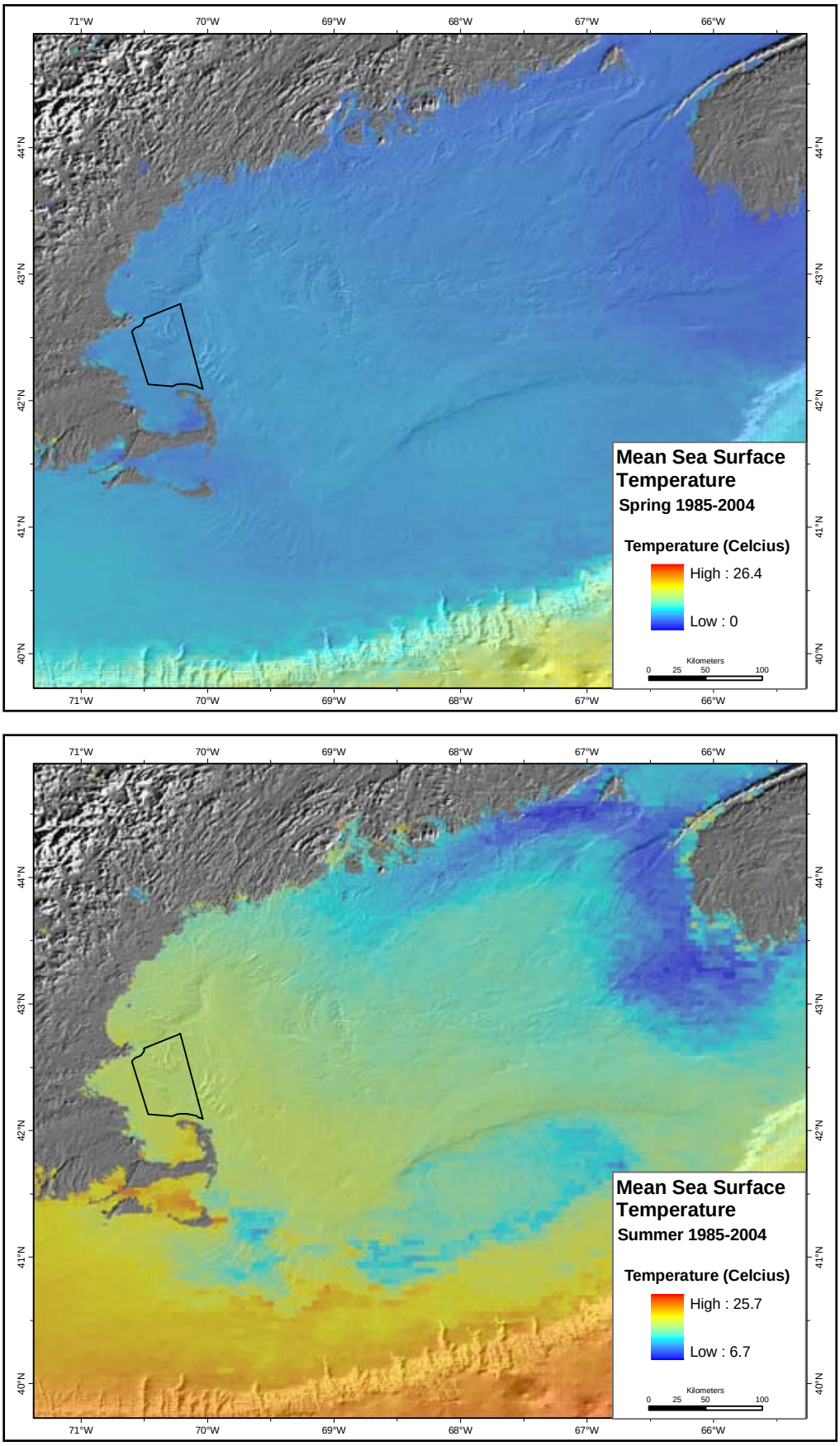

Figure 1.5.1. Spring and summer mean sea surface temperature within the Gulf of Maine, 1985-2004.

and summer data and ranged from 17.6-19.6° C. Winter temperatures exhibited the most variability among seasons and ranged from 12.2-15.6° C. These patterns of variability can be seen in the bottom graph of Figure 1.5.3. The greatest seasonal anomaly was observed during Fall 1995 when temperatures were 3° C above the mean. In general, annual seasonal means matched the grand mean (all seasons average) with slightly colder than average mean temperatures observed during spring 1987-1992 and warmer than average during summer 1989, 1994, 1999, and 2003.

Within Massachusetts Bay there is strong seasonal stratification during the summer, which acts as a barrier to exchange between the surface and deeper waters (Geyer *et al.,* 1992). This stratification leads to higher water temperatures at the surface which can be 10-12° C warmer than found at depth (Geyer *et al.,* 1992).

Thermal Fronts

Flow of water across topographic features produces patterns of vertical circulation, fronts, or eddy-like motions which can affect biological distributions. These patterns can also arise independently of bottom topography from ocean current confluence, unevenly applied wind stress, or from heat and water exchange across the sea surface (Owens, 1981). Fronts are created by a variety of physical processes and have a variety of biological consequences. A frontal system denotes areas of water mass convergence and usually pro-

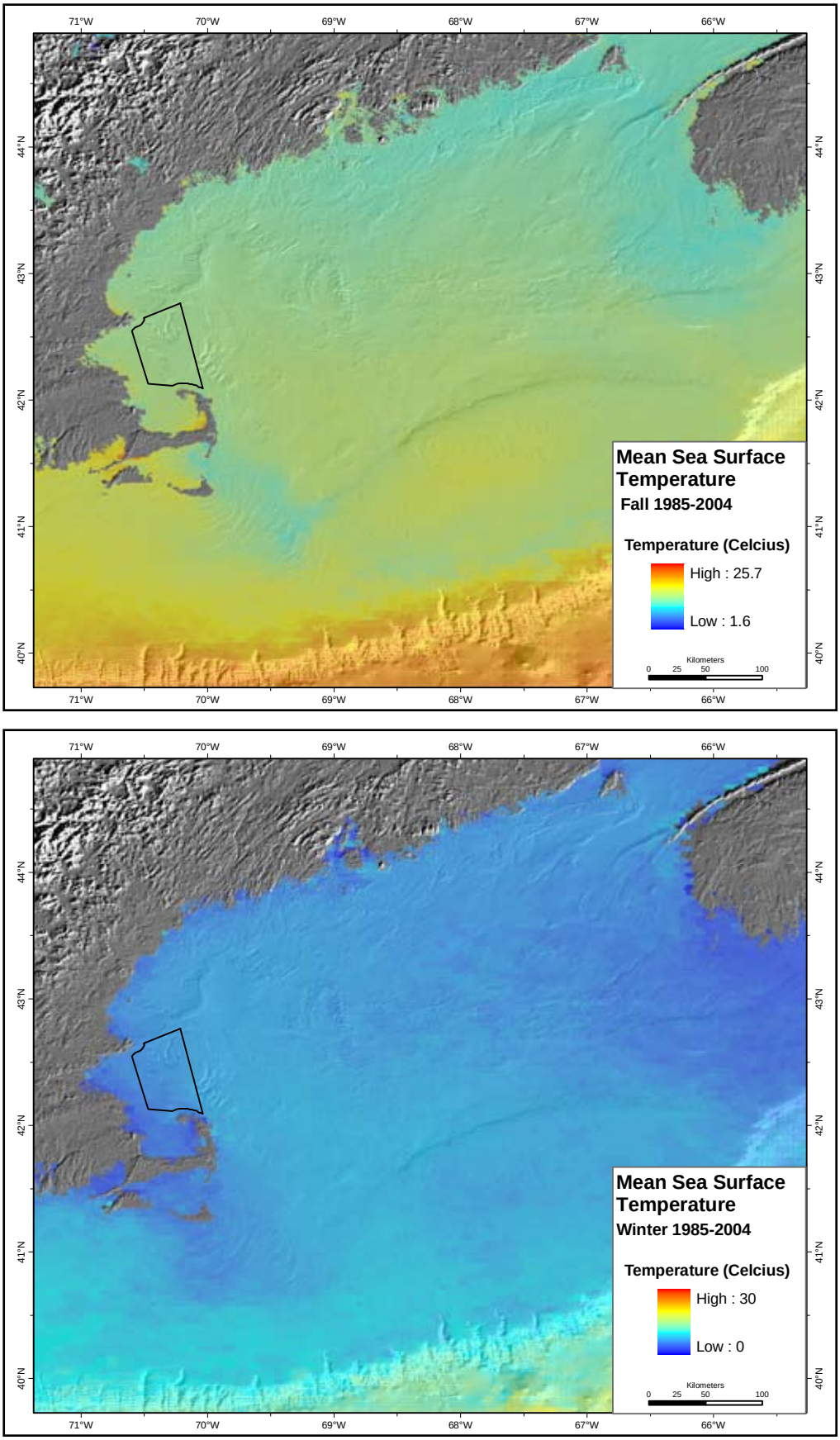

Figure 1.5.2. Fall and winter mean sea surface temperature within the Gulf of Maine, 1985-2004.

duce zones of downwelling and upwelling flow. These vertical displacements have considerable ecological effects because environmental gradients, such as light, pressure, temperature, salinity, oxygen, nutrients, etc., are steepest in the vertical axis of the water column (Owens, 1981).

Vertical motion in fronts is often highly localized and can be easily identified with remote sensing techniques (Ullman and Cornillon, 1999). Several areas within the Gulf of Maine region have sustained and well defined frontal areas. These areas include the shelf/slope interface, Georges Bank, and along the Eastern Maine Coastal Current and are visible as distinct color gradients in Figures 1.5.1 and 1.5.2.

Areas with frontal activity tend to be areas of high biological activity. The vigorous mixing of the water column at water mass confluence stimulates phytoplankton photosynthesis and sustains concentrations along the frontal zone (Savidge, 1976; Savidge and Foster, 1978). In response, zooplankton tend to concentrate along the fronts which in turn, are preyed upon by higher trophic groups. Marine birds (Kinder *et al.,* 1983; Haney and McGillivary, 1985; Briggs *et al.,* 1987; Brown and Gaskin, 1988; Hoefer, 2000), marine mammals (Gaskin, 1976; MacGarvin and Simmonds, 1996; Macleod *et al.,* 2005) and fish (Roberts, 1980; Brandt and Wadley, 1981; Laevastu and Hayes, 1981; Magnuson *et al.,* 1981; Fiedler and Bernard, 1987; Nero *et al.,* 1990) often aggregate at frontal areas. Worms *et al.* (2005) state that biological diversity is positively correlated with thermal fronts.

Oceanographic frontal habitats are poorly understood in the Gulf of Maine, as well as marine ecosystems worldwide and warrant additional studies to improve knowledge for ecosystem management.

1.6 CIRCULATION AND CURRENTS

Currents

The Gulf of Maine's intricate topography, strong tidal mixing, and seasonal atmospheric interactions results in a complex circulation pattern. Numerous shelf processes interact

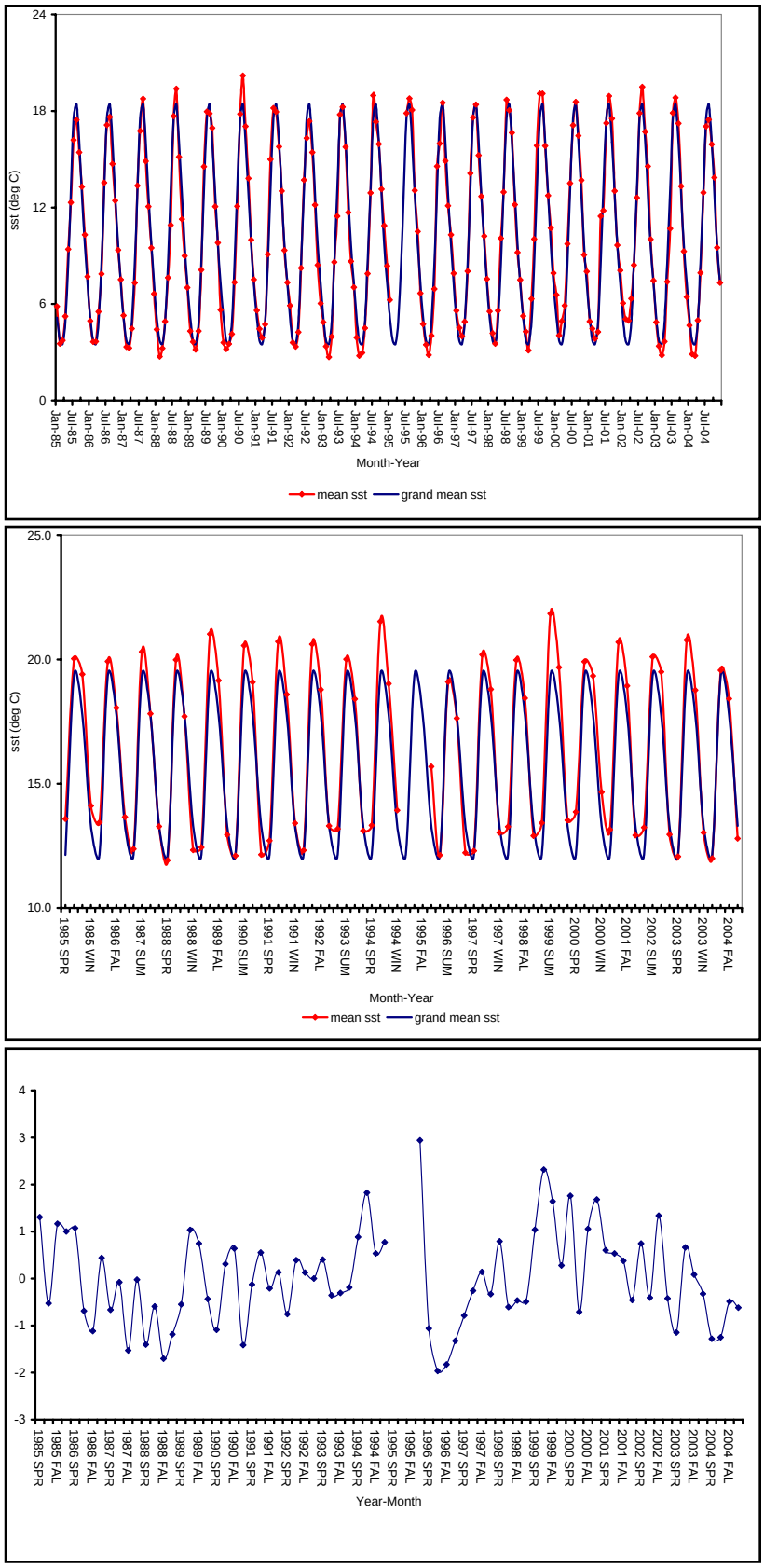

Figure 1.5.3. Sea surface temperature analysis within Stellwagen Bank NMS: top-monthly mean; middle-seasonal mean; bottom-temperature anomaly. Data were unavailable for Feb-June 1995.

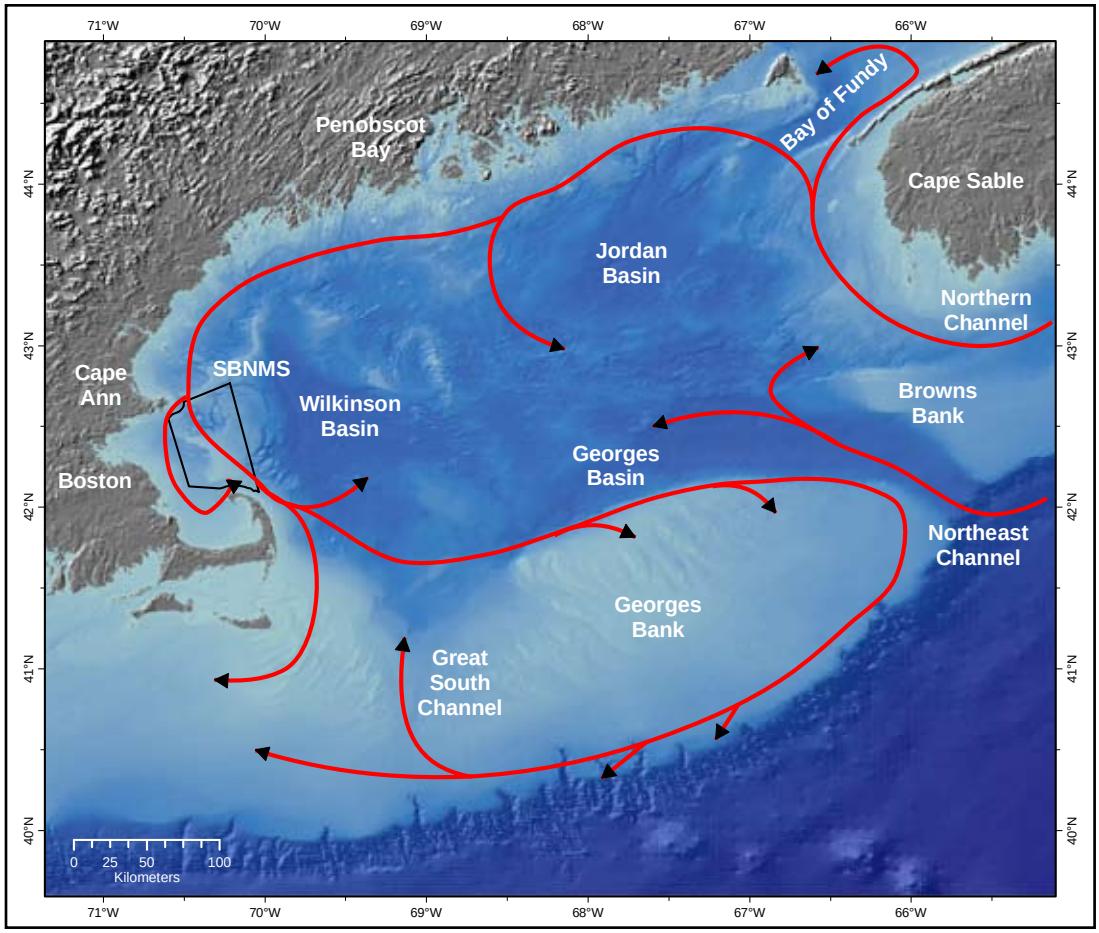

Figure 1.6.1. General pattern of non-tidal surface circulation within the Gulf of Maine (Lynch et al., 1996.

at various length and time scales within the Gulf of Maine that support such complexity. These include: two distinct inflows through the Northern Channel (Scotian shelf water) and the Northeast Channel (slope water); deep water formation within three large basins; tides, tidal mixing, and tidal rectification; wind; seasonal stratification and frontal circulation; freshwater inflow, and local estuarine processes (Lynch *et al.,* 1996). Freshwater river input from more than 60 rivers along the coastline contributes to circulation in the Gulf. In general non-tidal surface currents in the Gulf of Maine flow in a counter clockwise motion (Figure 1.6.1). In the spring and summer, dense slope water tends to accumulate in the Gulf which enters from the Northeast and Great South Channels. As a result, counterclockwise gyres form in the deep basins, in particular George's Basin and Jordan's Basin. In the summer surface waters follow the contour of the mainland moving southward, feeding an outflow past Cape Cod and along George's Bank. This circulation pattern strengthens in the spring and persists through the summer. At the onset of winter cooling, the Gulf gyre weakens and circulation is more heavily influenced by winds (Sherman *et al.,* 1996). These general circulation patterns are dynamic and are primarily influenced by several features in the Gulf of Maine:

- Maine Coastal Current
- Northeast Channel Inflow
- Gyre Circulation

Maine Coastal Current

This current flows southwesterly from the Bay of Fundy to Penobscot Bay, where it is deflected seaward by outflow from the Bay and circulates cyclonically (anti-clockwise) within the Jordan Basin Gyre. Current deflection varies due to seasonal freshwater outflow from the Bay. Flow continues parallel to the shoreline where a second branch near Cape Ann directs flow into Massachusetts and Cape Cod Bays. A third branch occurs east of Cape Cod that diverts flow to the eastern flank of Georges Bank and the remainder leaves the Gulf via the Great South

Channel (Lynch *et al.,* 1996). The current is seasonally enhanced by runoff from rivers where on average 250 billion gallons of fresh runoff/year enters the Gulf.

Seawater Inflow

The Northeast Channel is the primary conduit for slope water flowing into the Gulf of Maine and is an important source for inputs of mass, heat, and freshwater. This nutrient rich water mixes with water from the Scotian Shelf to form Maine Bottom Water (Bisagni *et al.,* 1996). A pressure gradient is established as the basins fill with dense slope water adjacent to the less dense Maine Coastal Current that contributes to the cyclonic (counterclockwise) flow.

Gyre Circulation

The interior Gulf of Maine has cyclonic circulation regions situated over three deep basins–Georges, Jordan and Wilkinson. The gyres are influenced by the deep inflow of saline waters through the Northeast Channel and forced by topography (Hannah *et al.,* 1996; Lynch, 1999). It has been observed that the dominant temporal variability in the gyres or between gyres occurs over several months (Xue *et al.,* 2000). The current patterns in the Gulf of Maine are greatly affected by the physical characteristics of the Gulf and its coastline. In general, cold water enters the Gulf over the Scotian Shelf, Browns Bank and through the Northeast Channel. Water flows around Nova Scotia and into the Bay of Fundy. The coast then deflects currents southwestward forming the Gulf of Maine Gyre, which rotates counterclockwise, moving surface waters about 7 nautical miles per day. Tidal fluctuations and shallow water over Georges Bank form a secondary, clockwise-spinning gyre. Water leaves the Gulf through the Great South Channel and over the eastern portion of Georges Bank. It takes about three months for surface water to completely circle the Gulf of Maine. Deep waters also circulate, but much more slowly, taking about a year to complete the circuit (Xue *et al.,* 1999).

The combination of tidal rectification and density driven fronts create a clockwise flow around Georges Bank. Currents are dominated by strong semidiurnal tidal components and a mean clockwise gyre that intensifies with increasing stratification in the summer. During the summer period, the gyre becomes partially closed with water parcels recirculating around the Bank with an approximate period of 50 days (Flagg *et al.,* 1982). Changes in the magnitude of the subtropical Gulf Stream and sub-polar Labrador Current transport due to differences in wind forcing, air temperature, and salinity could significantly impact the position and dynamics of ocean fronts, gyres, and other features in the Georges Bank area. Such changes may also affect the timing, intensity and location of stratification on the region's submarine banks. Other important processes, including water formation in the Labrador Sea (Lazier, 1981) and sea ice development (Hill and Jones, 1990), may be linked to climate change and other long-term fluctuations.

There is growing evidence that the circulation within Penobscot Bay and the eastern Maine shelf are strongly coupled. The outflow from Penobscot Bay may have an important influence on the circulation of the Gulf of Maine by causing a portion of the generally southwestward-flowing Maine Coastal Current to be deflected offshore and to recirculate cyclonically (counterclockwise) within the Jordan Basin Gyre (Brooks, 1994; Lynch *et al.,* 1997; Pettigrew *et al.,* 1998).

Among the three basins, Wilkinson Basin is the farthest away from the inflow region of the Northeast Channel and nearest to the outflow region through the Great South Channel. Furthermore, the underlying topography in this basin is fragmented, as compared to those in the Jordan and Georges Basins. Such physical constraints trigger vigorous water mass transformation processes in this particular basin throughout the year. The cyclonic gyres over the Jordan and Georges Basins are linked, and show evidence of seasonal coalescence. The gyre over the Wilkinson basin appears to be less well-defined than the other gyres, and geostrophic calculations suggest that it may rotate in either cyclonic or anticyclonic directions. Analysis of recent and historical data indicates substantial seasonal and interannual variability (Pettigrew *et al.,* 1998).

Massachusetts Bay Circulation

Circulation in Massachusetts Bay is controlled by the large-scale circulation in the Gulf of Maine, localized wind forcing, and freshwater inflow (Signell *et al.,* 2000). The Maine Coastal Current flows south at 5-15 cm/s along the Maine and New Hampshire shoreline and a weak branch (2-5 cm/s) occurs near Cape Ann. The stronger current flows southward over Stellwagen Bank and east of Cape Cod (Normandeau Associates, 1995; Vermersch

et al., 1979; Blumberg *et al.,* 1993; Lynch *et al.,* 1997). This branch follows the western shoreline of the Bay and drives a weak counter-clockwise flow that exits at Race Point (Bumpus, 1973; Geyer *et al.,* 1992). The circulation pattern can be altered by seasonal wind and runoff events (Signell *et al.,* 2000). The current joins smaller coastal currents and flows southward often penetrating deep into Cape Cod Bay (Jiang and Zhou, 2004). Seasonal variation in stratification occurs in Massachusetts Bay, with well-mixed conditions during winter and strong stratification during summer (Geyer *et al.,* 1992). The stratification greatly reduces vertical exchange between surface and bottom waters and isolates the bottom water from the direct influence of wind stress and river runoff (Signell *et al.,* 2000).

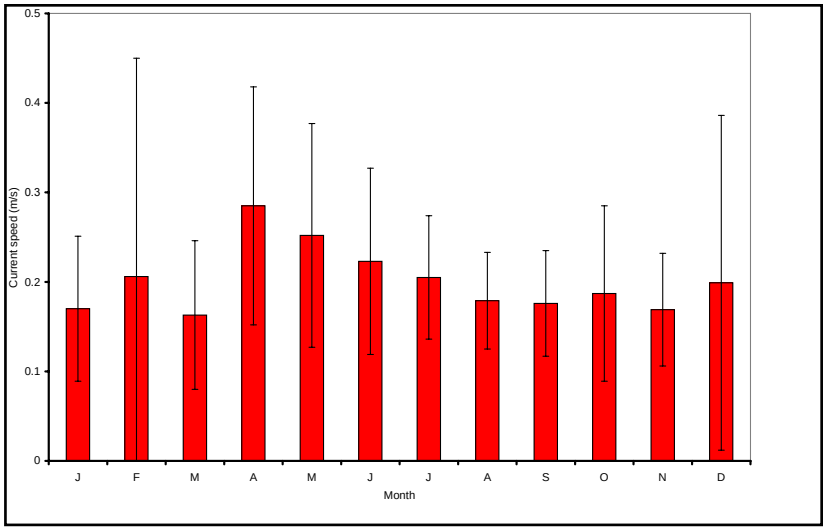

Figure 1.6.2. Mean monthly current speed and standard deviation for in-situ measurements (2002-2006) taken at GoMOOS Buoy A0116 within Massachusetts Bay.

Seasonal variations in stratification, wind stress, and river discharge change transport mechanisms and dispersion processes in the Bay. During winter, strong northerly winds enhance the counter clockwise circulation along the shoreline and northward flow in the deeper portions of the Bay (Butman, 1975; Brickley, 1994). In the spring, shallow (5-15 m) fresh water plumes enter the Bay, commonly generating strong currents (20-30 cm/s) with 10-30 km spatial scales (Butman, 1976; Lee, 1992). Summer conditions stratify the water column and frequent southwesterly winds can result in localized upwelling along the western and northern coast. During the fall, mean circulation reverses and flows northward as the result of strong cooling (Geyer *et al.,* 1992). Current speed and direction can vary spatially and temporally throughout the Gulf of Maine. Over 20 buoys are stationed throughout the Gulf that collect hourly oceanographic and meteorological data (see the Gulf of Maine Ocean Observing System, GoMOOS: < http://gomoos.org/buoy/buoy_data.shtml>). Hourly current speeds were obtained from the GoMOOS Buoy A (42° 31’40” N, 70° 33’59” W) during 2002-2006 to examine monthly and inter-annual patterns. During this time period mean current speed was highest (and most variable) during April and May and lowest speeds were observed during the summer and fall (Figure 1.6.2). Appendix 2 displays mean daily current speed per year during 2002-2006.

The significance of these patterns are of interest for the Stellwagen Bank NMS. Stellwagen Bank serves as a boundary between the Gulf of Maine to the east and Massachusetts Bay to the west and is an important determinant of the water properties within Massachusetts Bay. The Sanctuary is located along the path of the Maine Coastal Current, however the Sanctuary may receive surface and subsurface flows from Massachusetts Bay. The physical processes in Massachusetts Bay, and Stellwagen Bank NMS, are critical to the local fishing industry, recreation, and resource conservation. Understanding circulation patterns can help identify biological sources (larval fish recruitment, zooplankton distribution) to the Sanctuary and may provide insight into transport and deposition of sediments and potentially harmful contaminants from local sewage discharges.

Water circulation has been modeled intensively throughout the Gulf of Maine (Lynch *et al.,* 1996; Xue *et al.,* 2000). Three dimensional hydrodynamic models have been created for Massachusetts Bay to examine contaminated sediment accumulation and transport (Signell *et al.,* 2000) and deepwater renewal (Jiang and Zhou, 2004). The model used in these studies is called ECOM-si, a semi-implicit variant of the three-dimensional Estuary, Coastal and Ocean Model (ECOM) described by Blumberg and Mellor (1987). The model includes many parameters (e.g. wind stress, river runoff) to model circulation and was designed to allow realistic simulations. The model was configured on a horizontal curvilinear orthogonal grid exhibiting grid width from approximately 600 m in Boston Harbor to 6,000 m along the open boundary with the Gulf of Maine. The grid extends well off shore of Massachusetts Bay to allow exchange with the Gulf inside the model domain, and extends northward to include the Merrimack River, a large source of freshwater in the region. In-situ salinity, temperature, wind data

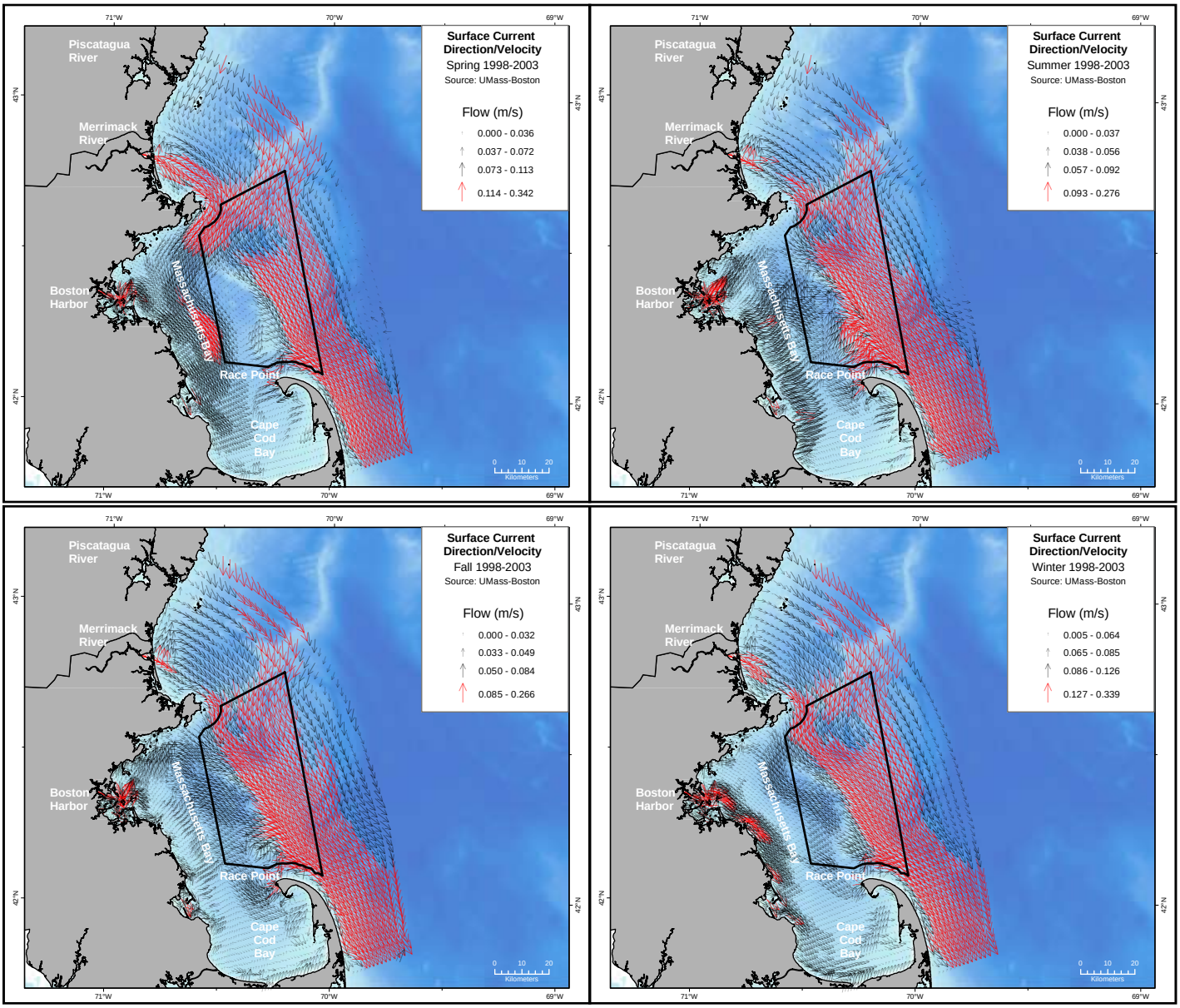

Figure 1.6.3. Simulated seasonal mean surface current magnitude and direction,1998-2003. Vectors with the highest 25% flow speeds are highlighted in red.

were gathered from 10 monitoring stations within Massachusetts Bay to facilitate the model. Meteorological data were taken from the Boston Buoy located 16 nm offshore from Boston (Signell *et al.,* 1996).

The bathymetry for the model was obtained by interpolating NOAA sounding data on the model grid using an inverse distance weighted method. The resulting grid had a maximum depth of 140 m to eliminate the deep complex topography offshore of Massachusetts Bay and a minimum depth of 3 m to avoid flooding and drying.

Model simulation results were obtained from researchers at the University of Massachusetts-Boston to examine spatial and temporal trends of water circulation within the eastern Gulf of Maine and Massachusetts Bay to examine water circulation and its possible effects to the physical and biological dynamics within Stellwagen Bank NMS. Seasonal surface (Figure 1.6.3) and subsurface, 25 m, (Figure 1.6.4) circulation data were obtained for

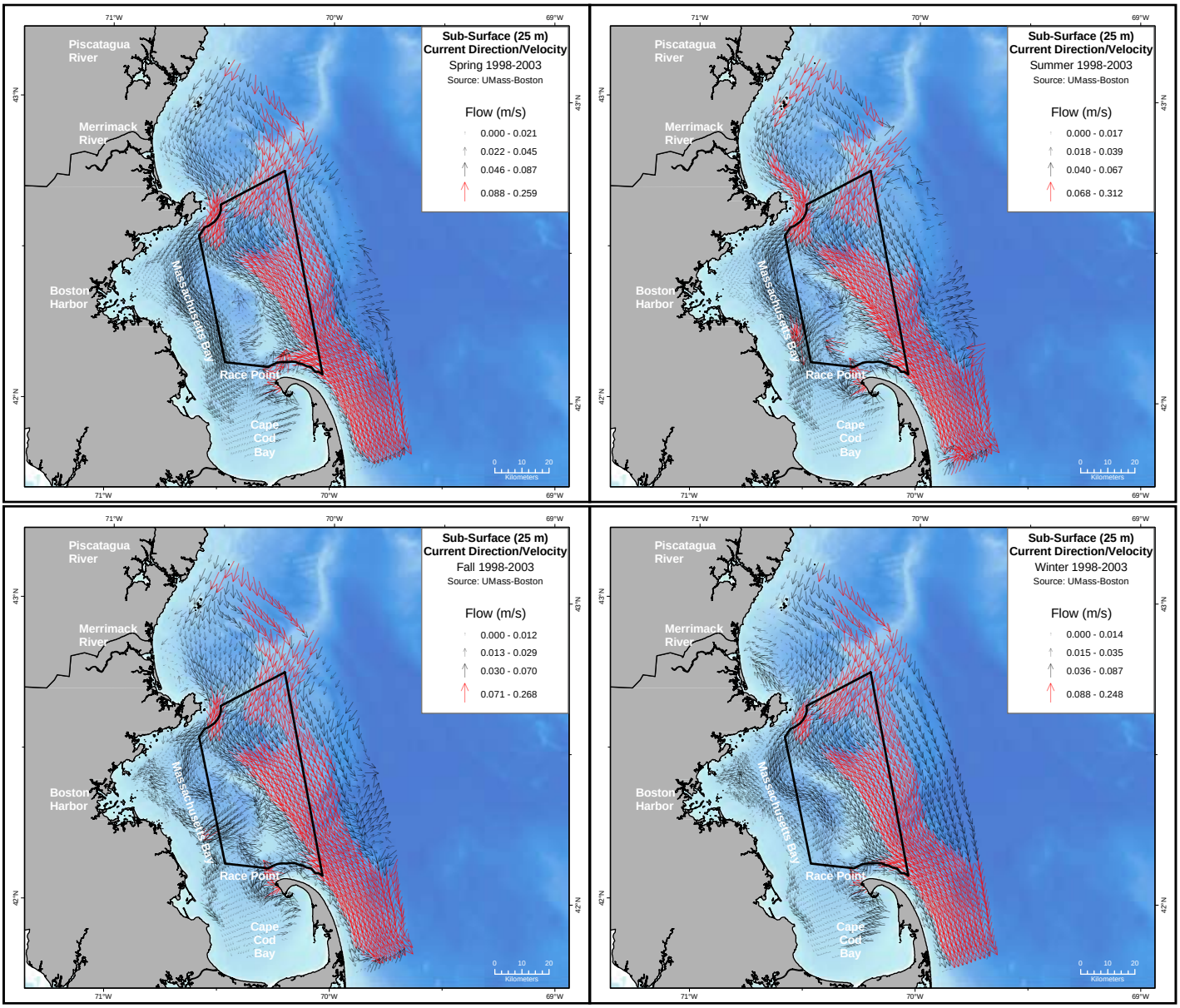

Figure 1.6.4. Simulated seasonal mean sub-surface (25 m) current magnitude and direction,1998-2003. Vectors with the highest 25% flow speeds are highlighted in red.

Massachusetts Bay for the years 1998-2003. Surface and subsurface mean monthly circulation patterns are displayed in Appendices 3 and 4.

Surface current model results provide a distinct image of the Maine Coastal Current entering the northern portion of the Sanctuary and exiting out the southeastern corner off Cape Cod during all months. The current appears strongest from December through June as a result of snow melt and spring runoff. This is also evident as flows from the Merrimack River are strongest from March-May and moderate from December-February. During this high flow period (March-May) the bifurcation of the Maine Coastal Current into Massachusetts Bay is clearly evident as the flow follows the shoreline of the Bay and goes through Cape Cod Bay and exits at Race Point and joins the Coastal Current flowing southeasterly. Heavy flow from Boston Harbor is observed during this period also and it flows south along the Bays shoreline through Cape Cod Bay and out through Race Point. In the lower flow months surface flows from the Merrimack River and Boston Harbor flow through the Sanctuary until converging with the Coastal Current.

Subsurface current (25 m) model results (Figure 1.6.4) exhibit similar patterns to that seen at the surface. At 25 m, the Coastal Current is strongest between February-May and the bifurcation into Massachusetts Bay is also

present. Flows from the Merrimack River and Boston Harbor are minimal and are variable in direction. It appears that flow from the Merrimack River casually meets up with the Coastal Current and either follows it through the Sanctuary or diverges through Massachusetts Bay. Flows from Boston Harbor generally move southward through Massachusetts Bay and converge with the Coastal Current off Cape Cod. The model results indicate high variability in directional flow within Stellwagen Basin between March-November. This may be an artifact of the averaging process with the data, or it displays a variation in flow as the current moves through the basin and is deflected off the sides of Stellwagen Bank possibly forming a weak underwater gyre.

These model results provide a good example of mean flow and direction over extended time periods (months). However, over short time periods (days/weeks) current flow and direction can be highly variable. Oceanographers from NOAA's Woods Hole Oceanographic Institute have been deploying and tracking ocean drifters to examine short term current flow, direction, and residence time.

A select group of drifters are displayed to depict the variability of flow direction and residence time (Figure 1.6.5). This figure displays the initial placement of the drifter (open circle), its track, and ending location (closed circle). Drifters released in the area near Cape Ann tracked southeasterly and exhibited small scale directional variability but were transported through the Sanctuary within 5-10 days. Drifters released in Boston Harbor exhibited slightly slower speeds and increased residency time within the Sanctuary (Figure 1.6.6).

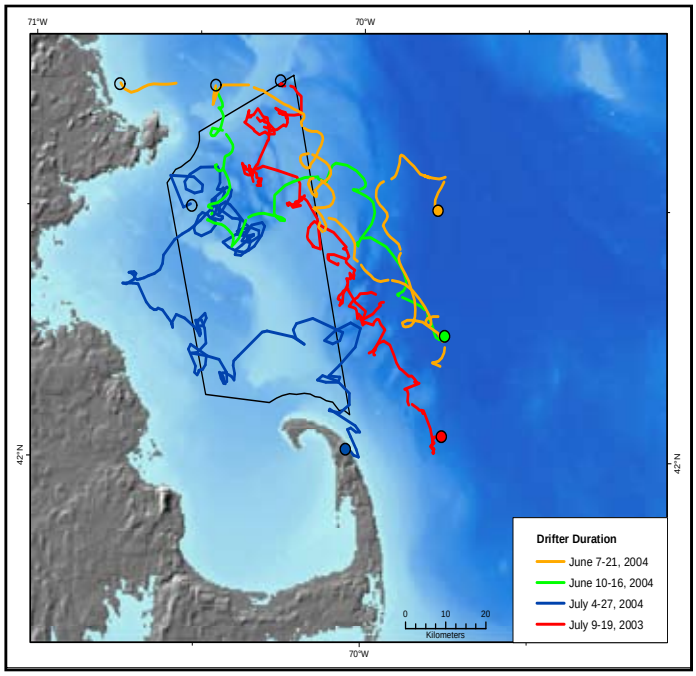

Figure 1.6.5. NOAA drifter tracks in southwestern Gulf of Maine.

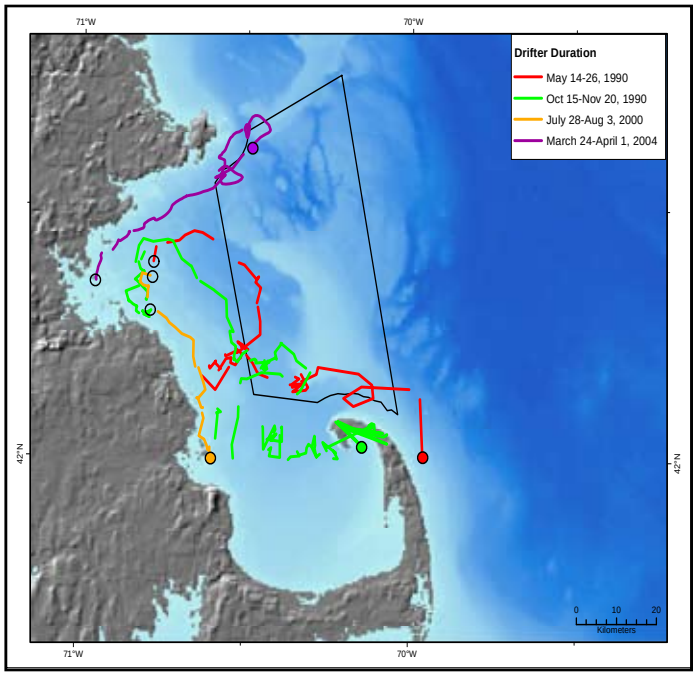

Figure 1.6.6. NOAA drifter tracks in Boston Harbor and Massachusetts Bay.

The significance of this work is to identify the current patterns in the southern Gulf of Maine and develop the context for sources and sinks for benthic fish and invertebrate pelagic larvae. Many marine demersal organisms have pelagic egg and larval stages that are greatly influenced by physical processes (Bradbury and Snelgrove, 2001) and their distribution has significant consequences for recruitment and population stability (Cowen, 1985; Gaines and Roughgarden, 1987; Sinclair, 1988). Most of these species have relatively limited swimming ability, thus the rate of advection is highly dependent on passive transport (Butman, 1986; Carlon and Olson, 1993). The Gulf of Maines Gyre circulation and associated convergent fronts should result in a greater capacity to retain eggs and larvae within the Gulf (Gagne and O'Boyle, 1984).

Stratification

Gulf of Maine

A significant part of the non-tidal circulation in the Gulf of Maine is related to density structure (Brown and Irish, 1993). Density and water property structure are regulated by: 1) fresh water inflow of near-surface water from the Scotian shelf, and saltier, deeper water from the upper continental slope coming in the Gulf via the Northeast Channel; 2) the dynamics of waters mixing, cooling in the winter, and local fresh water runoff; and

3) outflow of surface and intermediate depth water to Georges Bank and the adjacent shelf. During the summer in the central and western Gulf, water trapped between the coastline and George's Bank stratifies as it warms, forming three primary layers: 1) Maine Surface Water, 2) Maine Intermediate Water and 3) Maine Bottom Water. Maine Surface Water, which includes the top 30 m of water, is relatively warm and fresh. Maine Intermediate Water includes cooler and saltier water roughly between 50-150 m in depth. Maine Bottom Water, depth < 150 m, is warmer and saltier than Maine Intermediate Water (Sherman *et al.*, 1996; Petrie *et al.,* 2004; Brown, 2005).

Maine Surface Water forms during the spring and summer, as the sun warms the upper water layers, and as rivers discharge large amounts of fresh water into the Gulf of Maine. Maine Intermediate Water is not greatly influenced by these processes, leading to water column stratification. The interface between Intermediate Water and Surface Water disappears completely with the influence of winter cooling and convection (Sherman *et al*, 1996). Unlike Maine Surface Water, the interface between Intermediate and Bottom water layers exhibits little seasonal variability. Maine Bottom Water pulses into the Gulf through the Northeast Channel with the winter winds and as a result, water replacement occurs approximately every 11 months ± 2 months (Ramp *et al.,* 1985; Sherman *et al*, 1996).

Bay of Fundy and Georges Bank

The Bay of Fundy and southwestern coast of Nova Scotia experience the coolest summer surface water temperatures in the Gulf of Maine. Strong tidal mixing keeps waters uniformly cool, preventing stratification of the water column. (Casault *et al*, 2003). Similarly, Georges Bank also experiences cooler than average surface temperatures in the summer due to vertical current mixing (Brown *et al.,* 1989; Sherman *et al*, 1996).

Shelf-Slope Front

The shelf-slope interface, along the eastern edge of the Gulf of Maine, experiences the warmest and most saline surface water in the Gulf throughout the year. The presence of horizontal eddies mixes shelf water with warm water from the Gulf Stream, maintaining generally higher salinity and temperature (Sherman *et al.*, 1996; Casault *et al.,* 2003). While this region of warm, salty water along the shelf slope is a permanent feature, it is also highly variable. It can move laterally as much as 50 km over days or weeks (Sherman *et al.,* 1996), but in general, moves farther offshore in the winter and closer to shore in the summer and early autumn (Petrie *et al.,* 2004).

Coastal Region

Nearer to the coastal region of the Gulf of Maine, the halocline begins to slope downward because of the Eastern Maine Coastal Current, which brings fresher water from the Scotian Shelf (Sherman *et al.*, 1996). This region also experiences a salinity minimum during the spring because of large freshwater inputs from river discharge (Casault *et al.,* 2003). The typical annual peak combined fresh water discharge of the Penobscot, Kennebec, Androscoggin and Merrimack Rivers into the Gulf of Maine is estimated to be about 7,000 m^3/s. The St. John River discharges a similar volume of water into the Bay of Fundy during the spring freshet, which also contributes to freshwater volume input into the Gulf of Maine. In total, an estimated 8,128 m^3/yr of river water is annually discharged into the Gulf of Maine (Townsend, 1998). This plume of relatively fresh surface water is typically 2 psu, but may be up to 10 psu below ambient salinity. It is usually around 10-20 m thick in depths of 50-100 m (Geyer *et al.,* 2004). Major fluctuations in the plume's width and depth are associated with upwelling and downwelling, for which changes in depth were inversely correlated with changes in width. The plume is also transported southwest, along the coast, at an average speed of 0.21 m/s between May and early June (Geyer *et al.,* 2004). Data also indicate that the plume moves offshore as it extends along the coast (Geyer *et al.,* 2004). Micro-transport of the plume, however, may vary considerably location to location due primarily to the effects of barotropic motions and, to a lesser extent, of baroclinic shears and wind-driven Ekman motions (Geyer *et al.,* 2004; Jiang and Zhou, 2004).

During the spring, the presence of the coastal current generates a strong vertical salinity gradient. This salinity stratification facilitates warming of the surface water by suppressing vertical mixing, developing a strong thermocline by late April. The thermocline continues to strengthen through the summer, with up to a 12° C difference between surface and bottom waters. The salinity of the surface water varies with the intensity and position of the coastal current, but remains lower than that of the deep water (Geyer *et al.,* 1992). Winter conditions are well mixed through most of Massachusetts Bay, with temperature and salinity both increasing with distance from shore. The coldest temperatures are found in shallow areas, presumably due to more rapid cooling of the shorter

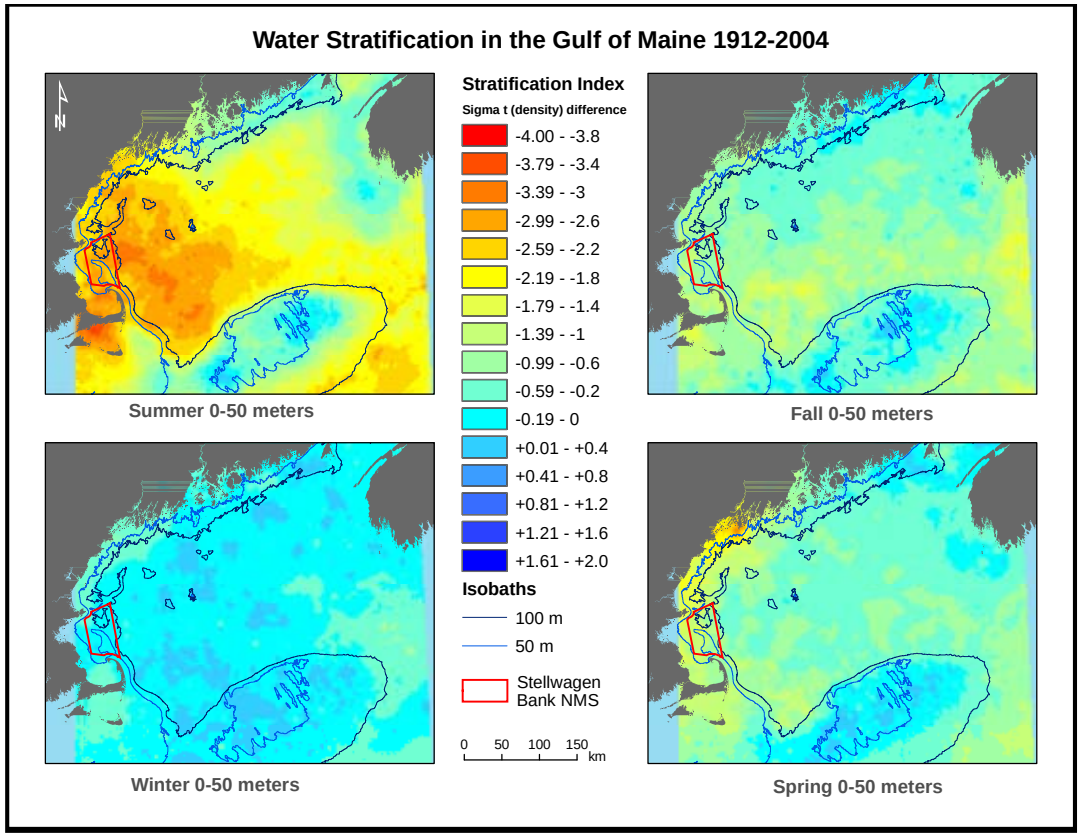

Figure 1.6.7. Water stratification index for the Gulf of Maine, 1912-2004. Data source: Bedford Institute of Oceanography.

water column. Deep water in Massachusetts Bay during winter is similar in properties to the Gulf of Maine intermediate water described by Hopkins and Garfield (1979). This water type is formed in coastal areas during winter, and the Bay may be a source of Maine Intermediate Water. The salinity gradient appears to be related to inflow from shore, with lowest salinities observed near Boston Harbor and in eastern Cape Cod Bay. During this period, conditions in the vicinity of Stellwagen Bank are similar to that of the Gulf of Maine.

An index to visually examine Gulf of Maine stratification was created using 92 years of oceanographic data acquired from Canada's Bedford Institute of Oceanography Hydrographic (Climate) Database. The hydrographic database is a collection of temperature and salinity data for the area roughly defined by 35°-80° N and 42°-100° W. The data was collated from a variety of sources including hydrographic bottles, CTD casts (either up or down casts), spatially and temporally averaged Batfish tows, and expendable, digital or mechanical bathythermographs. Near real-time data in the form of IGOSS Bathy or Tesac messages are also included. The database currently consists of approximately 525,000 profiles and 15 million individual observations from 1904 to the present. Data from 1904-2004 were used for this analysis. The data were grouped within three time series: 1904-2004 (Figure 1.6.7), 1994-2004 (Figure 1.6.8), and 2004 (Figure 1.6.9). Within each time series, seasonal subsets were generated that were defined as: spring (March 22-June 21), summer (June 22-September 21), fall (September 22-December 21), and winter (December 22-March 21). Seasonal time series data were further parsed to depth categories: surface, 10 m, 20 m, 30 m, 40 m, and 50 m.

The data were assimilated into distinct geodatabases, imported into ArcMap and converted to shapefiles. For each seasonal time series, approximately 25% of the data were subset from the analysis to serve as validation data. Using ArcGIS Geostatistical Analyst, three interpolation methods were chosen to examine the spatial patterns of water stratification: Inverse Distance Weighting, Radial Basis Function (spline with tension), and Radial Basis Function (completely normalized spline). Seasonal time series for each depth category were interpolated. These methods were chosen based on previous investigations (WWF, 2003) and personal correspondence

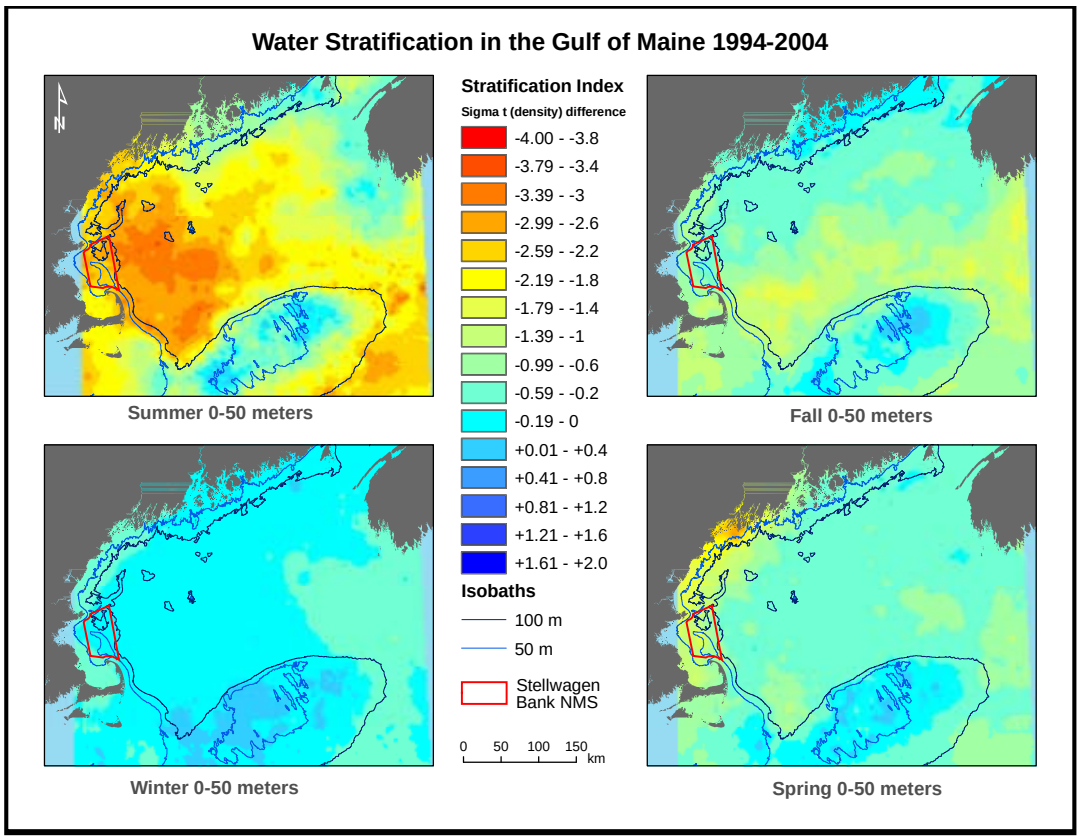

Figure 1.6.8. Water stratification index for the Gulf of Maine, 1994-2004. Data source: Bedford Institute of Oceanography.

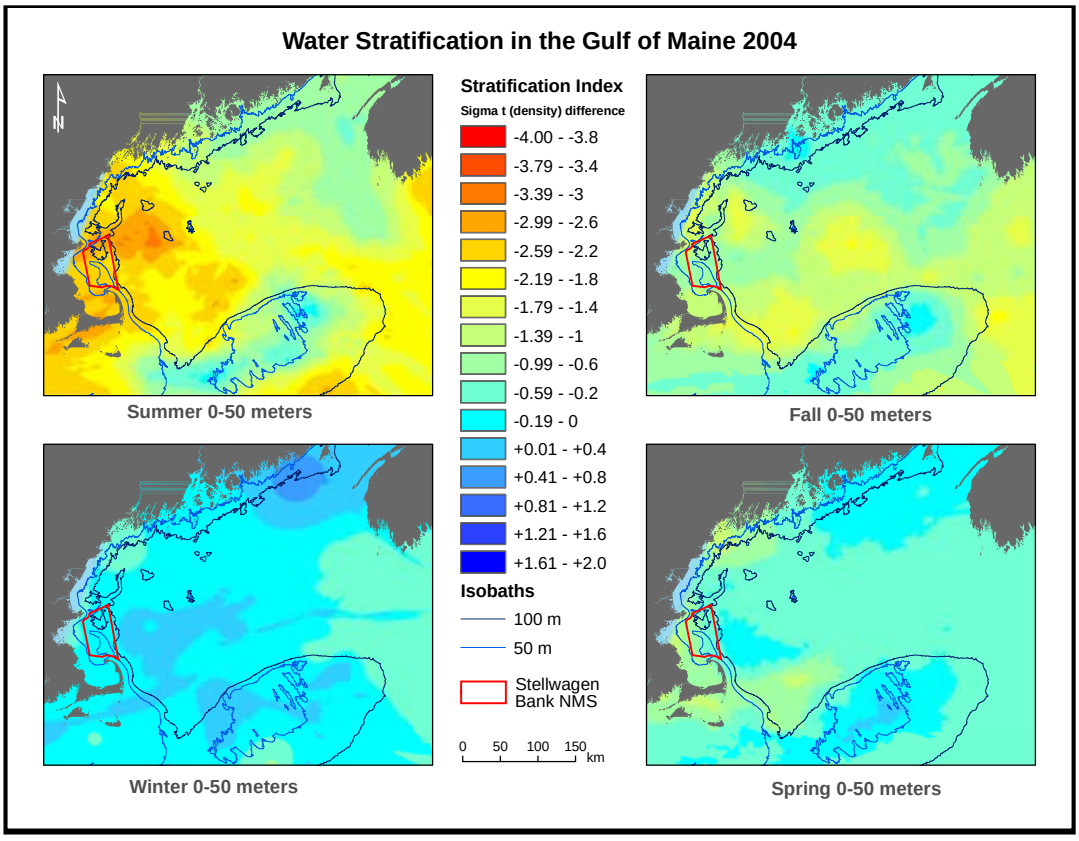

Figure 1.6.9. Water stratification index for the Gulf of Maine, 2004. Data source: Bedford Institute of Oceanography.

with physical oceanographers (Manley, Keith, Mountain, O'Reilly, Fogarty, pers. comm.). Interpolation results were compared and the Radial Basis Function-spline with tension method was selected as the most appropriate method for the stratification analysis as the 50 m boundary exhibits the greatest difference in stratification strength (buoyancy frequency squared) between layers in the water column (Brown and Irish, 1993). Examination of depths shallower than 50 m may be confounded as waters between the surface and 10 m may be subject to wind and convective mixing. Waters from the surface to 30 m may be influenced by internal seiches (Cushman-Roisin *et al.,* 2005). Bisagni (1992) observed weak stratification during all months at depths greater than 60 m on Georges Bank. Using ArcGIS Spatial Analyst's raster calculator, the sigma *t* difference between the surface and 50 m raster was calculated and classified in 0.2 sigma *t* intervals (Brown and Irish, 1993). Negative sigma *t* values indicate that surface water is less dense than water at 50 m and is thus stratified. Positive sigma *t* values indicate more dense surface water than at 50 m signifying some degree of upwelling. Values close to zero represent mixed layers.

The observed stratification patterns throughout the long-term time series (1904-2004) are similar to those described in the literature with higher levels of stratification during the summer, some stratification in localized areas, mainly near the coastline, and well mixed conditions during the winter. During the summer, stratification is strongest in the eastern Gulf of Maine, including Massachusetts and Cape Cod Bays, and Wilkinson Basin. Areas of high stratification during summer are also evident in Jordan and Georges Basin. Stratification is also noticeable on the southern flank of Georges Bank during the summer while the top and northern flank of the bank remain well-mixed during all seasons. Tidal influence interacting with the shallow bottom topography of Georges Bank generate strong tidal currents that maintain a vertically well-mixed water column inside the 60 m isobath throughout the year (Yentsch and Garfield, 1981; Loder and Greenberg, 1986; Brown *et al.,* 1989; Bisagni, 1992; Xue *et al.,* 2000). In contrast, areas with weak tidal currents, such as the central and western Gulf basins, vertical mixing is inhibited, allowing for stratification (Brown *et al.,* 1989; Sherman *et al.,* 1996). These patterns are similar for the Gulf of Maine during the past 10 years (Figure 1.6.8) and during 2004 (Figure 1.6.9).

The pattern of seasonal stratification is well defined during 1994-2004 where the summer index was greater in spatial extent and severity than the 100 year average (Figures 1.6.7 and 1.6.8). The eastern portion of the Gulf of Maine, most notably over Wilkinson Basin, was strongly stratified and may be correlated with above average temperatures within the region. Spring, fall, and winter were not significantly different than the long term average. The index for 2004 (Figure 1.6.9) indicated a more consistent pattern with the long term average.

Stratification within Massachusetts Bay and the Stellwagen Bank NMS can be separated into four seasonal intervals (Geyer *et al.,* 1992), based on winds and surface waves, temperature and thermal stratification of the water column, salinity, salinity stratification, horizontal salinity gradients caused by river discharge, and the density stratification which results from the temperature and salinity. During November through March the water column is vertically well-mixed and the wind and surface waves are the largest of the year. In April and May fresh water runoff is greatest from the spring snow melt, the surface layer freshens, and the water column is vertically stratified. In spring, there are typically strong horizontal salinity gradients in the surface layers caused by rivers that discharge fresh water along the coast. During June through August, a seasonal thermocline develops, the vertical density stratification reaches a maximum, and the winds and surface waves are the weakest of the year. From September through October the water cools and the vertical stratification of the water column transitions from the strong summer stratification to well-mixed conditions.

Internal Waves

Internal waves are non-sinusoidal waves that occur at the interface between two water layers of differing densities (Brown *et al.,* 1989). They occur when seasonally stratified water is forced over abrupt topographic features, such as banks or ledges, by diurnal tides. Internal waves disappear as they approach shallow water (typically 25 to 40 m in depth) because of increasing bottom attenuation (Jackson and Apel, 2004). Internal waves were first documented in 1971 (Halpern, 1970; 1971) and there has been a considerable amount of investigations of internal wave occurrence in the Gulf of Maine (Haury *et al.,* 1979; 1983; Chereskin, 1983; Trask and Briscoe, 1983; Chang *et al.,* 1998; Chang and Dickey, 1999, 2001; Colosi *et al.,* 2001; Porter *et al.,* 2001).

Most tidal currents in the Gulf of Maine tend to be barotropic (i.e., depth independent). Internal or baroclinic tidal currents, however, also occur in the Gulf of Maine. These tidal currents are generated by the interaction between

the Gulf's barotropic tidal currents and its varied bathymetry in the presence of water stratification. This interaction generates both a highly nonlinear internal solitary wave once every tidal cycle as well as a more regular internal tidal wave (Brown, 2005). The internal tidal wave, in particular, appears to be generated continuously along Georges Bank and propagates northwesterly toward the interior Gulf with an estimated wave length of 20-30 km and speed of 0.40-0.70 m/s (Brown, 2005). In addition to contributing to vertical mixing, internal waves produced by semi-diurnal tides have been shown to create pockets of warm, plankton rich water, that nourish benthic communities. Cashes Ledge and Stellwagen Bank, most notably, are biologically productive areas as a result of internal wave dynamics (Sherman *et al.,* 1996).

Internal waves contribute to the energetics of the upper ocean in many ways, in particular, they enhance mixing and nutrient availability (Jackson and Apel, 2004). Plankton distribution exhibits strong vertical displacements and mixing associated with internal wave packet passage (Haury *et al.,* 1979). Strong convergence at the bottom favors sediment resuspension (Boczar-Karaiewicz *et al.,* 1991), including recently settled invertebrate larvae and toxic algae cysts (Scotti and Pineda, 2004). The existence of trapped cores (between internal wave crests) also suggests internal waves a prime candidate for transporting material such as the larvae of littoral species (Scotti and Pineda, 2004). Considering these and potentially other transport process, internal waves can exhibit a significant influence on coastal ecological patterns (Scotti and Pineda, 2004).

Non-linear internal waves and internal tidal waves are well documented in Massachusetts Bay (Halpern, 1971; Scotti and Pineda, 2004; Brown, 2005; MacKinnon and Gregg, 2005). They are generated by the interaction of the barotropic M_2 tidal currents and steep bathymetry in the presence of stratification (Brown, 2005). Internal waves usually occur in Massachusetts Bay between May and October when the water column is stratified. Internal waves have also been detected off Georges Bank in the winter months, propagating along the pycnocline close to the bottom. The effectiveness of the tidal mixing is enhanced by the nature of the flow of the stratified (light water over more dense water) water column. The interface between upper and lower water types is depressed over the crest of the bank, and the flow velocity in the lower layer is increased. Under appropriate conditions, this depression and increased velocity extend 'down-stream' of the bank, leading to large amplitude internal lee waves (Haury *et al.,* 1979; Chereskin, 1983; Hibiya, 1988). The flow associated with these waves, and with the large bottom velocity, probably accounts for some of the flux of nutrients into the upper layer in the vicinity of Stellwagen Bank.

When the tide turns (e.g. from ebb to flood), the lee waves are no longer supported by the tidal flow. The energy contained in the waves then propagates across Stellwagen Bank into Massachusetts Bay as a train of large amplitude internal waves (Halpern, 1971; Haury *et al.,* 1979; Haury *et al.,* 1983). These waves are regularly observed in the Bay during stratified conditions. The flows associated with the waves may be sufficient to cause mixing within the Bay, and probably result in considerable mixing at the point where the interface intersects the bottom. Observations during the Massachusetts Bays Program project in April, 1990 (Gardner, 1990) provided evidence that these waves may have considerable impact on the productivity within the Bay.

Table 1.6.1. Characteristic Scales for internal waves along the New England shelf and the Gulf of Maine.

Internal Wave Characteristic	Scale
Packet Length	1 to 10 km
Amplitude Factor	-5 to -25 m
Packet Separation	15 to 40 km
Long Wave Speed	0.5 to 1.0 m/s
Maximum Wavelength	0.6 to 1.5 km
Along Crest Length	10 to 30 km
Wave Period	8 to 25 min
Surface Width	100 m

Internal waves in Massachusetts Bay have similar physical characteristics, including packet length, amplitude, packet separation, wave speed, wavelength and crest length (Global Ocean Associates, 2004; Table 1.6.1). The signatures of internal waves are typically observed in imagery acquired between May and October when summer heating of the upper layers in coastal waters enhances the stratification necessary for internal wave occurrences (Figure 1.6.10).

Synthetic Aperture Radar (SAR) can detect internal waves by emitting pulses of microwave energy, producing a two-dimensional radar backscatter map (Figures 1.6.11 and 1.6.12) of the roughness of the ocean surface (Jackson and Apel, 2004). In SAR imagery, internal waves appear as packets or groups of waves characterized by:

1) Alternating bands of bright and dark bands. The bright band is associated with the convergence zone, as determined by the orbital particle motion within the internal wave.

2) Curvilinear wave crests, which were bent by refraction.

3) Decreasing wave crest lengths from front to back of each packet.

4) Decreasing wavelengths from front to back of each packet, indicating propagation direction and that nonlinear wave dispersion is in effect.

5) Decreasing wave amplitudes from front to back of each packet.

6) Propagation parallel to significant isobaths.

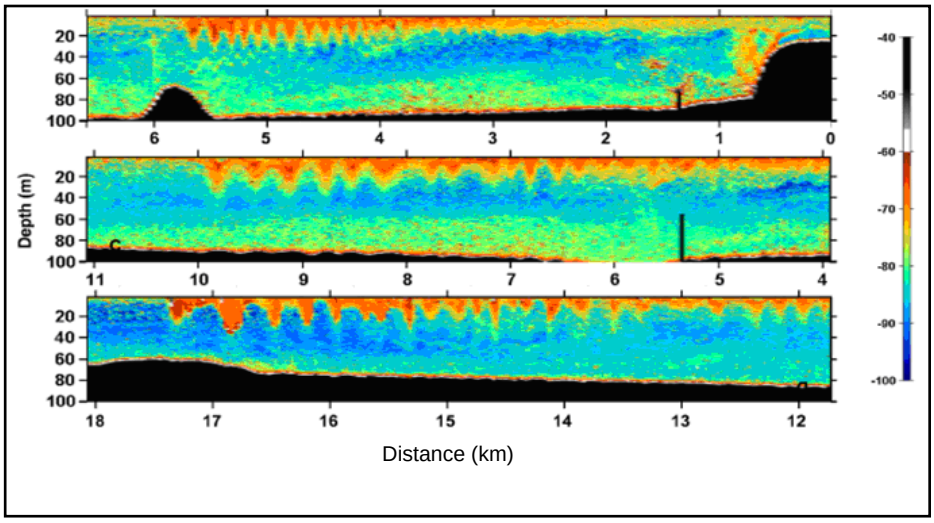

Figure 1.6.10. Internal wave profile (warm colors) along a survey transect between Scituate, MA and Stellwagen Bank, August 14-15, 1999 (Global Ocean Associates, 2004).

Wave packet size is variable, however, imagery from Massachusetts Bay and surrounding waters have shown high density (number of packets/km^2) within Massachusetts Bay and the area east of Cape Cod (Figure 1.6.13).

Less frequently, internal waves may be composed of only dark bands with no associated bright bands. This varying appearance is due to sensitivity to wind speed and wind direction, as well as to the orientation of the wave groups to the radar platform (Jackson and Apel, 2004).

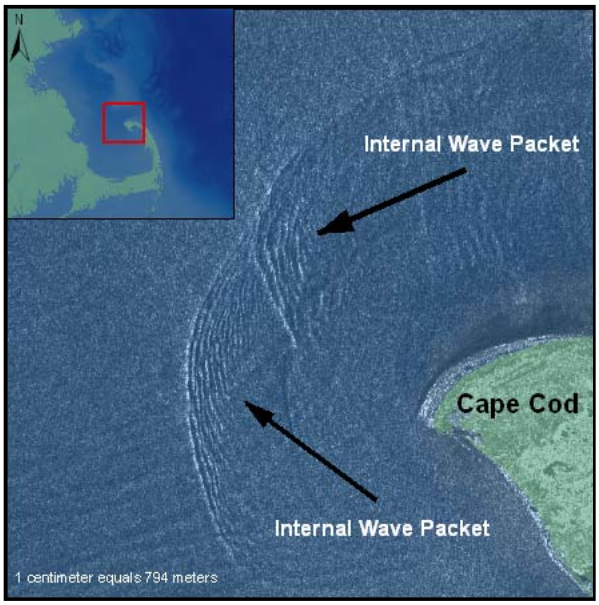

Figure 1.6.11. SAR image (August 22, 2003 6:51 am EST) of shoreward propagating internal wave packets off the tip of Cape Cod in Massachusetts Bay (Global Ocean Associates, 2004).

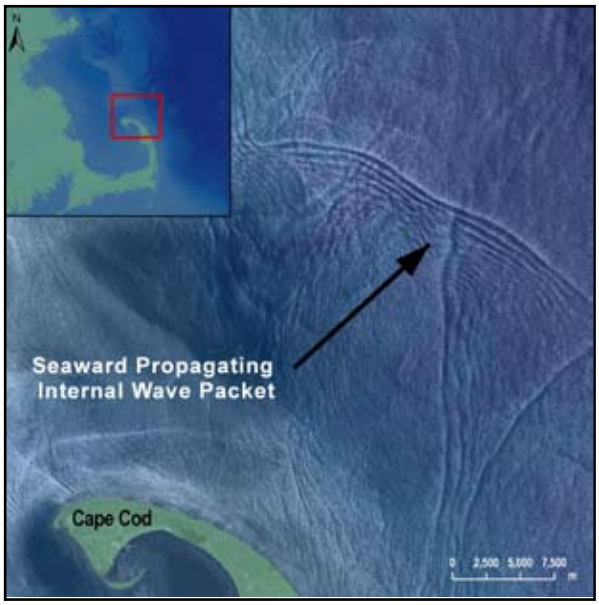

Figure 1.6.12. SAR image (August 8, 2002 6:23 pm EST) of shoreward propagating internal wave packets east of Stellwagen Bank in Massachusetts Bay (Global Ocean Associates, 2004).

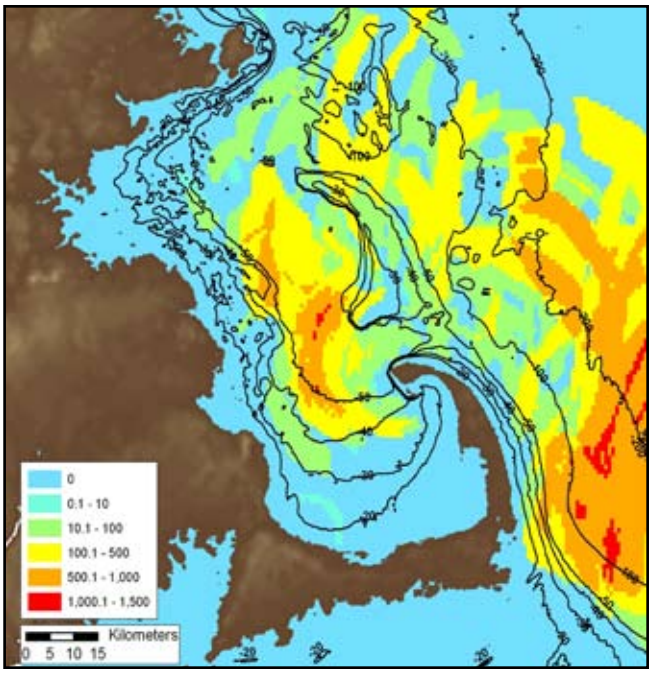

Figure 1.6.13. Internal wave packet density (km^2) May-September 1997, 1998, 2001, 2002, 2003 in Massachusetts Bay.

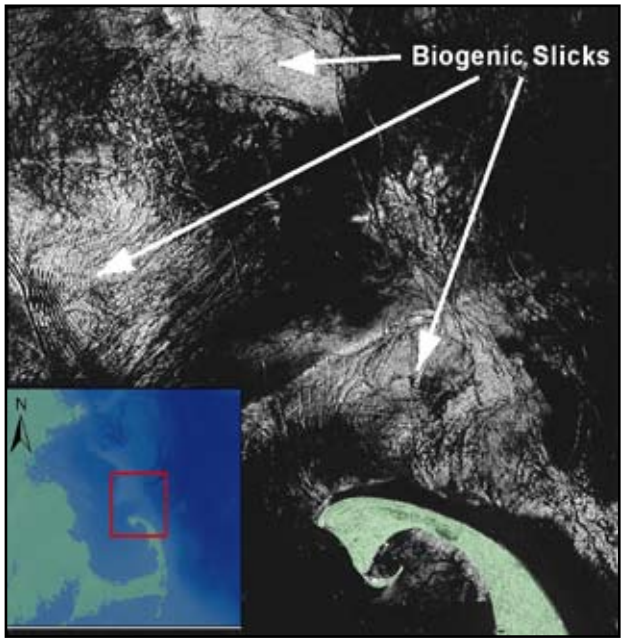

Figure 1.6.14. SAR image (August 8, 1997 5:24 pm EST) of biogenic slicks north of Cape Cod.

Synthetic Aperture Radar imagery can also be used to identify other oceanic mesoscale processes that influence the "roughness" of the ocean surface. Notably, SAR imagery also detects currents, fronts, areas of upwelling, ships/wakes, topographic features, surface waves, breaking waves as well as oils and biogenic surfactants (Jackson and Apel, 2004). Biogenic surfactants are natural surface films that originate from marine plants or animals, which dampen the rippling-action by surface winds (Ewing, 1950; Jackson and Apel, 2004). Biogenic slicks may be important indicators of marine mammal abundance, as the densities of small fish and zooplankton from surface waters have been found to be higher in slicks than in the rippled water adjacent to them (Kingsford and Choat, 1985). These slicks may attract marine mammals to these areas of high prey concentrations (Dorfman, 1990), and may be a significant area for future study (Figure 1.6.14).

In this study, the following methodology was used to identify and delineate internal wave packets in ESRI ArcGIS (ArcView) 9.1. First, a search extent was defined in order to narrow the geographic area in which to look for internal waves. This area covered an area from 42º 44' 19'' N to 41º 30' 2'' N and from 71º 8' 3'' W to 69º 36' 30'' W. Sixty-six SAR images (taken between May 14, 1997 and August 29, 2003) were visually examined for internal waves, using the internal wave packet characteristics listed above as an identification guide. An ESRI polygon shapefile was created with columns recording the SAR image tile name, its year, date and time, as well as the internal wave packet area, packet propagation direction and moon phase during which it occurred. All internal wave packets were digitized at a 1:350,000 scale and saved in this shapefile, along with the necessary attribute information. The internal wave packet data were analyzed using a non-parametric Kruskal-Wallis test for significant differences in the median with a Dunn's post hoc test.

Internal waves occur primarily because of the interaction between diurnal tides and seasonally stratified water. Tides and water stratification have been discussed previously in this chapter and are briefly summarized here.

Tides are an important aspect of the Gulf of Maine's physical oceanography. Semi-diurnal tides are typically weak in open near-shore waters off the coast (Babb and DeLuca, 1998; Brown, 2005), and generally strong near the Bay of Fundy and Nantucket Shoals, over George's Bank, and along the continental shelf off the southwestern tip of Nova Scotia (Babb and DeLuca, 1998; Sherman *et al.,* 1996). Tides in the Gulf of Maine have larger amplitudes than many marine areas because they are in near-resonance with the principal lunar tide of the Atlantic Ocean (Sherman *et al.,* 1996). In most areas of the Gulf of Maine, tides advance towards the northeast and in a clockwise rotation because they are not refracted by land (Sherman *et al.,* 1996). However, in the western Gulf

of Maine between Cape Cod and Cape Ann tides move in a southerly direction because they are refracted by Cape Cod (Sherman *et al.,* 1996).

Tides are also important to the Gulf of Maine's physical oceanography because they vertically mix water, influencing the degree to which water becomes stratified in the Gulf. Frictional drag on Georges Bank, for example, produces a strong vertical current shear that keeps the waters over this shallow bank vertically well mixed (Brown *et al.,* 1989; Xue *et al.,* 2000), resulting in consistent cold surface temperatures and well-oxygenated water year round (Sherman *et al.,* 1996). In other areas where tidal currents are weak (such as in the central and western Gulf basin), there is little vertical mixing, allowing for the stratification of water during the summer months (Brown *et al.,* 1989; Sherman *et al.,* 1996).

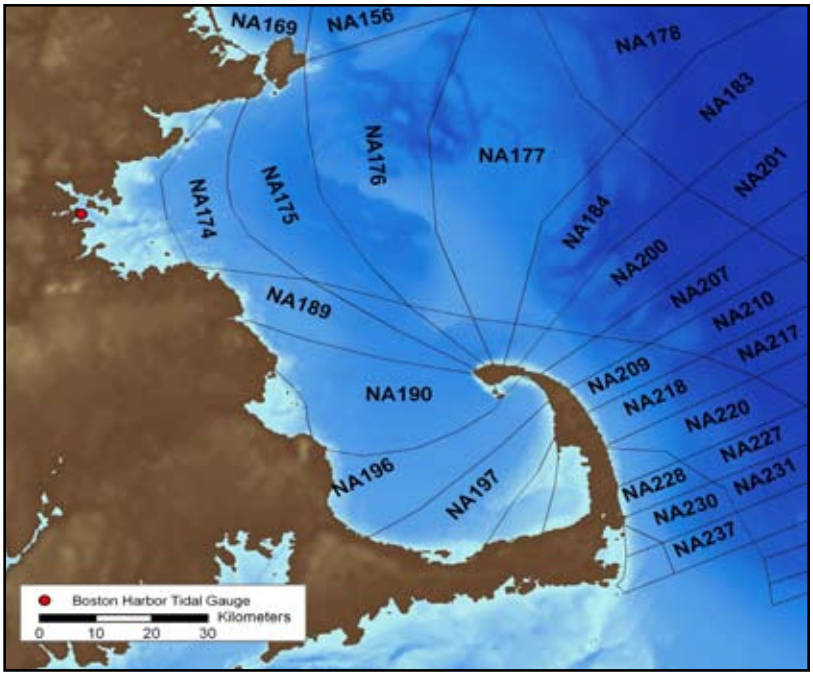

Figure 1.6.15. Tidal zones in Massachusetts Bay as delineated by NOAA's COOPS.

In order to link the frequency and location of internal waves to the tidal phases and the intensity of water stratification, data was compiled for tidal zones, moon phases, and water density in Massachusetts Bay.

The complexity of tidal processes in the Gulf Basin was simplified by categorizing tidal cycles into a spatial and temporal component. NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) have previously created tidal zones (Figure 1.6.15) that encompass the study area. Temporally, the presence and absence of internal waves were recorded for each SAR scene by date, and subsequently overlaid the phases of the moon (new moon, first quarter, full moon, last quarter) on the same calendar (Appendix 5).

Spatial and temporal characterization of stratification were conducted using a similar process as outlined above. Sigma *t* profiles were obtained (where and when available), which corresponded to the same day and general area as the SAR image acquisition. For the spatial component, sigma *t* values at 0 meters and 50 meters were interpolated to create a mean water stratification index for the summer (July-September) of 1997, 1998, 2001, 2002 and 2003. For more information on the process used to create these water stratification coverages, see the section on water stratification.

After this information was compiled, all of the internal wave packets were examined with environmental data layers (bathymetry, slope, and water stratification) to determine whether significant spatial and temporal linkages existed. In order to extract these descriptive values, the environmental data with raster floating pixel values were converted to rasters with integer pixel values. To do this conversion, floating rasters were multiplied by a factor of one hundred million using the Raster Calculator in ArcMap's Spatial Analyst. This calculation was made in order to preserve the accuracy of the data prior to converting it to integers. Subsequently, the data were converted to polygon shapefiles, and intersected with the internal wave packet polygon shapefile. The area (m^2) of the resulting raster polygons was calculated within each internal wave packet, and multiplied these by the raster polygon value, i.e., depth, slope and density difference. The product of this calculation was divided by the total area of the internal wave packet to weight the mean (based on area) for each internal wave.

To establish linkages with the tidal data, we downloaded and formatted six minute tide data for Boston Harbor tidal gauge <http://tidesandcurrents.noaa.gov/> which corresponded with the 66 SAR scenes. In ArcMap, we then assigned each internal wave packet to a NOAA CO-OPS delineated tidal zone which contained the majority of the internal wave packet's area. Tidal height values associated with the Boston Harbor tidal gauge were cor-

rected using the average time corrector and Range Ratio corrector values supplied by NOAA CO-OPS.

We examined the temporal and spatial variation of internal wave packet frequency, area and density/ location in Massachusetts Bay using non-parametric Mann-Whitney two-tailed *T*-tests and Kruskal-Wallis tests with a Dunn's post hoc test.

SAR imagery were available for May 1997, 2001, 2002; June 2001; July 2001, 2003; August 1997-1998, 2001-2003; September 1998. Comparison by year indicated that internal waves did not occur more frequently during any one year nor did they occur more frequently during any one month from May-September (Figure 1.6.16, $p \geq 0.1961$).

Internal wave packet frequency was compared by east (or shoreward) and west (or seaward) propagation. Results indicated that shoreward propagating internal waves did not occur more frequently than seaward waves among years. Among months, however, a significant relationship was observed between propagation direction and frequency (Figure 1.6.17, $p \leq 0.0001$) where internal waves were significantly greater in frequency propagating towards the east than to the west.

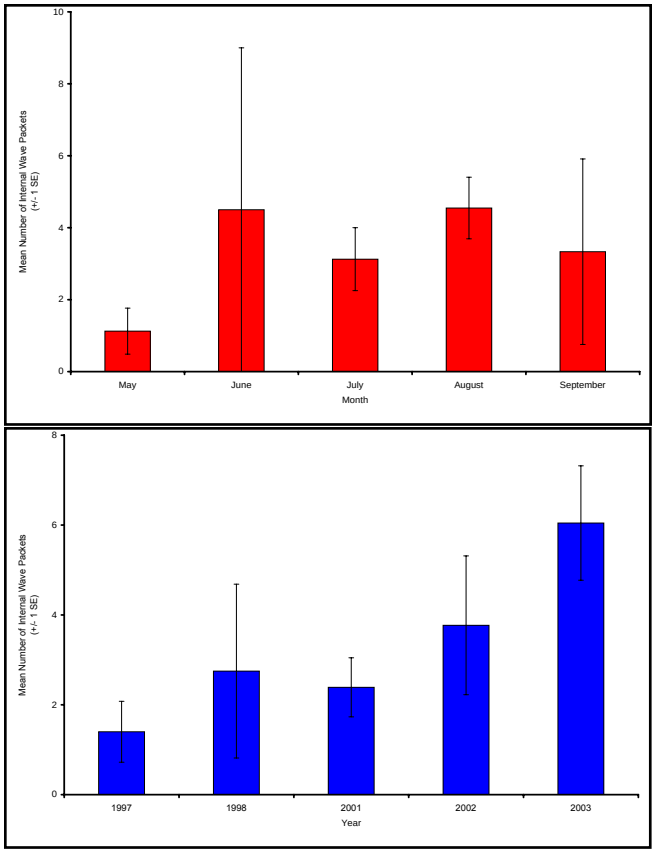

Figure 1.6.16. Mean frequency of internal wave packets by month (top) and year (bottom).

Internal wave packets did not occur more frequently ($p \geq 0.2575$), nor did their propagation direction change significantly (east $p \geq 0.4984$ and west $p \geq 0.259$) during any one phase of the moon. Results also indicated that internal wave packets did not occur more frequently ($p \geq 0.62$), nor was their propagation direction affected (east $p \geq 0.535$ and west $p \geq 0.0.62$) during either spring or neap tides.

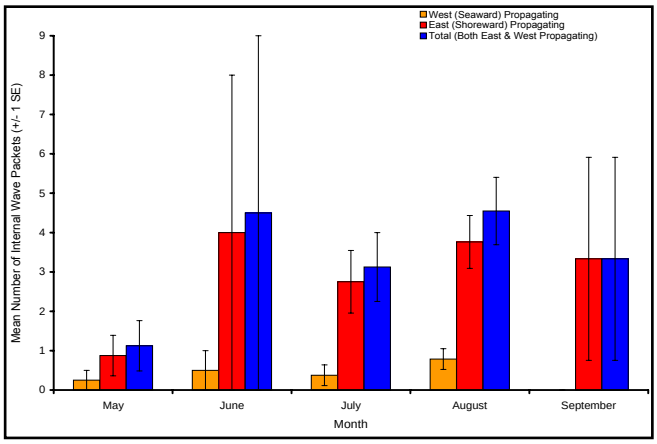

Figure 1.6.17. Mean frequency of internal wave packets (±1 SE) propagating west (seaward), east (shoreward) and both directions in Synthetic Aperture Radar (SAR) imagery 1997-2003.

The area of internal wave packets were also analyzed by year, month, propagation direction, and in relation to moon and tidal phase. Mean internal wave packet area was greatest during June and was significantly greater than that observed during September. Internal wave area was not significantly different for other monthly mean and median comparisons (Figure 1.6.18 top, $p \geq 0.1055$). Area differences were significantly greater during 2001 than in 1998 and 2003 (Figure 1.6.18 bottom, $p < 0.05$). Shoreward propagating internal waves were not significantly greater in area than those propagating seaward among months ($p \geq 0.2091$, Figure 1.6.19, top), years ($p > 0.05$, Figure 1.6.19, bottom), lunar phases ($p \geq 0.1358$) or tide cycles ($p \geq 0.1464$). Internal wave packet area was not significantly correlated with any one lunar phase ($p \geq 0.1275$) or tide cycle ($p \geq 0.1013$).

Internal waves were observed over depths between 10-282 m and slopes ranging from 0-6.8°. Comparison of internal wave packet frequency and water density revealed little correlation other than packet frequency was highest during the summer when stratification was most prevalent.

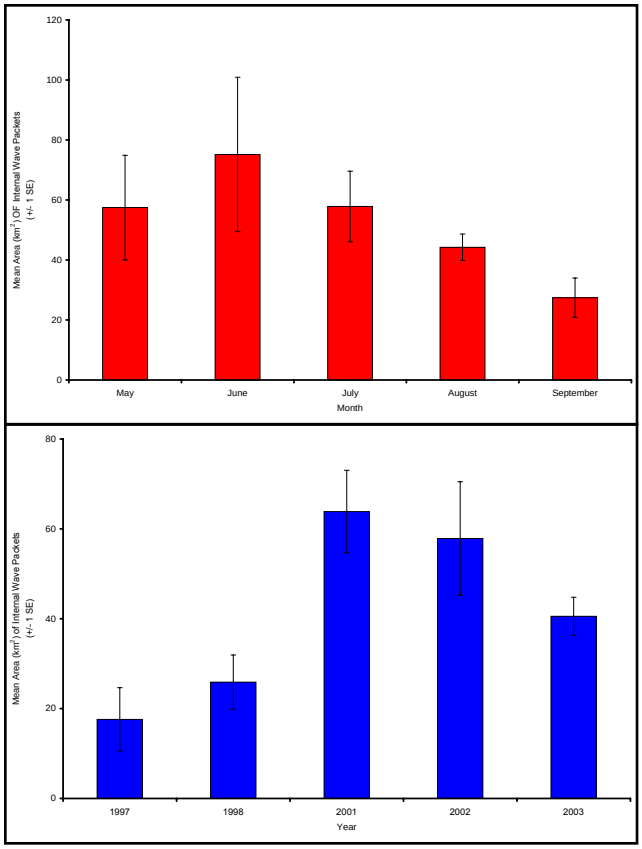

Figure 1.6.18. Mean internal wave packet area (km² ±1 SE) by month (top) and year (bottom) delineated from Synthetic Aperture Radar (SAR) imagery May-September, 1997-2003.

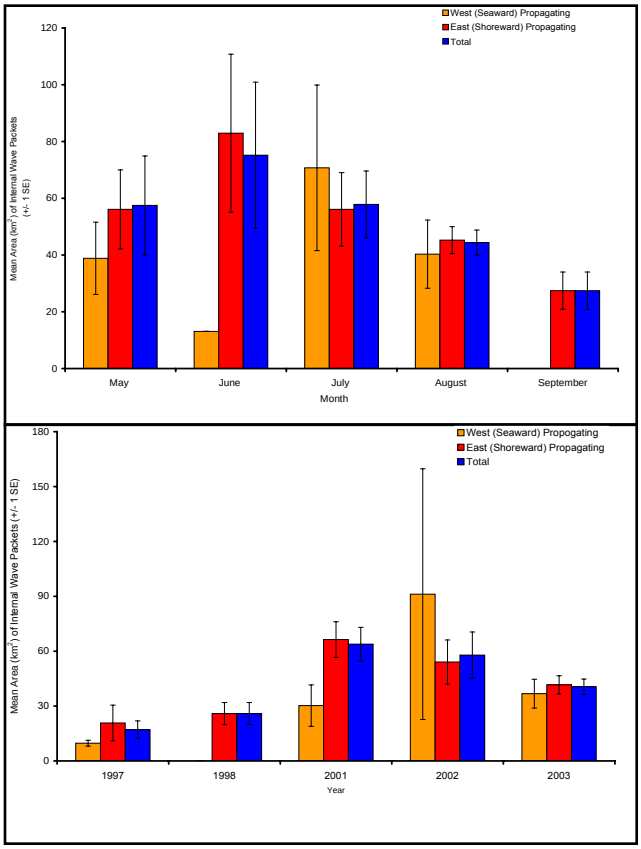

Figure 1.6.19. Mean internal wave packet area (km² ±1 SE) by propagation direction for month (top) and year (bottom) delineated from Synthetic Aperture Radar (SAR) imagery May-September, 1997-2003.

The ability of internal waves to mix stratified water layers during the summer provide a mechanism for benthic-pelagic trophic coupling by moving phytoplankton downward to benthic communities (Witman *et al*., 1993). Experiments on the Ammen Rock Pinnacle (Witman *et al*., 1993) have shown that internal waves frequently (8-20 times daily) push down surface chlorophyll and warmer water to the benthos, resulting in high secondary production of active suspension feeders on the top and upper slopes of the pinnacle and probably other topographically high regions within the euphotic zone in the Gulf of Maine. This mechanism may also serve as vertical transport for passively dispersed larvae of benthic invertebrates and fish (Witman *et al*., 1993; Meekan *et al*., 2006). Internal waves can also have additional benthic impact by resuspending sediments. Recent evidence (Butman *et al*., In Prep) has shown that benthic currents associated with internal waves caused sediment resuspension within Stellwagen Basin at depths between 50-85 m. Sediment resuspension at depths less than 50 m are not known as internal waves have not appeared in SAR imagery at depths less than 50 m (Witman *et al*., 1993). Net transport direction was offshore and currents were of considerable speed to carry sediments 5-20 km. Thus, sediments in shallower portions of Massachusetts Bay are frequently resuspended and carried offshore and are typically deposited in the deeper Stellwagen Basin. Due to weaker current flows, sediments resuspended in Stellwagen Basin do not typically leave the basin, but are redeposited (Butman *et al*., In Prep).

Mixing on the continental shelf is an important process for redistributing nutrients, sediments, freshwater, pollutants, plankton, and fish larvae (Carter et al., 2005). During periods of stratification (summer), internal waves may play a significant role in localized mixing. Presently, the degree of environmental impact from internal waves is unknown and more research is warranted within the Gulf of Maine and Stellwagen Bank NMS.

1.7 BIOTA

The preceding sections examined the spatial and temporal patterns of the physical oceanography within the Gulf of Maine and Stellwagen Bank NMS. This section examines the lower biological trophic levels (primary and secondary producers) and how their abundance and distribution patterns are influenced by the physical oceanography within the study area. Macrofauna (fish, birds, and mammals) will be addressed in subsequent chapters.

Phytoplankton

The Gulf of Maine is regarded as an area of high biological productivity and the annual spring phytoplankton bloom is one of the most important oceanographic events in the Gulf of Maine (Townsend *et al.,* 2004). The principle source of nutrients into the Gulf is attributed to the inflow of deep slope water entering via the Northeast Channel (Ramp *et al.,* 1985; Schlitz and Cohen, 1984; Townsend, 1991; Townsend, 1998). Recent evidence has shown that nutrients may also be deposited into the Gulf via surface water from Scotian Shelf Water (Townsend, 1997; 1998). The physical characteristics within the Gulf of Maine characterized by deep basins and limited exchange with the Atlantic Ocean are coupled with other important processes that regulate nutrient delivery to the surface (Townsend, 1998). These processes include: vertical mixing by tides (Garrett *et al.,* 1978); seasonal extremes in heat flux which lead to winter convection and vertical stratification in the summer; pressure gradients from density contrasts developed from slope water inflow and river runoff (Brooks, 1985); and, cold water inflow from the Scotian Shelf (Smith, 1983). During the summer, when offshore waters are stratified, upwelling and internal waves may also promote vertical nutrient flow (Denman and Herman, 1978; Townsend *et al.,* 1987; Brooks and Townsend, 1989).

Tides exert a strong influence on the spatial pattern of hydrographic structure in the Gulf, nutrient delivery to the euphotic zone, and biological productivity. The strong tidal influence promotes vertical mixing throughout the year in the Maine Coastal Current which brings nutrient-rich waters to the surface supporting biological productivity. The coastal current system is the main factor in regulating the nutrient budget and biological oceanography within the Gulf. Tidal ranges increase from east to west across the Scotian Shelf and into the Gulf of Maine, with some of the highest tides in the world found at the upper reaches of the Bay of Fundy. Tidal current speeds on the southwest Nova Scotian Shelf and over Browns Bank are on the order of 100 cm/s and produce significant vertical mixing of the water column (Garrett *et al.,* 1978). Shelf waters off southwest Nova Scotia are conspicuously colder than surrounding areas, especially during the warmer months. Vigorous tidal mixing, combined with the flow of cold Scotian Shelf water from the east (as the Nova Scotia Current), and localized upwelling, maintain cold temperatures here year-round. This tidal mixing in combination with upwelling off southwest Nova Scotia (Lauzier, 1967), a result of centrifugal effects of tidal currents following the curved bathymetry (Garrett and Loucks, 1976) and/or longshore density gradients (Smith, 1983), act together to promote significant nutrient additions onto the shelf (Fournier *et al.,* 1984).

In general, phytoplankton biomass is greater nearshore where land source nutrients are most abundant. Phytoplankton are most abundant during the spring resulting from increased nutrient supply via winter convection and increased freshwater inflow. Abundance declines during the summer and a second bloom occurs during the fall, however the duration is generally longer than the spring bloom, but amplitude is decreased (Thomas *et al.,* 2003). The spring bloom typically begins nearshore during January-March, appears later over offshore banks (March-April), and appears over the deep basins during April-May (Riley, 1947). Along the coast of Maine, strong vertical mixing occurs throughout the year bringing nutrients and supporting elevated phytoplankton biomass that are advected southwest (via the Maine Coastal Current) along the coastline (Townsend *et al.,* 1987). Near Penobscot Bay, the Maine Coastal Current is often deflected away from the coastline and is characterized as a plume of cold, nutrient-rich water that flows over the central Gulf and Jordans Basin (Brooks and Townsend, 1989; Bisagni et al., 1996; Lynch *et al.,* 1997; Pettigrew *et al.,* 1998). Plume strength and duration are highly variable. The main flow of the coastal current brings nutrients to the southern Gulf, Georges Bank, and exits through the Great South Channel. The Maine Coastal Current and its offshore plume are one of the most important factors in regulating phytoplankton species composition and abundance. Approximately 44% of the inorganic nutrient flux required to meet new primary production for the entire Gulf are delivered by the Maine Coastal Current-plume system (Townsend *et al.,* 1987).

Phytoplankton biomass can be estimated from the concentration of chlorophyll measured in the water column or on the surface either from in-situ observations or satellite imagery. Chlorophyll is often used as a proxy to estimate phytoplankton abundance. Eight years of chlorophyll products were derived from data obtained from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) on the Orbview-2 satellite (operated by ORBIMAGE Corp.). The ocean color dataset from SeaWiFS provided a eight-year (October 1997 to December 2005) time series of chlorophyll. The Remote Sensing Team at the Center for Coastal Monitoring and Assessment (CCMA-RST) has developed algorithms, implemented by NASA for standard processing, to improve the generation of ocean color data and estimation of chlorophyll from SeaWiFS in the coastal zone (Stumpf *et al.,* 2002).

Time series image sets of chlorophyll were created for the Gulf of Maine in Geotiff format. These images are useful for determining spatial trends in algal bloom patterns. The final products were projected using the Albers Conical Equal Area projection using the North American Datum 1983. The imagery time series generated from the SeaWiFS data included monthly means and monthly medians. Seasonal images were created from the monthly images using the following grouping:

Spring-March, April, May
Summer-June, July, August
Fall-September, October, November
Winter-December, January, February

Figures 1.7.1 and 1.7.2 display the seasonal patterns of mean chlorophyll concentration in the Gulf of Maine. Mean monthly patterns of chlorophyll concentration are displayed in Appendix 6. Spatial and temporal patterns agree with Thomas *et al. (*2003) where chlorophyll concentrations are highest during the spring and fall blooms, decrease moderately during the summer, and reach a chlorophyll minimum during the winter. Chlorophyll is most elevated along the coastal margin, in the Bay of Fundy, over Georges Bank and Nantucket Shoals throughout the year.

Within the deeper portions of the Gulf of Maine, lowest chlorophyll concentrations were observed during the winter (December-February), increased during the spring (March-May) bloom and decreased during the summer (June-August). Concentrations rose again during the fall bloom (September-November) and were lowest during winter (December-February). Georges Bank is an area of persistent elevated chlorophyll concentration relative to the greater Gulf of Maine with highest concentrations in the spring and fall. This trend is also apparent within the Nantucket Shoals region. The spring and fall blooms are most noticeable in the western portion of the Gulf over Stellwagen Bank, Wilkinson Basin, and along the coastline. Higher chlorophyll concentrations were observed offshore from the central coastline near Penobscot Bay during April-October. This region is where colder, nutrient-rich surface waters of the Maine Coastal Current turn cyclonically offshore (Townsend *et al.,* 1987; Bisagni *et al.,* 1996; Pettigrew *et al.,* 1998).

Within Massachusetts Bay, chlorophyll concentrations are lowest during late winter and early spring (January-March), but slightly elevated compared to the Gulf of Maine. Along the coastal margin, chlorophyll levels are moderate or high year round, peaking during the spring and fall blooms. During these blooms, chlorophyll abundance increases within the Sanctuary, however the duration and amplitude are variable. Mean monthly and seasonal chlorophyll concentration data were extracted for the area within the Sanctuary boundary to examine temporal patterns (Figure 1.7.3). The temporal patterns are consistent with the overall patterns observed within the Gulf of Maine: high chlorophyll abundance during the spring and fall, reduced levels during the summer, and smallest concentrations during the winter. Individual monthly mean chlorophyll concentrations generally follow the same trend as the mean for all months combined with the exception of lower than average concentrations during the fall of 1997 and higher than average concentrations during spring 1999, spring 2000, and fall 2000. Comparison of these data with precipitation data obtained from North Atlantic regional watershed precipitation data indicate that these higher and lower than mean values correlate with significant increases or decreases with precipitation.

In summary, the Gulf of Maine is among the most productive marine ecosystems in the world, accounting for a rich fishery heritage. The high rate of productivity is made possible by the combination of topography and dynamic seasonal climatology that constitutes the base of the coastal and marine food web. Within the Sanctuary two

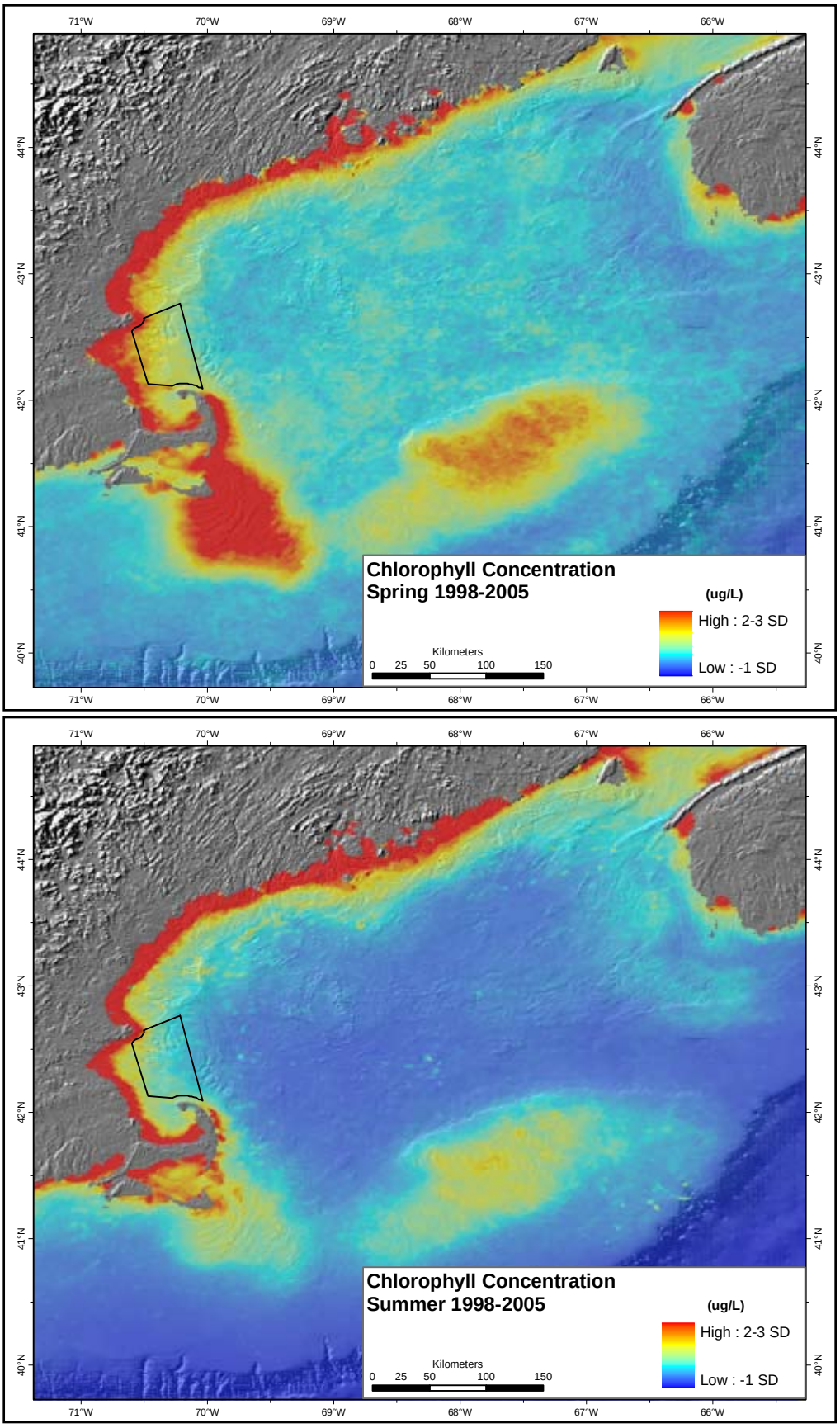

Figure 1.7.1. Spring and summer mean chlorophyll concentration within the Gulf of Maine, 1998-2005. Values are colored according to standard deviations above and below mean chlorophyll concentration.

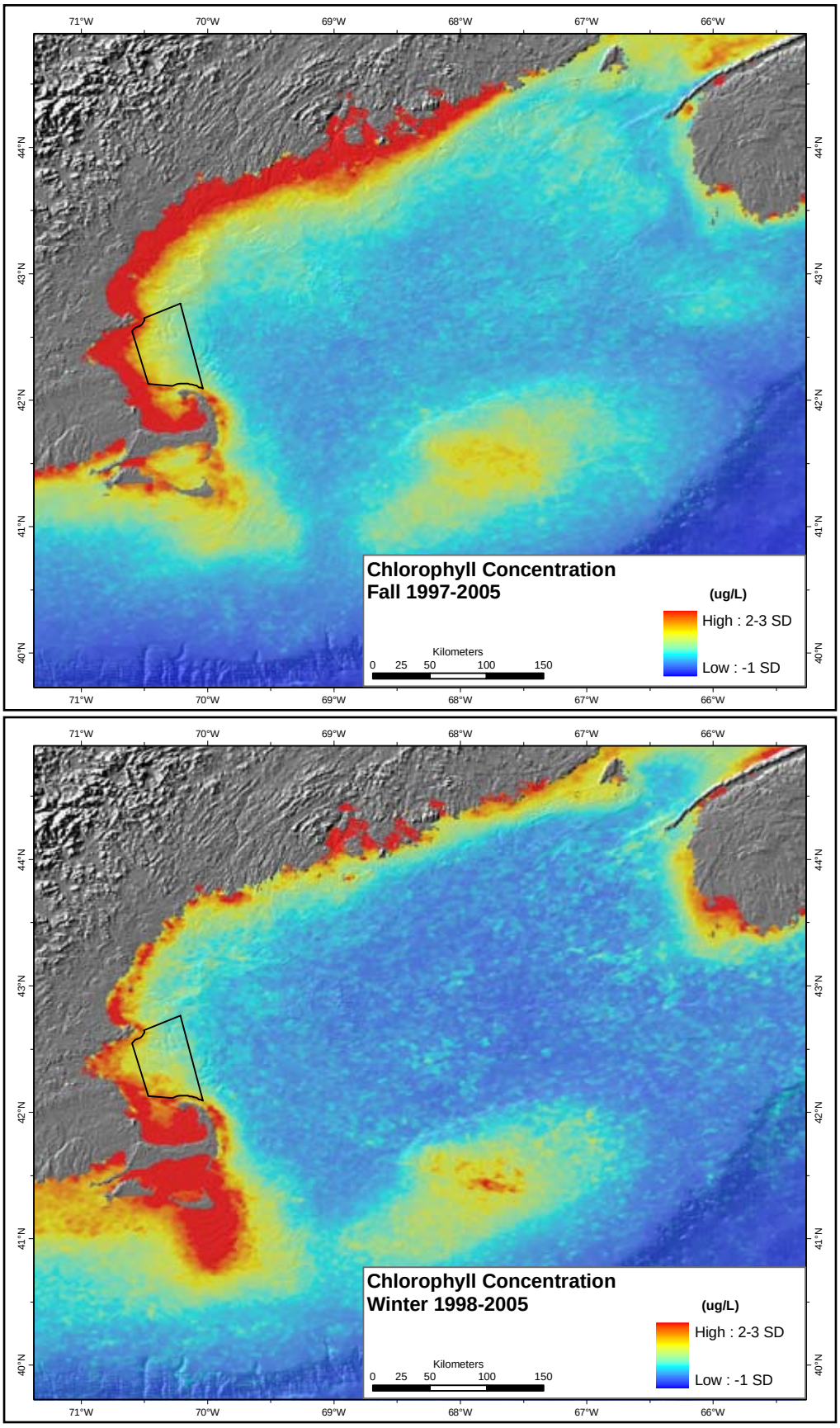

Figure 1.7.2. Fall (1997-2005) and winter (1998-2005) mean chlorophyll concentration within the Gulf of Maine. Values are colored according to standard deviations above and below mean chlorophyll concentration.

distinct productivity periods (spring and fall) occur where increased nutrients from riverine input and deep water mixing drive enhanced phytoplankton production that in turn support a wide variety of marine organisms.

Zooplankton

Zooplankton play in important role in marine food webs both as a link between primary producers and higher trophic levels. Zooplankton consumption rates primarily determine the amount of primary productivity that enters the food web, whereas the remainder is consumed by microorganisms or settles to the bottom to fuel benthic communities (Parsons and Lalli, 1988; Townsend and Cummen, 1988). The timing of zooplankton production cycles is a key factor in controlling larval fish survival, the degree of coupling with phytoplankton, and channeling primary production between pelagic and benthic foodwebs (Cushing, 1982; Townsend and Cammen, 1988; Durbin and Durbin, 1992). While many species comprise the zooplankton, copepods are most abundant numerically and in biomass and represent the dominant pathway of productivity to higher trophic levels (Durbin and Durbin, 1996).

Zooplankton abundance and distribution are regulated by temperature, food availability, and predation. High seasonal variability in temperature strongly regulates zooplankton abundance. Copepod life cycles have evolved to take advantage of spring phytoplankton blooms as a predictable seasonal event (Parsons and Lalli, 1988); however, the timing of phytoplankton and zooplankton biomass maxima may not be closely linked (Durbin and Durbin, 1992). In general, seasonally cooler temperatures impede zooplankton development during fall and winter and increases during spring and summer. The timing of this cycle affects the trophic web through its influence on reproductive, grazing, and secondary production rates. A prolonged difference of +/- 1° C can affect zooplankton maturation rates which can affect higher trophic levels and primary productivity distribution. For example, in a warmer than average spring zooplankton may mature early and significantly graze down phytoplankton biomass. Rapidly advancing growth stages can represent a 45% increase in biomass and can significant-

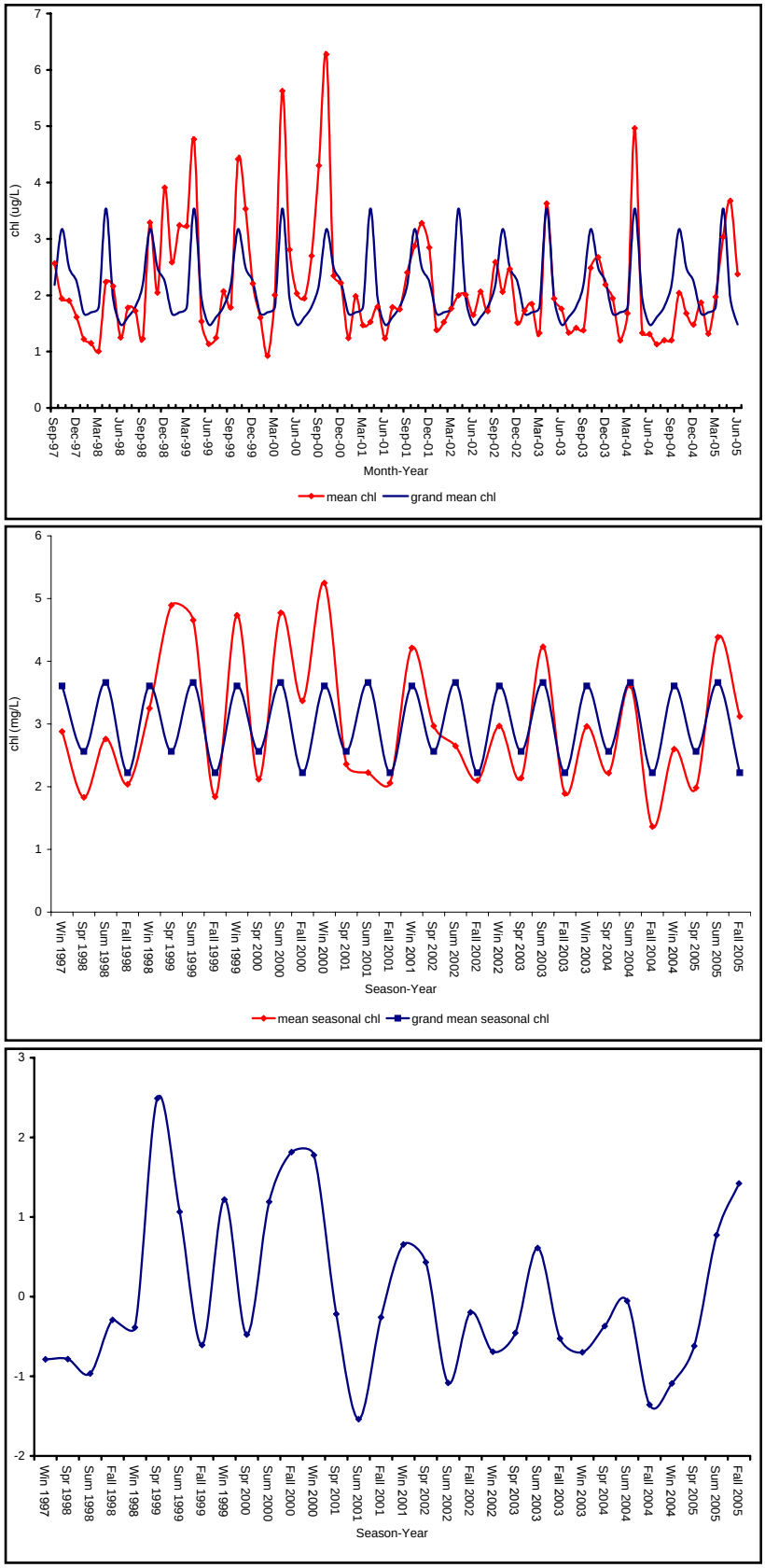

Figure 1.7.3. Chlorophyll concentration within Stellwagen Bank NMS: top-monthly mean; middle-seasonal mean; bottom-chlorophyll anomaly.

ly increase the populations grazing pressure. This could have severe implication to benthic communities (Durbin and Durbin, 1996).

Zooplankton feeding rates, copepods in particular, are strongly correlated with food concentration and particle size. Copepods have a preferred range of food size and is correlated with seasonal phytoplankton dynamics. In temperate coastal and shelf waters phytoplankton composition changes seasonally, where large diatoms dominate in the winter and spring and small flagellates are most abundant during the summer and fall. This general pattern greatly affects the quantity and quality of food available and directly affects secondary production rates. Food availability may limit secondary production even if phytoplankton biomass is high, however, the size of the phytoplankton community may have negative impacts (Durbin and Durbin, 1996).

Predation on zooplankton can significantly alter community structure. Planktivorous fishes, such as menhaden, Bay anchovy, sand lance, herring, and mackerel as well as ctenophores have significant impacts on zooplankton community structure. In general, fishes remove larger zooplankton and invertebrates prefer smaller sized zooplankton. In response to predation, zooplankton undergo diel movements to avoid predators (Ohman, 1988; Bollens and Frost, 1989; Dagg *et al.,* 1989; Durbin *et al.,* 1990).

Community structure within communities undergoes seasonal cycles. On Georges Bank copepods are the most dominant organism in the zooplankton with several species, *Calanus finmarchicus, Pseudocalanus newmanii, Pseudocalanus moultoni* most abundant during the winter and spring. Other copepod species are abundant during the fall. *Centropages typicus, Centropages hamatus, Paracalanus parvus*, and *Oithona similis* are abundant throughout the year (Davis, 1984). Nearshore species show similar patterns (Kropp, 2003). Polychaete, barnacle, other invertebrate larvae, and fish larvae can be major seasonal components of zooplankton communities.

Zooplankton distribution is linked to the dynamic physical and oceanographic features within the Gulf of Maine. Zooplankton communities can exhibit small-scale homogeneity to 10 km (Davis and Gallagher, 2000). Additionally, some zooplankton taxa may respond to much broader-scale phenomena such as the North Atlantic Oscillation (NAO). For example, the NAO index has been positively correlated with the copepod, *Calamus finmarchicus,* abundance. Zooplankton availability as food for larval fish is considered a key factor that determines year class strength of commercial fish species (Cushing, 1978).

Zooplankton communities have been well studied in the northeast Atlantic (Sherman *et al.,* 1983) and on Georges Bank within the Gulf of Maine (Bigelow, 1927; Davis, 1984; Backus, 1987; Kane, 1993; Pershing *et al.,* 2004). Few studies have examined zooplankton spatial patterns within the Gulf of Maine. Twelve years (1977-1988) of zooplankton data from the National Marine Fisheries Service Northeast Fisheries Science Center (NEFSC) Marine Resources Monitoring Assessment and Prediction Program (MARMAP) were obtained to examine spatial and temporal patterns. A subset of the entire database was selected to include all zooplankton surveys in the Gulf of Maine during this time period (Figure 1.7.4). Overall, 6,864 samples were collected within this area; sampling methodology is described in Sibunka and Silverman (1989).

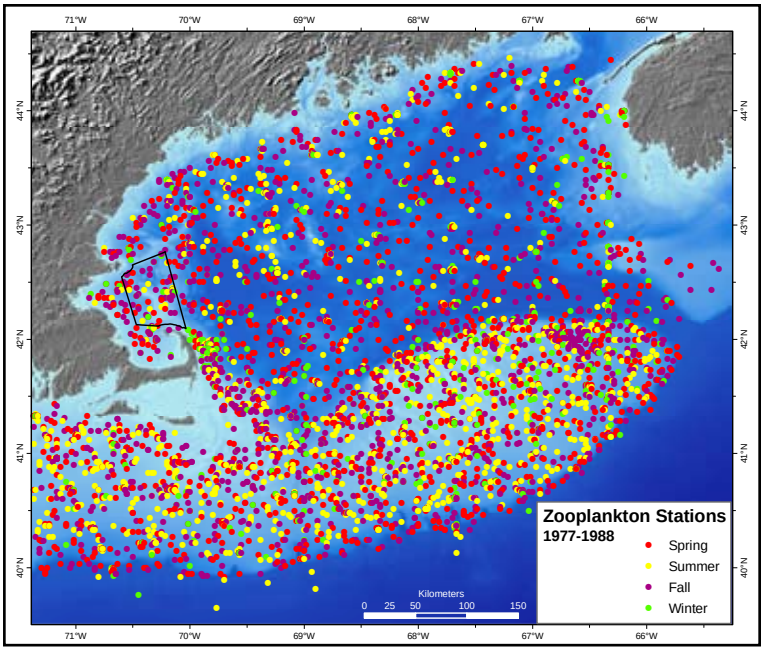

Figure 1.7.4. Location of NEFSC MARMAP zooplankton surveys, 1977-1988.

Interannual variability is common within the Gulf of Maine, as many species of zooplankton exhibit life cycles that peak at various times throughout the year. To examine the spatial and temporal patterns of zooplankton abundance and distribution the data were divided into three-year sea-

sonal bins. Yearly bins included 1977-79, 1980-82, 1983-85, 1986-88 and seasons include: spring-March, April, May; summer-June, July, August; fall-September, October, November; and, winter-December, January, February. These binned data were separately mapped in a GIS and interpolated to create a predictive surface of zooplankton abundance throughout the Gulf of Maine. Prior to interpolation, all data were tested for spatial autocorrelation. Spatial autocorrelation is frequently encountered in ecological data, and many ecological theories and models assume an underlying spatial pattern in the distributions of organisms and their environment (Legendre and Fortin, 1989). Typically, species abundance is positively autocorrelated, such that nearby points have similar values than distant points. Moran's I and Geary's C statistics were calculated for all the data to identify significant autocorrelation (Levine, 2002). Detrending was done to standardize estimates across the analysis extent, and is a prerequisite for the interpolation used here. Empirical variograms show the decrease in relatedness between pairs of points as a function of distance. In order to calculate the empirical variogram, pairs of points must be binned by distance and an average value calculated for all pairs in a given bin. The size of the bin is called the lag size. A variogram model is fit to the empirical variogram and its parameters are later used in the interpolation. Empirical variograms were calculated using the default lag size and number of lags, as well as for 10, 15, 20 and 30 km lag sizes. The appropriate lag size and number of lags were chosen to optimize variogram coherence.

The interpolation method used is termed ordinary kriging. Kriging is a linear interpretation method that allow predictions of unknown values of a random function from observations at known locations (Kaluzny *et al.,* 1998). Ordinary kriging is the method generally used for interpolation of a single continuous variable of unknown mean. Kriging is a preferred method because weights are based on the data's spatial structure (the variogram) and has been shown to outperform other interpolation techniques, such as inverse distance weighting and triangulated irregular networking, when data is spatially autocorrelated (Guan *et al.,* 1999). Trend analysis was conducted using JMP statistical software (SAS Institute), while detrending, variogram modeling, and kriging were conducted using ArcMap Geostatistical Analyst Extension (ESRI, Inc.).

In addition to creating predictive maps, probability maps were developed using indicator kriging. Indicator kriging is a technique used to identify areas or values that exceed a certain threshold (Isaaks and Srivastava, 1989). Through indicator kriging, data values are transformed into binary indicator values (1 or 0), values which exceed a chosen threshold are coded 1, those below coded 0. These indicators are then analyzed to determine their spatial direction variability with a series of variograms. By inspection of these variograms, orientations of greatest and least spatial continuity are determined. Variogram models are fit to the experimental variograms corresponding to the directional continuity. Then the indicator data are kriged using the variogram models to determine the probability of exceeding the threshold value in a spatial extent. For this analysis, the spatial mean of the zooplankton data was used as the threshold to compare predicted estimates and to also identify areas of high zooplankton abundance.

The kriging neighborhood was set to the nearest 5 neighbors with a minimum of 2 to capture small scale variability (NCCOS, 2003). Cross validation was conducted to assess model accuracy by regressing observed versus predicted values (See modeling statistics Table 1.7.1). Maps of the kriging standard error were also generated and used to exclude poorly interpolated areas within the analysis extent. The lowest 50% of standard error was clipped from the interpolated map to depict the areas of strongest interpolation.

A subset of all MARMAP zooplankton surveys were used to examine spatial and temporal patterns. Overall 6,864 samples were conducted between February 1977 and December 1988. Mean zooplankton abundance was highest from April-September, generally following the spatial and temporal abundance of phytoplankton distribution. Zooplankton abundance during the spring was variable, but showed consistent patterns of high abundance within the western portion of the Gulf of Maine, in particular Massachusetts Bay, and over Nantucket Shoals and Georges Bank (Figure 1.7.5). Areas of high abundance were also observed off of Cape Sable, Nova Scotia. Maps of probability (Figure 1.7.6) exhibited similar abundance patterns through the time series. Survey effort close to the shoreline and in the Bay of Fundy were inadequate to confidently model zooplankton abundance and interpolation standard error was high, thus nearshore areas were excluded from the maps. Zooplankton samples were also subset for the area comprising the Stellwagen Bank NMS and examined for species composition and relative abundance compared with the rest of the Gulf of Maine.

Table 1.7.1. Summary statistics for NEFSC MARMAP zooplankton ordinary and indicator kriging.

Analysis	Sample size	Lag Size	Number of Lags	Cross Validation Prediction Map -r^2	Cross Validation Probability Map -r^2	Neighbors (total, minimum)
spring 77-79	364	20	12	0.02	0.03	5, 2
spring 80-82	352	20	12	0.02	0.02	5, 2
spring 83-85	391	20	12	0.58	0.26	5, 2
spring 86-88	320	20	12	0.27	0.26	5, 2
spring all	1,223	20	12	0.14	0.14	5, 2
summer 77-79	231	20	12	0.36	0.32	5, 2
summer 80-82	298	20	12	0.30	0.25	5, 2
summer 83-85	367	20	12	0.37	0.39	5, 2
summer 86-88	346	30	12	0.58	0.53	5, 2
summer all	1,029	30	12	0.36	0.32	5, 2
fall 77-79	446	20	12	0.36	0.23	5, 2
fall 80-82	320	20	12	0.39	0.31	5, 2
fall 83-85	402	20	12	0.58	0.50	5, 2
fall 86-88	463	20	12	0.55	0.47	5, 2
fall all	1,352	20	12	0.47	0.39	5, 2
winter 77-79	175	30	12	0.24	0.19	5, 2
winter 80-82	152	20	12	0.36	0.35	5, 2
winter 83-85	147	20	12	0.54	0.45	5, 2
winter 86-88	225	30	12	0.58	0.55	5, 2
winter all	445	20	12	0.45	0.40	5, 2

Within Stellwagen Bank NMS, zooplankton abundance (based on 15 samples) during the spring was consistently high compared to the Gulf of Maine. Highest abundance and probability were observed in the western portion of the Sanctuary and declined eastward. Copepods were most abundant in the surveys and were dominated by *Calanus finmarchicus*, and *Pseudocalanus minutus*. *C. finmarchicus* has already been identified as a dominant zooplankton community member throughout the North Atlantic (Mauchline, 1998) and its life cycle has been well documented (Conover, 1988; Miller *et al.,* 1991; Greene *et al.,* 2004). Other copepods, *Metridia lucens*, *Centropages hamatus*, and *Oithona spinirostris*, and the water flea, *Evadne nordmanni*, were less abundant but ranked high in overall relative abundance. Species abundance and dominance within the Sanctuary exhibited similar patterns compared to the Gulf (Figure 1.7.7).

During summer months, zooplankton abundance increased Gulf-wide and areas of highest abundance and probability were more ubiquitous throughout the Gulf of Maine. Areas of lower abundance and probability occurred over the deeper basins and the seaward edge of Georges Bank (Figures 1.7.8 and 1.7.9). A substantial increase in the relative abundance of *C. finmarchicus* was observed within the Sanctuary, however, within the Gulf of Maine relative abundance was lower than spring (Figure 1.7.7). *P. minutus* was again dominant throughout the Gulf and the Sanctuary, and a significant increase was observed for *C. hamatus* and *C. typicus*. Copepods of the genus *Acartia* were also present in high numbers, but relatively low compared to the dominant copepod species.

High variability was observed when comparing the fall time series. Areas within Massachusetts Bay, Nantucket Shoals, and Georges Bank consistently yielded high zooplankton abundance. Areas of high abundance (Figure 1.7.10) and probability (Figure 1.7.11) were most wide-spread during 1983-1985 extending north to areas over Jeffreys Ledge and Jordan Basin. Lowest abundance and probability values were associated with deeper waters at the shelf/slope interface, over the Northeast Channel, Georges Basin, and the central Gulf of Maine. Species composition was dramatically different than that observed during spring and summer (Figure 1.7.7). *C. typicus* was the most dominant zooplankton species, with a relative abundance greater than 60% within Stellwagen Bank NMS and greater than 50% in the Gulf. Relative abundance for *C. finmarchicus* declined significantly (approximately 60%) during the fall, as well as *P. minutus* (approximate 20% decline). *M. lucens* and *Acartia* spp. exhibited relative abundance similar to that observed during the summer.
Zooplankton surveys during the winter months were not as frequent as other seasonal periods, thus model results were more patchy. Regardless, data was sufficient to model abundance and probability maps. Abundance and probability patterns during winter were similar to those seen during the fall. Highest zooplankton abundance was located in the western Gulf, primarily in Massachusetts Bay, Georges Bank, and Nantucket Shoals (Figure

1.7.12). Moderate zooplankton abundance was observed throughout the time series over the region of Jordans Basin and at the mouth of the Bay of Fundy. The winter probability maps indicate that most of the eastern Gulf, excluding Georges Bank, exhibits lower than average zooplankton abundance (Figure 1.7.13). Similar to the fall, *C. typicus* was the dominant species with relative abundance declining slightly from the fall (Figure 1.7.7). *C. finmarchicus* also declined slightly, while *P. minutus*, *M. lucens,* and *C. hamatus* remained at approximately the same relative abundance levels as in the fall.

Climate variability influences the ecology of many species, such as zooplankton, and can have important impacts to ecosystem dynamics (Pershing *et al.,* 2004). The patterns of zooplankton abundance and distribution may be used to provide context for explanation of distribution patterns for higher trophic levels within the Stellwagen Bank NMS and the Gulf of Maine in the following chapters. In general these data indicate similar patterns of abundance and distribution to that observed for the remote sensing ocean color data. Thus it seems logical that the areas of high primary productivity will be followed by areas of high secondary productivity. Zooplankton abundance within the Sanctuary appears to be high throughout the year and is a possible ecosystem “hot spot” within the Gulf of Maine. Zooplankton populations throughout the Gulf can be comprised of many different species, and can exhibit strong spatial and temporal variability. Interannual variability in zooplankton communities is believed to be an important determinant to larval fish survival and subsequent recruitment to adult populations (Kane, 1993). Sherman *et al.,* (1981) observed that zooplankton biomass closely resembled those of northern sand lance (*Ammodytes dubius*) population estimates. Zooplankton are important for larval fishes, such as herring, sand lance, mackerel, which are subsequently preyed upon by marine birds and mammals, many of which utilize the Sanctuary’s waters. The distribution of humpback whales has been shown to be significantly correlated with the number of sand lance obtained from standardized trawl tows (Payne *et al*., 1986).

1.8 SUMMARY

The Gulf of Maine connects New England states (e.g. Massachusetts, New Hampshire, and Maine) and Canadian provinces (New Brunswick and Nova Scotia) with 93,239 km^2 of ocean, 19,424 km^2 of shoreline, and approximately 5,000 islands. A combination of physical and oceanographic characteristics in the Gulf of Maine result in cycles of biological productivity that support exceptionally large and diverse populations of fish, seasonal populations of cetaceans (including several classified as endangered) and seabirds. Bounded by underwater offshore banks, the prevailing counterclockwise circulation resulting from currents, freshwater inflow, and the configuration of shoreline and underwater topography create a self-contained oceanographic system. The Stellwagen Bank NMS is an important feature within this self-contained system and its water properties are largely determined by the large-scale patterns within the Gulf. From a management and ecological perspective, it is necessary to understand the large-scale oceanographic patterns and how they influence the smaller-scale management unit of the Sanctuary. This chapter synthesizes and summarizes the wealth of scientific information for the large-scale ecosystem and its implications to the oceanographic patterns observed within the Sanctuary. Many processes (tides, currents, sea surface temperature, internal waves, etc.) comprise the oceanographic character of the region and their interactions drive large and small-scale biological dynamics which will be discussed in subsequent chapters.

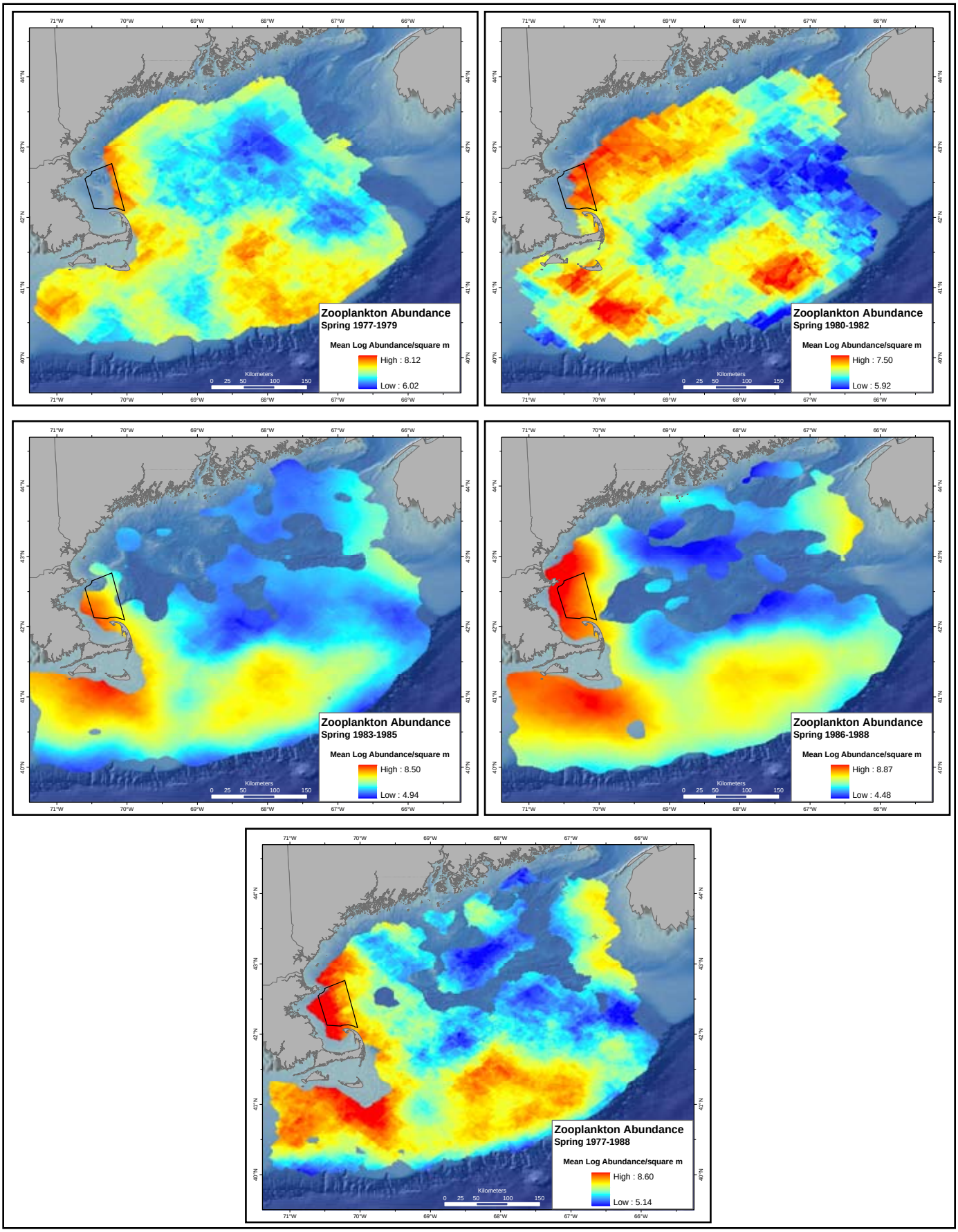

Figure 1.7.5. Predicted zooplankton abundance during spring (1977-1998) within the Gulf of Maine. Data source: NEFSC MAR-MAP.

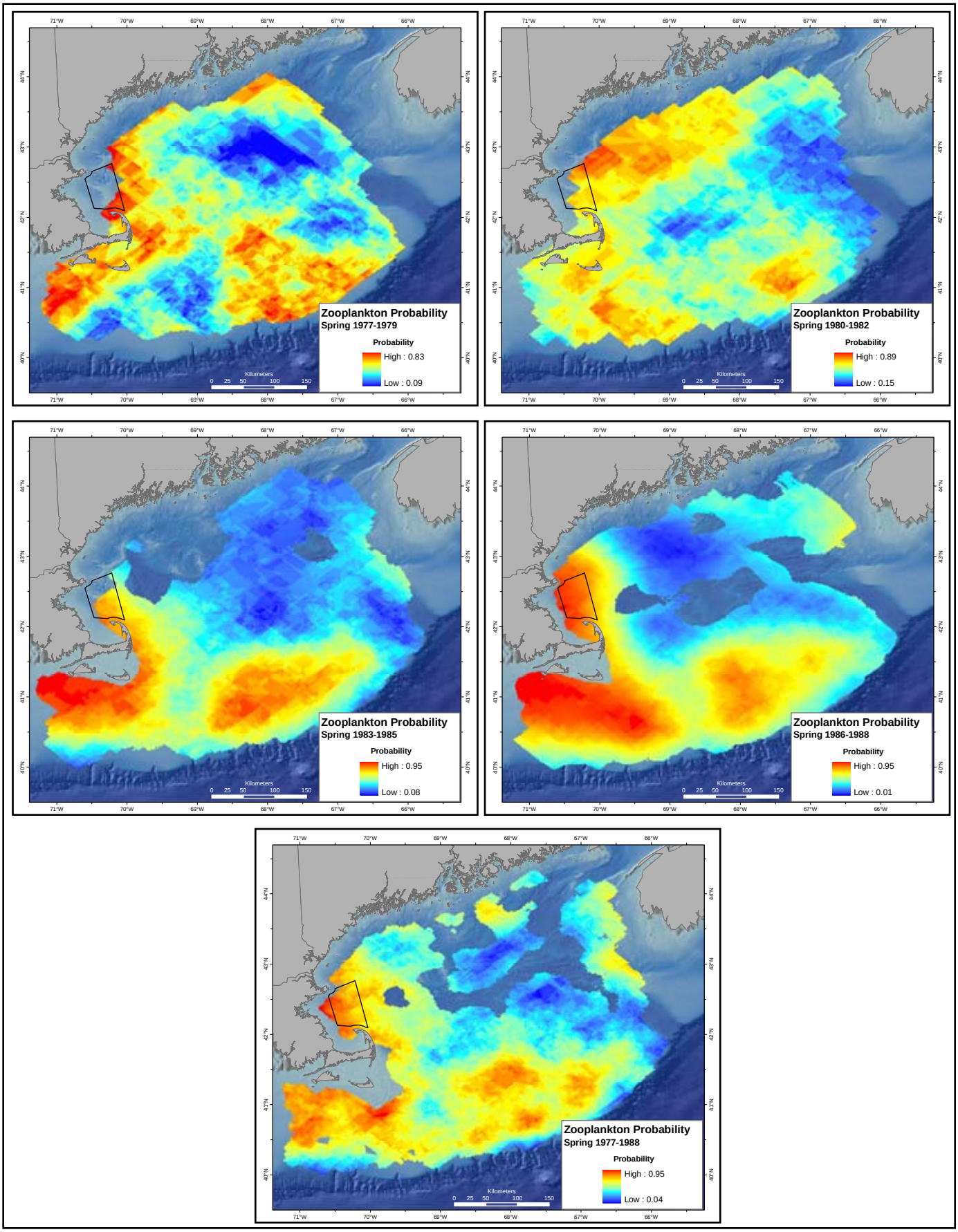

Figure 1.7.6. Probability of zooplankton abundance greater than the mean for the study area, spring 1977-1988. Color scale indicates standard deviation from the mean. Source: NEFSC MARMAP.

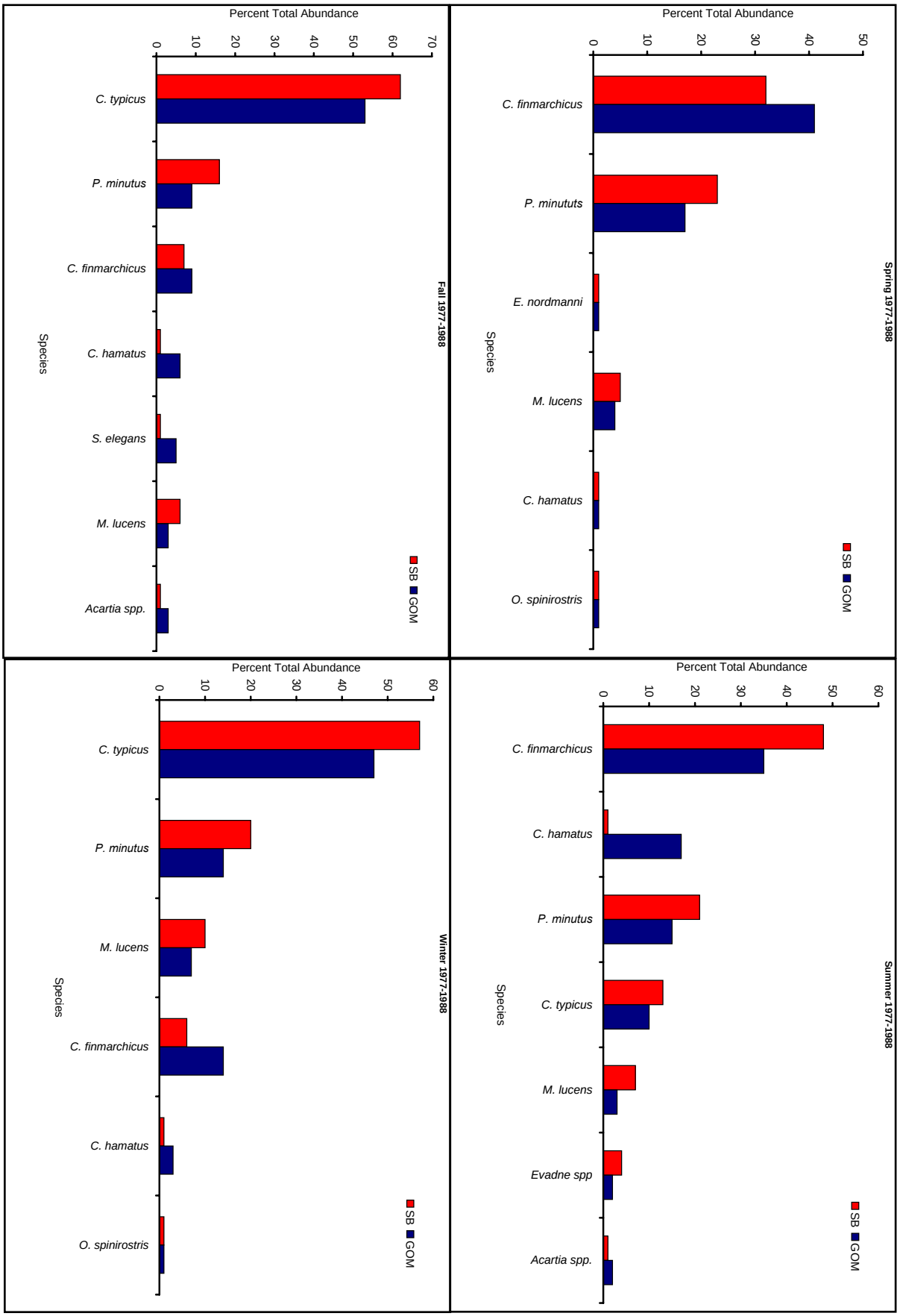

Figure 1.7.7. Seasonal relative abundance of dominant zooplankton captured in NEFSC MARMAP zooplankton surveys, 1977-1988. Red bars indicate relative abundance within Stellwagen Bank NMS, blue bars indicate relative abundance within the Gulf of Maine.

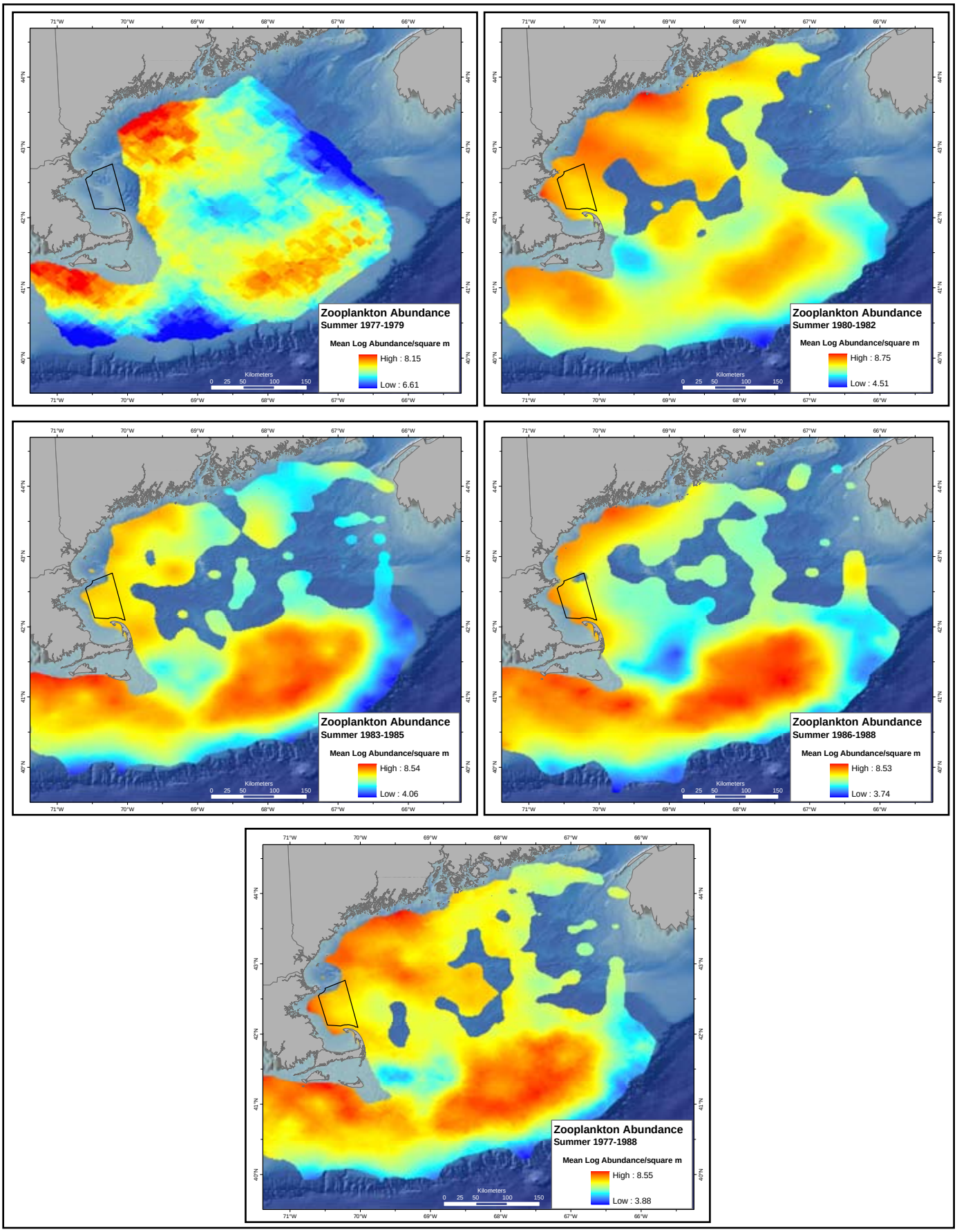

Figure 1.7.8. Predicted zooplankton abundance during summer (1977-1998) within the Gulf of Maine. Data source: NEFSC MAR-MAP.

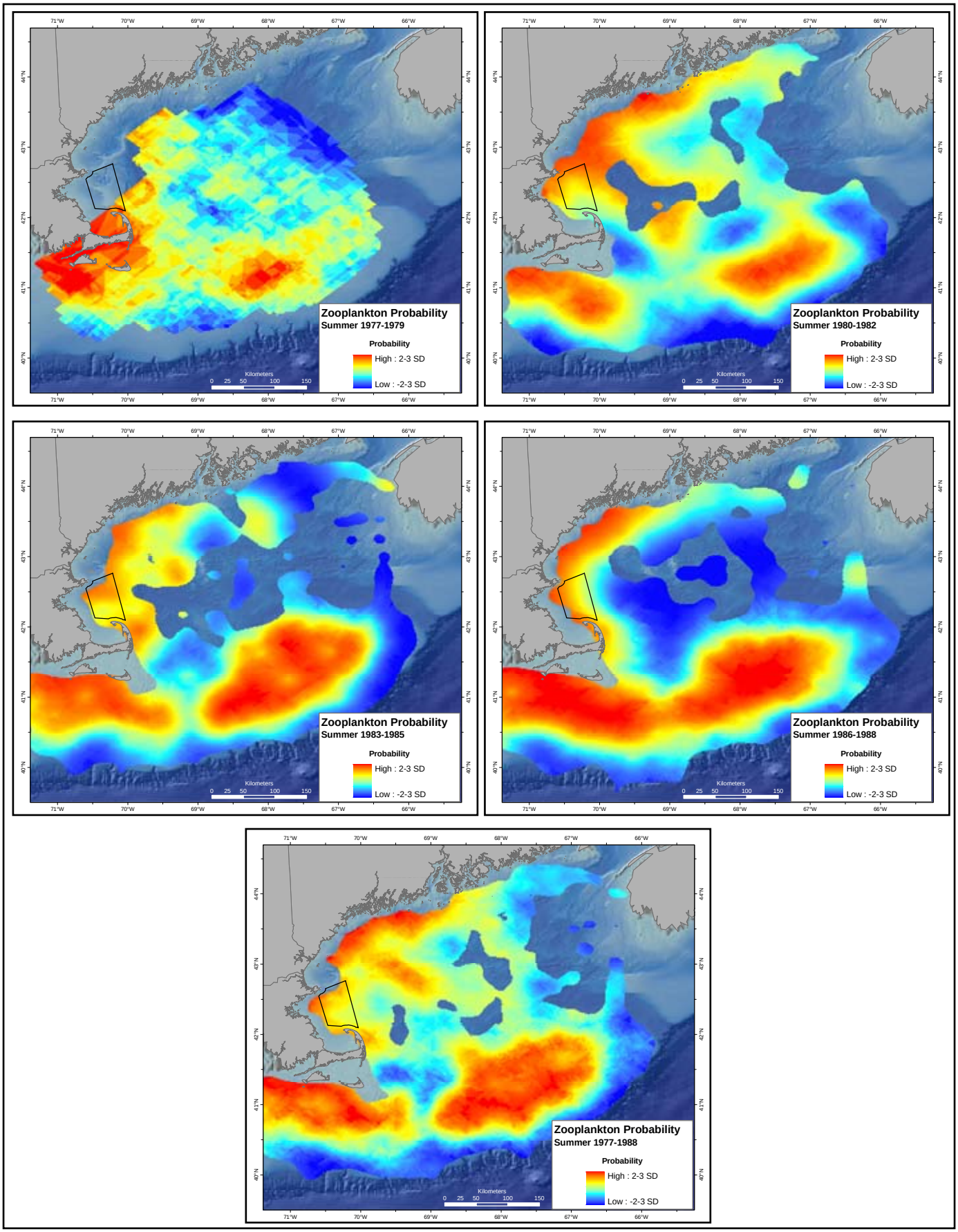

Figure 1.7.9. Probability of zooplankton abundance greater than the Gulf of Maine mean, summer 1977-1988. Color scale indicates standard deviation from the mean. Source: NEFSC MARMAP.

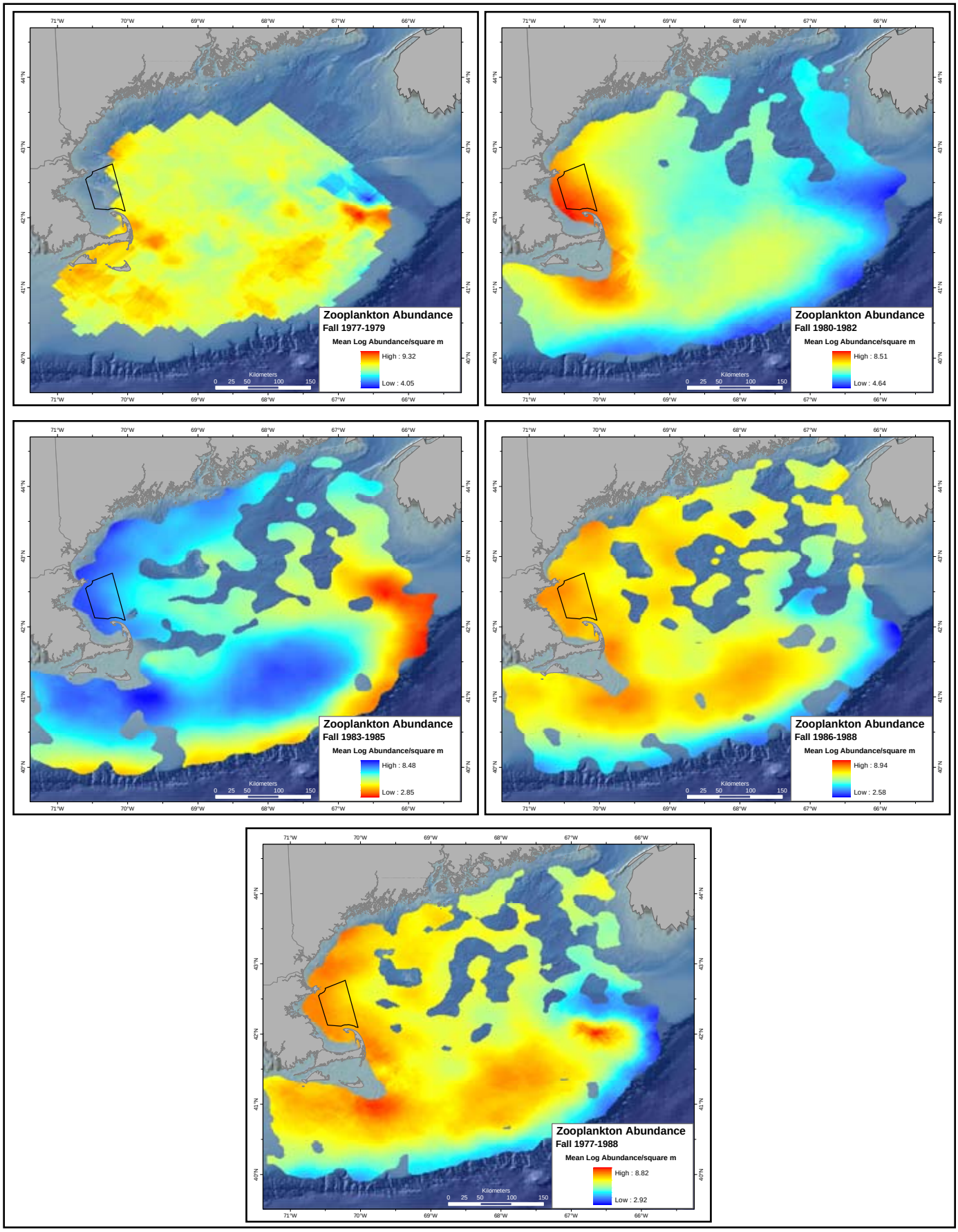

Figure 1.7.10. Predicted zooplankton abundance during fall (1977-1998) within the Gulf of Maine. Data source: NEFSC MARMAP.

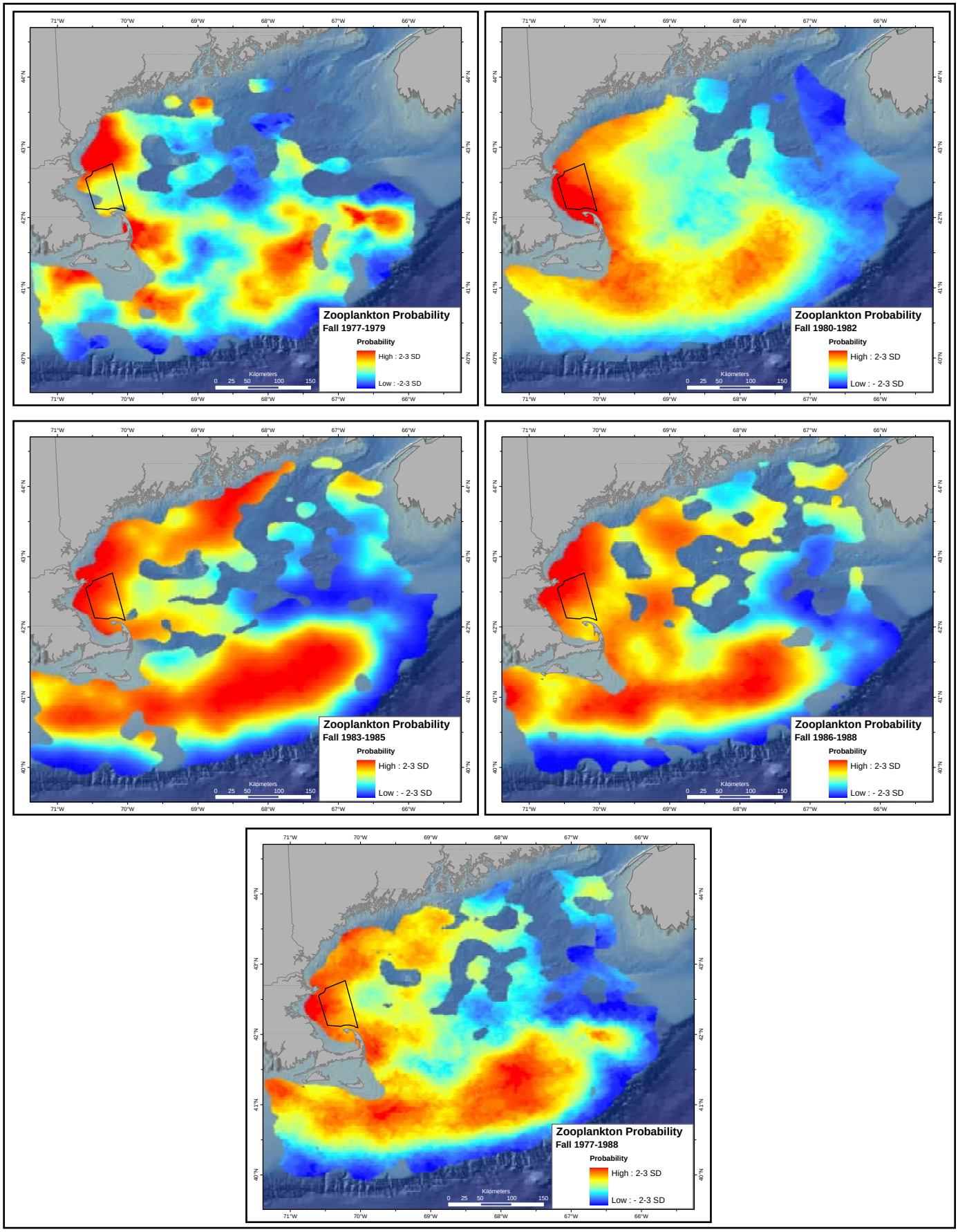

Figure 1.7.11. Probability of zooplankton abundance greater than the Gulf of Maine mean, fall 1977-1988. Color scale indicates standard deviation from the mean. Source: NEFSC MARMAP.

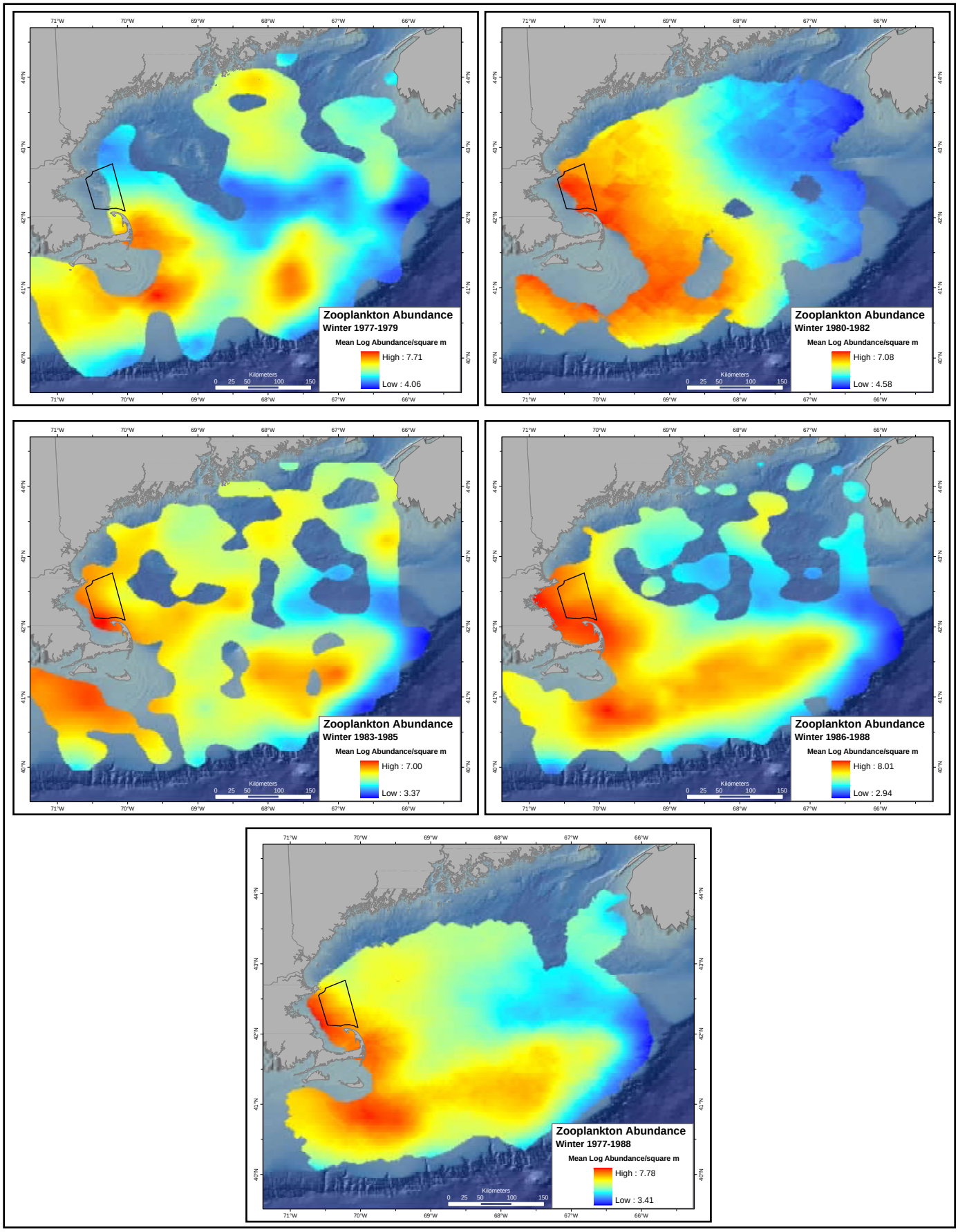

Figure 1.7.12. Predicted zooplankton abundance during winter (1977-1998) within the Gulf of Maine. Data source: NEFSC MAR-MAP.

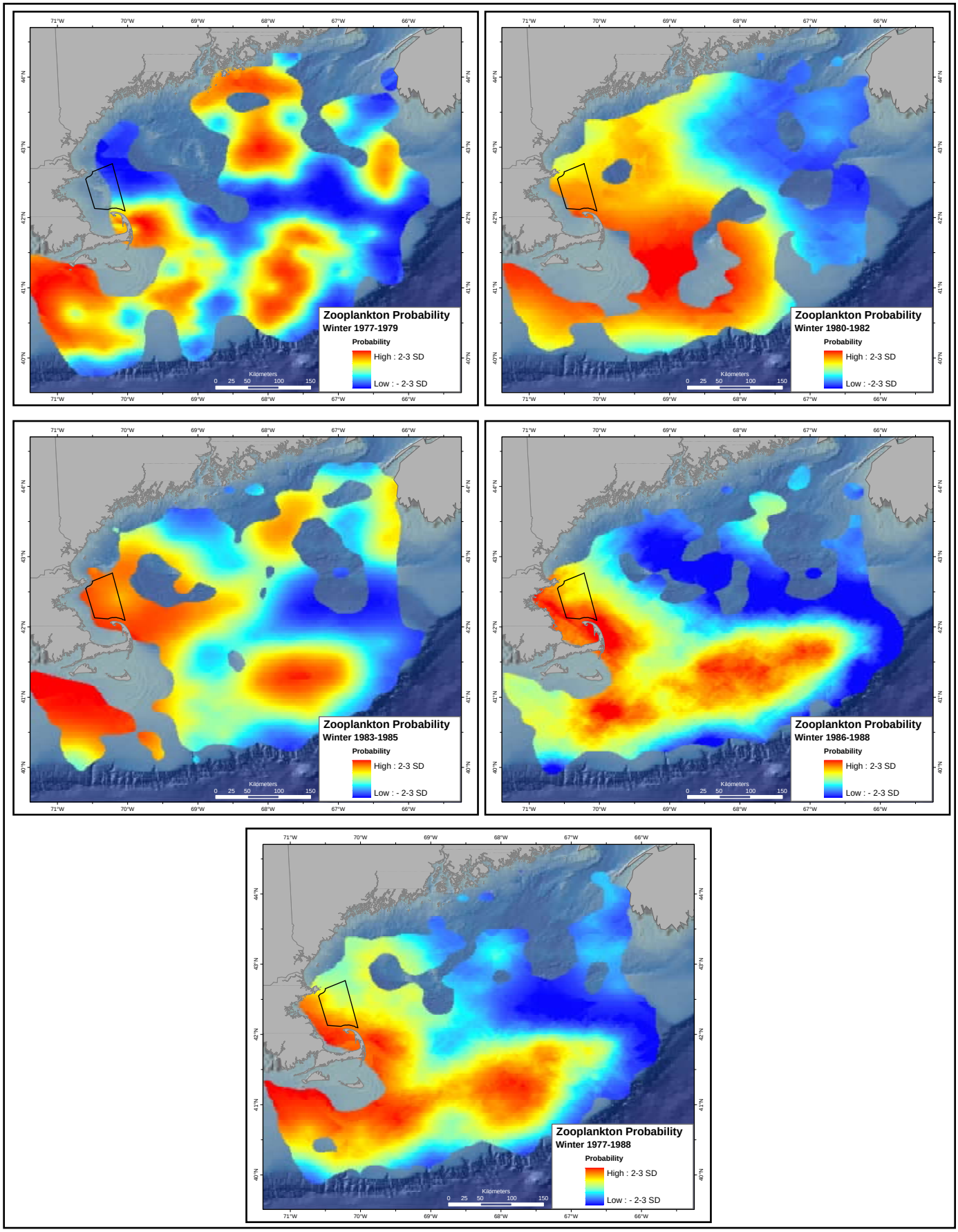

Figure 1.7.13. Probability of zooplankton abundance greater than the Gulf of Maine mean, winter 1977-1988. Color scale indicates standard deviation from the mean. Source: NEFSC MARMAP.

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CHAPTER 2 - CHARACTERIZATION OF CHEMICAL CONTAMINANTS

Ian Hartwell, Dennis Apeti, Mark Myers, and Andrew Mason

2.1 INTRODUCTION

In 2004, field samples were taken to assess the status and trends of chemical contamination in sediments and resident biota, and to assess the biological condition of the various habitat types found in the Stellwagen Bank National Marine Sanctuary (NMS) region. Sampling efforts employed a combination of the NOAA National Status and Trends (NS&T) Bioeffects (BE) Program and the National Benthic Surveillance (NBS) Program protocols. The Bioeffects Program assesses sediment contamination, toxicity, and benthic community impacts associated with contaminant exposure. Regional studies, with one to four year durations, have been conducted throughout the U.S. using the Sediment Quality Triad approach. The approach includes sediment and water chemistry for organic and inorganic contaminants, a suite of toxicity and biomarker assay; and benthic community assessment. Federal and State agencies and local stakeholders cooperate on these studies. The Benthic Surveillance Program also addresses sediment contamination, in addition to contaminant body burdens and histological indicators in resident fish. This was a collaborative effort between NS&T and the NOAA National Marine Fisheries Service (NMFS). The National Benthic Surveillance Project analyzed chemical and biological contaminant trends in sediment and fish tissue collected at 183 coastal sites from 1984 to 1993. The database includes: sediment, fish liver and fish bile chemistry for organic and inorganic contaminants, and associated diseases in the fish livers. Sampling results reported in this document were a coordinated effort between NS&T and the Northwest Fisheries Science Center. Data from 2004 were contrasted with historical NOAA data, and data from the Massachusetts Water Resources Authority (MWRA) to assess the spatial and temporal trends in chemical contamination in the Stellwagen Bank NMS region as a whole.

Boston Harbor, Stellwagen Basin, and Cape Cod Bay are long-term sinks for fine-grained sediments and associated contaminants from all sources in the region. Bottom deposits on the inner shelf of the western shore of Massachusetts Bay are gravel, coarse sands, and bedrock. Fine sediments do not accumulate here because storm currents resuspend and displace them. During much of the year, a weak counterclockwise circulation persists in Massachusetts and Cape Cod Bays, driven by the southeastward coastal current from the Gulf of Maine. Currents flow southwesterly into Massachusetts Bay south of Cape Ann, southward along the western shore, and easterly out of the Bay north of Race Point. This flow pattern may reverse in the fall, especially near the western shore. In most of Massachusetts Bay, the flow-through flushing time for the surface waters ranges from 20 to 45 days (USGS, 1998).

Storm events with strong winds from the northeast, commonly referred to as “Northeasters”, generate large waves that enter Massachusetts Bay from the east. The currents associated with these waves cause resuspension of the bottom sediments in exposed areas along the western shore of Massachusetts Bay. The wind-driven currents flow southeastward parallel to the coast (with an offshore component near the bottom) and carry the suspended sediments toward Cape Cod Bay and offshore into Stellwagen Basin. Sediments settle to the sea floor along these transport pathways. Currents caused by surface waves are the principal cause of sediment resuspension. Cape Cod Bay is sheltered from large waves by the arm of Cape Cod, and waves are rarely large enough to resuspend sediments at the seabed in the deep areas of Stellwagen Basin. Thus, once sediments reach Stellwagen Basin or Cape Cod Bay, carried either by the mean flow or transported by storms, resuspension and advection is less likely (USGS, 2005).

2.2 METHODS

Field Sampling

The BE approach selects sample sites uses a stratified-random design to determine the spatial extent of sediment contamination and toxicity in U.S. coastal waters. The Massachusetts/Cape Cod Bay region was divided into six strata; Boston Harbor (BH), western Massachusetts Bay (MB), the deep area (DD) in Massachusetts Bay known as Stellwagen Basin, Cape Cod Bay (CC), the zone simply referred to as the area between Massachusetts and Cape Cod Bays (ABB), and portions of Stellwagen Bank (SB) shallower than 120 ft (~36m). The general location of the strata and the Stellwagen Bank National Marine Sanctuary boundaries are presented in

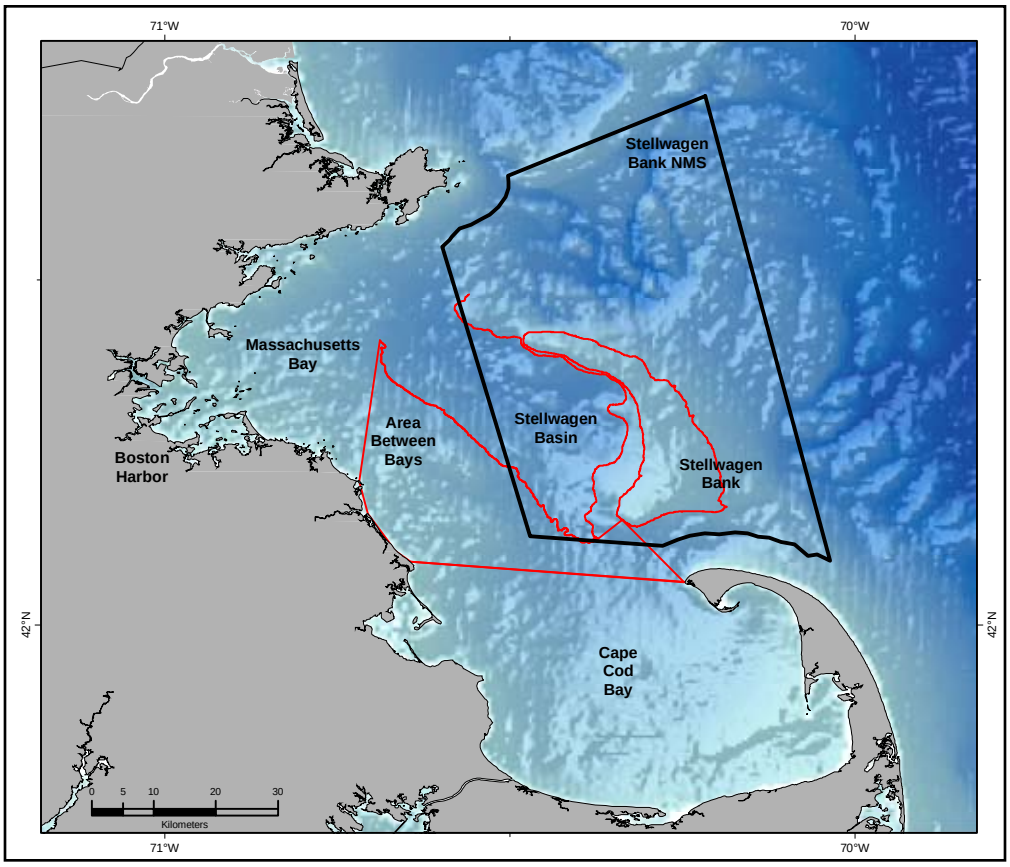

Figure 2.2.1. Study area with six sampling strata within Massachusetts Bay and the Stellwagen Bank NMS.

Figure 2.2.1. Strata boundaries were established in consultation with regional scientists and resource mangers, and were based on bathymetric, hydrographic, and regional environmental considerations, and previous studies detailing geochemical reservoirs, sediment grain size distribution, and organic carbon maps.

Five sampling sites were randomly selected within each stratum. This approach combines the strengths of a stratified design with the random-probabilistic selection of sampling locations, allowing the data generated within each stratum to be attributed to the dimensions of that stratum with a quantifiable degree of confidence (Heimbuch *et al.,* 1995). Within each stratum, two randomly selected alternate sites were also selected for each primary sampling site. In instances where the primary site could not be sampled due to non-accessibility or an unsuitable substratum, the next sequential alternate site was sampled. In this study, sediment contamination and benthic infauna were assessed, but overt toxicity was not. In addition to the five planned sites in each stratum, samples were taken at Deer Island flats, the new POTW (Publicly Owned Treatment Works) outfall diffusers in Massachusetts Bay, and at Plymouth, Mass., at the entrance to Duxbury Bay to coordinate with the Benthic Surveillance sampling regime (Figure 2.2.2). Exact locations are listed in Table 2.2.1.

The NBS Program established sampling locations in the Boston Harbor region dating as far back as 1984. Histological evaluation of resident fish for assessing the impact of chemical contaminants was performed by the Seattle NMFS lab from 1988-1992. Sampling had not been repeated until 2004. Historical sampling locations in the region (Figure 2.2.3) included portions of Boston Harbor (Presidents Roads -BOSPR, Deer Island Flats -BOSDI, Quincy Bay -BOSQB, and Hull Bay -BOSHB), Salem Harbor (SALFP), a single site in Massachusetts Bay (MASBS), and a reference site at the entrance to Duxbury Bay at Plymouth, Mass. (MASPE). Sediment chemistry, tissue (liver) contaminant concentrations, and histological evaluation of benthic dwelling fish for lesions associated with contaminant impact were evaluated. In 2004, NBS sites were sampled at the historic sampling sites at Deer Island in Boston Harbor and in the vicinity of the diffusers from the Boston sewage outfall for the first time (Figure 2.2.3). The control site for this region remained at Plymouth, Mass., however no fish were captured there in 2004.

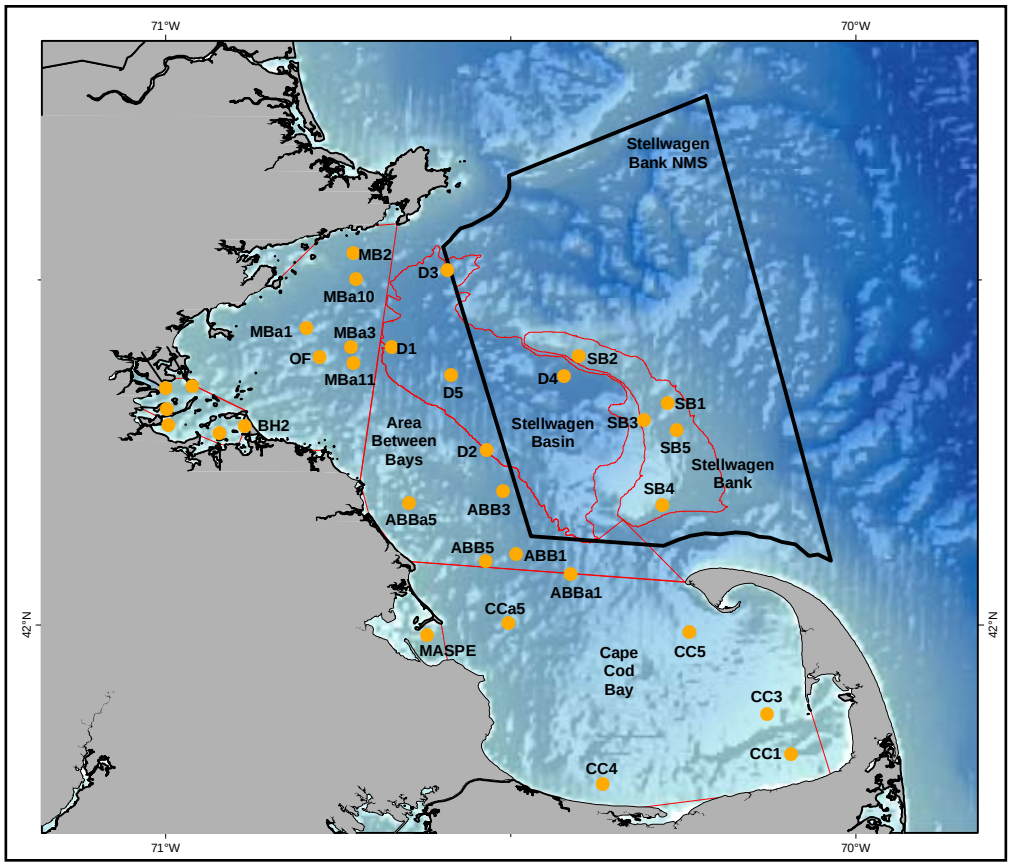

Figure 2.2.2. Location of NS&T Bioeffects sampling sites within the Massachusetts Bay sampling strata, 2004.

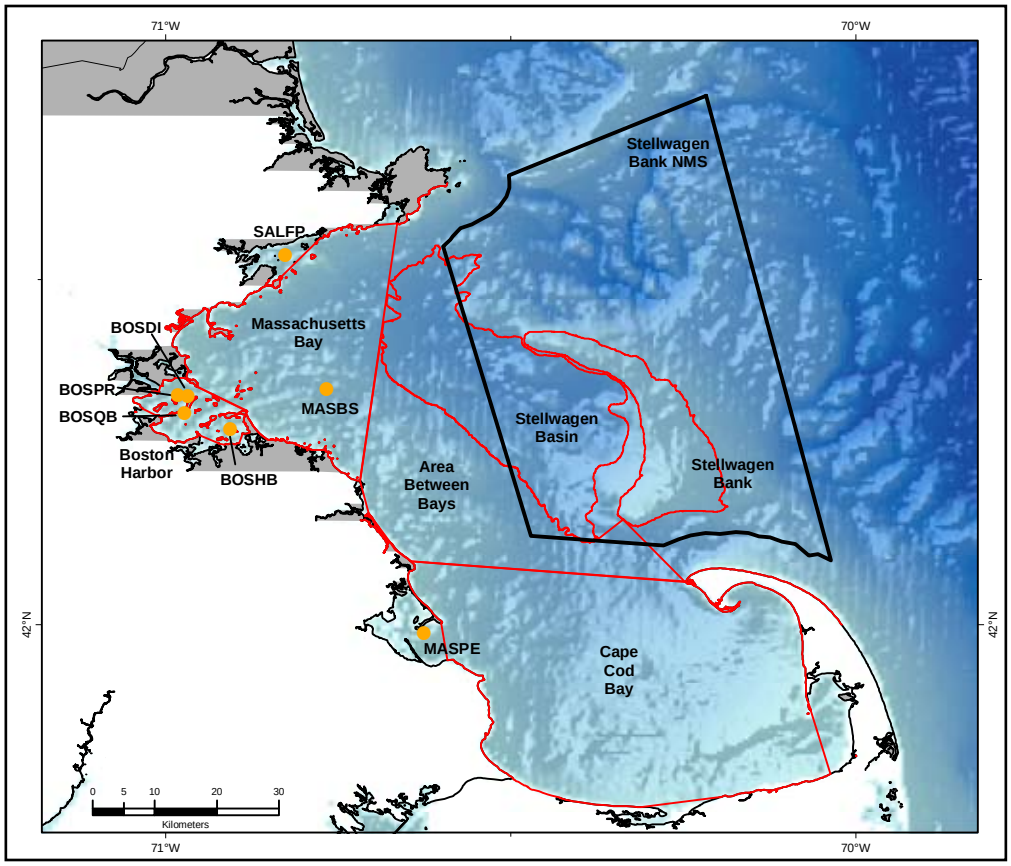

Figure 2.2.3. Location of National Benthic Surveillance sites within Massachusetts Bay.

In early June, 2004, samples were collected on board the NOAA ship Nancy Foster, or from her launch at shallow water stations. Two sediment samples were taken at each BE site in addition to water quality measurements with a CTD or YSI meter readings at the surface and bottom of the water column. A total of 33 sites were sampled. Samples were collected with a Kynar-coated 0.04 m^2 PONAR grab sampler. The sampler was initially washed, rinsed with acetone and deionized water, followed by an acid wash with 10% HCl and again rinsed with deionized water. At each site, the sampler was rinsed with acetone and deionized water immediately prior to sampling. Only the upper 2-3 cm of the sediment was retained in order to assure collection of recently deposited materials. A sediment sample was discarded if the jaws of the grab were open, the sample was partly washed out, or if the sediment sample in the grab was less than 5 cm deep. Sediments were removed with a scoop made of high-impact styrene. All subsamples were either stored on ice or frozen, as appropriate, prior to shipment to analytical labs.

A second sediment sample was taken for benthic community analysis. The entire contents of an acceptable sample (at least 5 cm deep) were sieved on site through 0.5 mm mesh. All organisms were retained in Nalgene bottles and preserved in buffered formalin containing Rose Bengal stain. Several stations along the length of the POTW diffuser were sampled but no benthic community sample was taken due to unsuitable gravel/cobble substrate.

Table 2.2.1. Location of Bioeffects sample sites and strata within Boston Harbor and Massachusetts Bay.

Site Name	Stratum	Latitude	Longitude
BH2	Boston Harbor	42.289	-70.885
BH3	Boston Harbor	42.314	-70.999
BH4	Boston Harbor	42.278	-70.922
BH5	Boston Harbor	42.345	-71.001
BHa2	Boston Harbor	42.291	-70.996
DI	Boston Harbor Deer Island	42.347	-70.962
MB2	Massachusetts Bay	42.540	-70.728
MBa1	Massachusetts Bay	42.432	-70.797
MBa3	Massachusetts Bay	42.403	-70.732
MBa10	Massachusetts Bay	42.503	-70.724
MBa11	Massachusetts Bay	42.380	-70.728
OF	Outfall	42.389	-70.777
D1	Stellwagen Basin	42.403	-70.673
D2	Stellwagen Basin	42.255	-70.535
D3	Stellwagen Basin	42.515	-70.592
D4	Stellwagen Basin	42.361	-70.423
D5	Stellwagen Basin	42.364	-70.586
ABB1	Area Between Bays	42.104	-70.493
ABB3	Area Between Bays	42.194	-70.511
ABB5	Area Between Bays	42.093	-70.536
ABBa1	Area Between Bays	42.075	-70.413
ABBa5	Area Between Bays	42.177	-70.648
CC1	Cape Cod Bay	41.813	-70.094
CC3	Cape Cod Bay	41.872	-70.128
CC4	Cape Cod Bay	41.770	-70.367
CC5	Cape Cod Bay	41.990	-70.242
CCa5	Cape Cod Bay	42.004	-70.504
SB1	Stellwagen Bank	42.323	-70.272
SB2	Stellwagen Bank	42.391	-70.401
SB3	Stellwagen Bank	42.298	-70.306
SB4	Stellwagen Bank	42.175	-70.280
SB5	Stellwagen Bank	42.282	-70.260
MASPE	Reference site	41.986	-70.621

At the NBS sites, in addition to sediment samples, fish were collected by otter trawl. A trawl was deployed for standard 10 min tows at ~2-3 knot (~1/2 mi total distance). Trawling was repeated until enough winter flounder (*Pleuronectes americanus*) were taken for tissue chemical and histological analyses. Fish were culled by species and size to accumulate enough fish of proper age range for sampling. Gross pathological lesions, injuries, and/or infections were recorded for each fish. Liver, kidney, gonad, and muscle tissue samples were retained for laboratory analyses. The liver was subdivided for histopathology and organic contaminant analyses. Tissues were pooled into 2-3 composite samples for chemical analyses. Male and female fish were segregated in the composites. Unused fish were released. In the laboratory, tissue sections of liver, kidney and gonad of all flounder necropsied from Deer Island Flats and the new outfall site were preserved in Dietrich's fixative, and processed routinely for paraffin embedment. Sections were cut at 5 microns thickness, stained with hematoxylin and eosin and examined by light microscopy by a single histopathologist.

Chemical Analyses

Chemical analyses followed procedures routinely used in the NOAA NS&T program. A broad suite of sediment contaminants were analyzed at each station, including 59 polynuclear aromatic hydrocarbons (PAHs), 15

chlorinated pesticides including DDT and its metabolites, 25 polychlorinated biphenyls (PCBs), 13 trace elements, and butyltins. Other parameters included grain size analysis, total organic/inorganic carbon (TOC/TIC), and percent solids. Table 2.2.2 summarizes the parameters measured and the analytical methods utilized. All methods followed methods from U.S. Environmental Protection Agency (1994), Lauenstein and Cantillo (1998), and American Society for Testing and Materials (1999a, b). Fish tissue samples were analyzed for the same suite of PAHs and chlorinated organic compounds as the sediment. All chemical analyses were performed at one laboratory.

Table 2.2.2. Summary of Bioeffects contaminant parameters and analytical methods.

Parameters	Units	Analytical methods
Ag, Al, As, Cu, Fe, Mn, Zn	ug/dry g	Inductively-Coupled Plasma Emission Spectrometry (ICP ES)
Cd. Cr, Pb, Ni	ug/dry g	Inductively-Coupled Plasma Mass Spectrometry (ICP MS)
Se	ug/dry g	Atomic Fluorescence Spectrometry (AAFS)
Hg	ug/dry g	Cold Vapor Atomic Absorption Spectrometry (CVAAS)
Butyltin	ng/dry g	High resolution, capillary Gas Chromatography with Flame Photometric Detection (GC/FPD)
Polycyclic Aromatic Hydrocarbons (PAHs)	ng/dry g	Gas Chromatography with Mass Spectrometry (GC/MS)
Polychlorinated Biphenyls (PCBs)	ng/dry g	Gas Chromatography with Electron Capture Detector (GC/ECD)
Pesticides: Dichloro-Diphenyl-trichloroethanes (DDT), Chlordanes (CDANE)	ng/dry g	Gas Chromatography with Electron Capture Detector (GC/ECD)
Total organic carbon (TOC)	Percent	Loss on Ignition (LOI)
Clay, Silt, and Sand	Percent	Sieve and pipette

Numerical sediment quality guidelines (Table 2.2.3) developed by Long and Morgan (1990) and Long *et al.,* (1995) known as ERM and ERL (effects range-median, effects range-low) express statistically derived levels of contamination, above which toxic effects would be expected to be observed with some level of frequency (ERM), and below which effects were rarely expected (ERL). The mean ERM quotient (Long *et al.,* 1998) is the average of the ratio of ERM values to sediment concentrations for each chemical. The mean quotient of the ERMs and observed contaminant concentrations were calculated on a site by site basis. The calculation included all the individual metals, low molecular weight PAHs, high molecular weight PAHs, total PCBs, and total DDT.

Benthic Community Analyses

Macroinvertebrates in the benthos samples were identified to the lowest practical identification level (LPIL), which in most cases was to species unless the specimen was a juvenile, damaged, or otherwise unidentifiable. The number of individuals of each taxon, excluding fragments, was recorded. Quantitative benthic community characterizations included enumeration of density, species richness, evenness, and diversity, followed by pattern and classification analysis for delineation of taxa assemblages. Density was calculated as the total number of individuals per square meter. Taxa richness is reported as the total number of taxa represented at a given site. Diversity was calculated with the Shannon-Weiner Index (Shannon and Weaver, 1949). Species evenness for a given station was calculated as Pielou's Index J' (Pielou, 1966).

Multivariate cluster analysis was employed to group site and species data. The objective was to produce a coherent pattern of association between sites and species. Cluster analysis is a two-step process including; 1) creation of a resemblance data matrix from the raw data, and 2) clustering the resemblance coefficients in the matrix. The input resemblance (similarity or dissimilarity) matrix can be created by a number of methods. Input data may or may not be standardized or transformed depending on the requirements of the method (e.g. Bray Curtis). Based on previous research (Hartwell and Claflin, 2005) the Jaccard method (Goodall, 1973) was used to generate the similarity matrix.

The Jaccard method is a binary method based only on presence/absence data, and thus ignores abundance values. Cluster analyses were calculated from the matrices using the Unweighted Pair-Group Method Using

Arithmetic Averages (UPGMA) procedure which clusters coefficients based on arithmetic mean distance calculations (Sneath and Sokal, 1973). To optimize the cluster analysis results, several manipulations of the input data were performed to remove confounding effects and bias:

1) Epiphytic species such as sea anemones and tunicates were eliminated from the data set as they are not truly infauna.

2) Artificial species (resulting from failure to identify some specimens all the way down to species) were identified as a data bias. For example where specimens of 2-3 species were identified in genus A, and there were other specimens that were identified only to genus A, or the family to which genus A belongs. This tends to artificially increase species richness and diversity of the sample when in fact that diversity is an artifact of imperfect taxonomic identification. To address this problem, specimens not identified to species level were eliminated, unless they were identified to a taxonomic level below which no other specimens in the collection belonged. That is, even though they were not identified to species, they were the only representative of that taxonomic line and did represent a non-redundant taxon. From an initial total of 305 taxa, 24 taxa were eliminated in this step. This only eliminated 420 animals out of 16,818 collected. To minimize loss of important community information there were instances where specimens identified to one level were combined into one taxon with specimens only identified to the next higher level. This reduced the number of taxa by 43. In 49 other cases, there were multiple species to choose from so they were not combined. The individual species were kept and the genus was also kept as a separate taxon. This retained 3,220 individuals.

Table 2.2.3. Chemical and chemical groups for which ERLs and ERMs have been derived (organics ppb, metals ppm, dry weight).

Chemicals/Chemical Groups	ERL	ERM
Total DDT	1.58	46.1
pp'-DDE	2.2	27
Total PCBs	22.7	180
Total PAHs	4022	44792
High weight PAHs (≥ 4 rings)	1700	9600
Low weight PAHs (≤ 3 rings)	552	3160
Acenaphthene	16	500
Acenaphthylene	44	640
Anthracene	85.3	1100
Flourene	19	540
2-Methyl Naphthalene	70	670
Naphthalene	160	2100
Phenanthrene	240	1500
Benzo-a-anthracene	261	1600
Benzo-a-pyrene	430	1600
Chrysene	384	2800
Dibenzo (a,h) anthracene	63.4	260
Fluoranthene	600	5100
Pyrene	665	2600
As	8.2	70
Cd	1.2	9.6
Cr	81	370
Cu	34	270
Pb	46.7	218
Hg	0.15	0.71
Ni	20.9	51.6
Ag	1	3.7
Zn	150	410

3) Rare and unique taxa were defined as those species that were found at no more than two stations. Although they do contribute to the overall assessment of biodiversity, they were eliminated from the cluster analysis data set. Because of their limited distribution, by definition, they do not provide information on the impact of contaminant gradients in the environment because they do not occur across a gradient.

After the data set had been finalized, a nodal analysis routine was applied to the data (Lambert and Williams, 1962). This consisted of combining independent cluster analyses in a graphical array. The first analysis clustered sites using species occurrence data. The second calculation clustered species together into groups. The intersection of site clusters on the abscissa and species clusters on the ordinate axis yields a pattern of species associations with site clusters, termed nodes. A schematic example of the resulting plot is illustrated in Figure

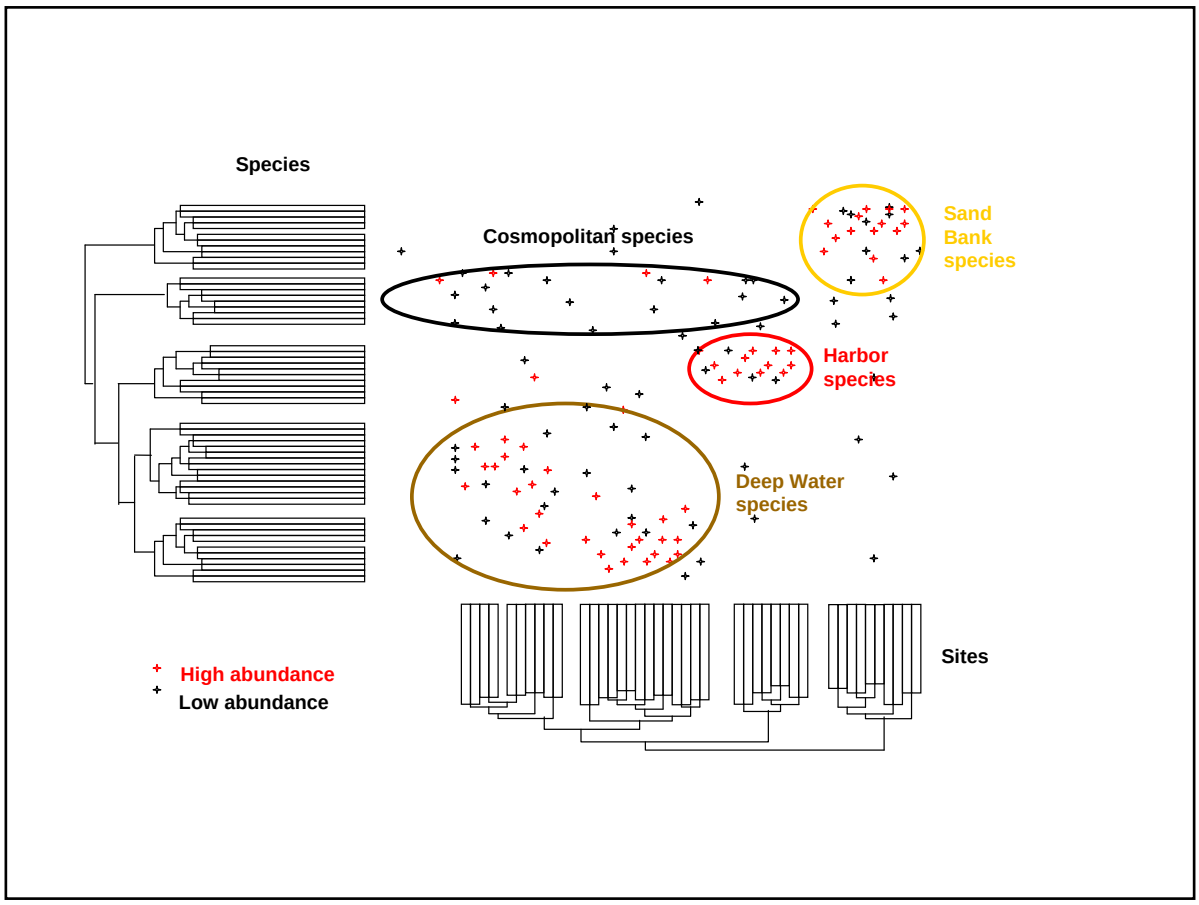

Figure 2.2.4. Schematic of nodal analysis illustrating the intersection of species abundance and site cluster analysis.

2.2.4. In this example, nodes are identified by the physical characteristics that are common to sites within the nodes, and that appear to influence the distribution of community assemblages present in each node.

Statistical Contrasts

Data from the current BE and NBS studies were combined with previous NBS study data, data from the NS&T Mussel Watch Program (MW), and monitoring data provided by the Massachusetts Water Resources Authority (MWRA). Analyses were conducted to assess the temporal and spatial trends in contaminant concentrations (if any) in the region that may have implications for the Stellwagen Bank NMS. The MW data include tissue body burden data for blue mussels (*Mytilus edulis*) collected at stations from Cape Anne to Plymouth, including a site on Brewster Island off the mouth of Boston Harbor (Figure 2.2.5). Mussel Watch data goes back to the mid-1980s. Samples are taken from the intertidal zone so there are not any sample locations off shore. Six sites (BHDB, BHDI, BHBI, BHHB, CAGH, and DBCI) were included in the analyses. In contrast, the MWRA offers sites with more extensive geographic coverage. The MWRA classifies stations as near field and far field for the purpose of assessing potential impacts from the POTW sewage outfall in Massachusetts Bay. For the purpose of this study, MWRA sites were regrouped into zones (MWRA1 to MWRA6) comparable to BE strata defined earlier (Figure 2.2.2). Using plots of monitoring sites, the following pairs of strata were defined from both data sets: 1) Boston Harbor (Bioeffects BH and MWRA1), Massachusetts Bay (MB and MWRA2 and 3), Stellwagen Basin (DD and MWRA5), Cape Cod (CC and MWAR6), and Stellwagen Bank as a separate stratum (Figure 2.2.6). Sediment and fish tissue chemistry data provided by the MWRA were included in both temporal and spatial contrasts to the NOAA data.

All chemical contaminant data were $\log_{10}$ transformed to normalize the data. Spatial distributions of transformed contaminant concentrations among sites and strata were evaluated using one-way ANOVA coupled with Duncan multiple-range test. Simple regression analysis was used to test for trends of increasing or decreasing contaminant concentrations at each site over time. Box-plots were used to visualize data variation and median com-

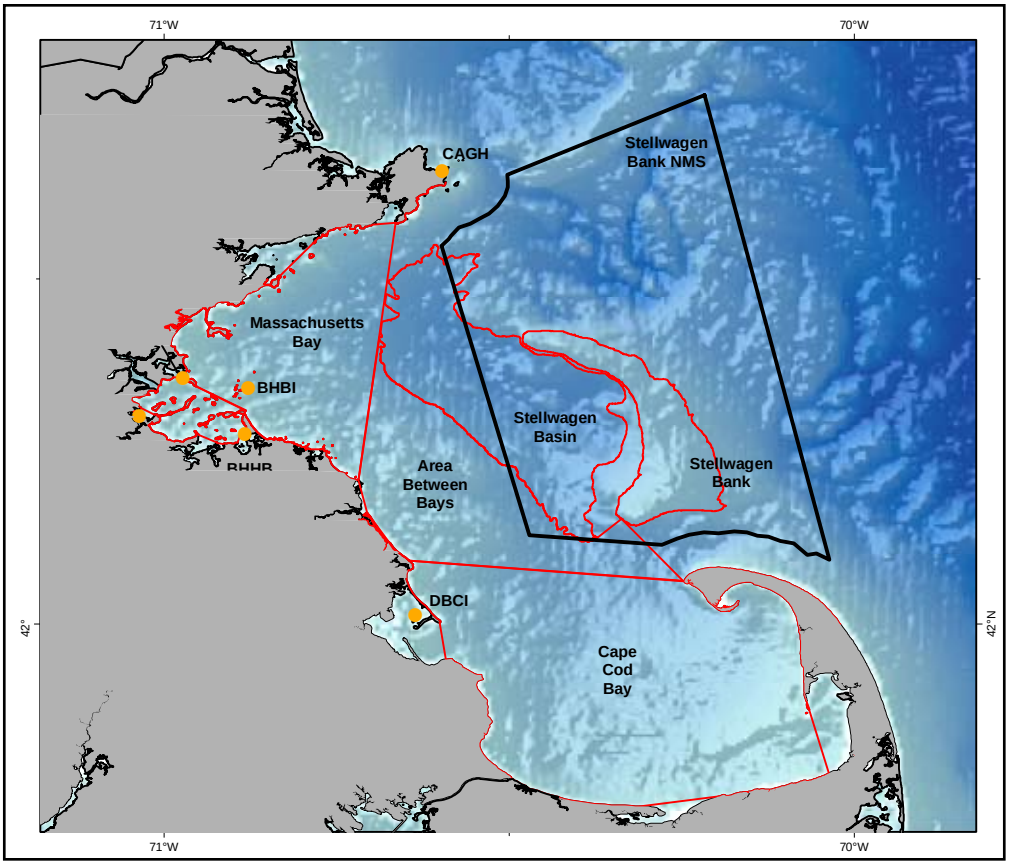

Figure 2.2.5. Location of NS7T Mussel Watch sites within Massachusetts Bay.

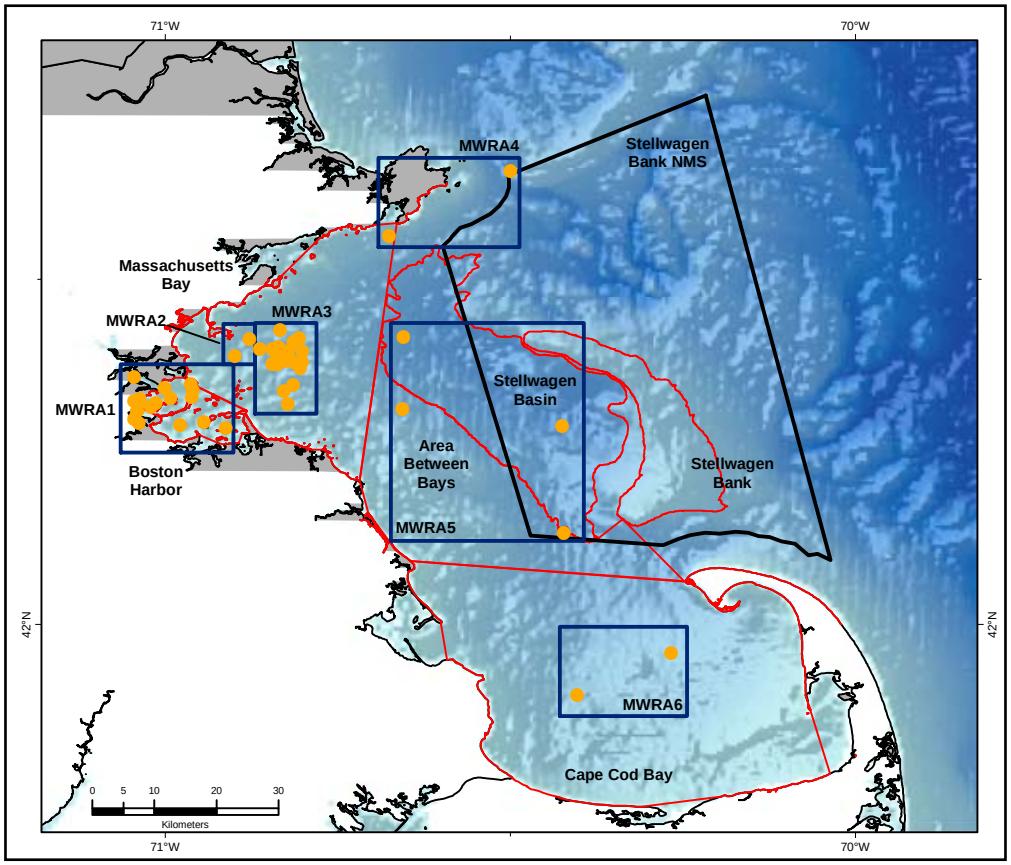

Figure 2.2.6. Location of MWRA sampling sites and statistical grouping areas within Massachusetts Bay.

parison among sites and strata. The Box-plots show the range of distribution of the data for each stratum, the median, the 25th and 75th percentile (bottom and top of the box) and the whiskers above and below the box represent extreme low and high values. The over-riding objective was to assess whether or not pollution conditions are improving in the region, and specifically, whether or not moving the Boston POTW effluent to an offshore location may pose a threat of increasing contaminant loading to the Stellwagen Bank NMS.

2.3 RESULTS AND DISCUSSION

Sediment Texture

Grain size characterization (Figure 2.3.1 a and b) shows that the surficial sediment in Stellwagen Basin, Boston Harbor and Massachusetts Bay are composed of heterogeneous materials with about 40% sand, 30% silt, and 20% clay. Total organic carbon averaged 2.4% and varied widely from 8.5% in Boston Harbor to less than 0.1% on Stellwagen Bank. Sediments at Stellwagen Bank and Cape Cod Bay were mainly sand, and the total organic content was much lower compared to that of the Boston Harbor and the deeper areas.

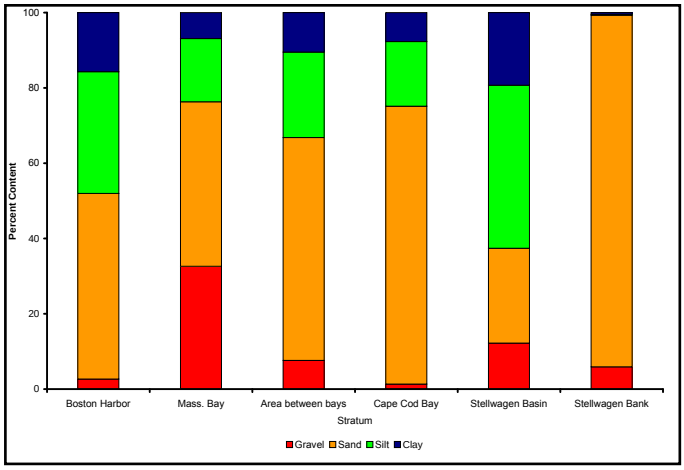

Figure 2.3.1a. Mean percent sand, silt, and clay content in sediments within sampling strata, 2004.

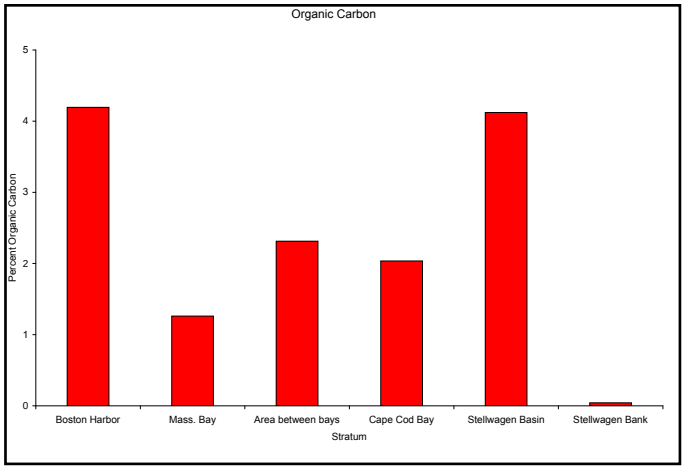

Figure 2.3.1b. Mean percent organic carbon in sediments within sampling strata, 2004.

Bottom sediment texture characterization is important since fine grained sediments are typically found in depositional areas, contain more organic carbon, and accumulate higher concentrations of contaminants (Long *et al.,* 1996). Therefore, Cape Cod and Stellwagen Bank strata are expected to have lower contaminant concentration levels compared to muddier (high silt and clay content) strata. Spearman Rank correlation analysis on $\log_{10}$ normalized data shows that in general, contaminant concentrations were positively correlated with total organic carbon and fine grain sediment (silt and clay) and negatively correlated with sand content of the sediment. Example relationships are shown for a selection of chemicals in Figure 2.3.2.

Spatial Contaminant Assessment

The spatial distribution of contaminants was assessed using the 2004 sediment chemistry data. Metal and organic contaminant concentrations were found to be significantly higher in the sediments collected in and around Boston Harbor than in all other strata. Intermediate concentrations were found in the middle and deeper areas of Massachusetts and Cape Cod Bays. The lowest contaminant concentrations were consistently found in the Stellwagen Bank sites. Detailed statistical analysis of the spatial distribution of contaminants in sediment is summarized in Table 2.3.1, while typical data are illustrated in Figure 2.3.3.

Contaminant data from the 2004 sampling effort are consistent with historical data. The NS&T NBS long-term sediment monitoring data (1984-1991) showed similar spatial distribution patterns. For most metal and organic contaminants, one-way ANOVA on the older NBS sediment data demonstrated that sites in Boston Harbor had the highest contaminant concentrations compared to the Salem Harbor and Plymouth, sites which are located north and south, respectively of Boston (Table 2.3.2).

To evaluate differences between the old (1984-1991) and current (2004) NBS data, Box-plots were used (Figure 2.3.4). These revealed that, in general, contaminant concentrations in the previous sediment collections were somewhat higher than those in the 2004 sediments. However, for the same stratum (Boston Harbor and BH), the range of data variability between the old and 2004 sediment data overlaps. Although the data show some

slight declines, there are no significant differences in concentration between the old and current sediment data as a whole in Boston Harbor.

Data from the MWRA monitoring program for the new POTW discharge in the near and far field stations were also used to evaluate spatial distribution of contaminants. The BE and MWRA (2000-2004) sediment data were matched by stratum (Figure 2.2.6). The box-plot evaluation (Figure 2.3.5) indicated that in general, there was little difference in contaminant concentrations within the paired data sets. However, for some contaminants (e.g. Pb, Zn, DDTs, PAHs), the Cape Cod Bay data show a lower range of concentrations than the MWRA6 data. This assessment revealed once again that Boston Harbor consistently demonstrates the highest contaminant concentrations followed by Mid-Bay and Cape Cod strata. Stellwagen Bank, although not paired with another stratum, is consistently shown to have the lowest contaminant concentrations. Overall, this assessment suggests that there is good agreement between the Bioeffects and MWRA data sets.

Consistent with the sediment data, tissue contaminant concentrations in blue mussels from the NS&T Mussel Watch Program also show higher concentrations from sites in the vicinity of Boston Harbor (Table 2.3.3). This has limited direct application to Stellwagen Bank NMS as the Mussel Watch stations are

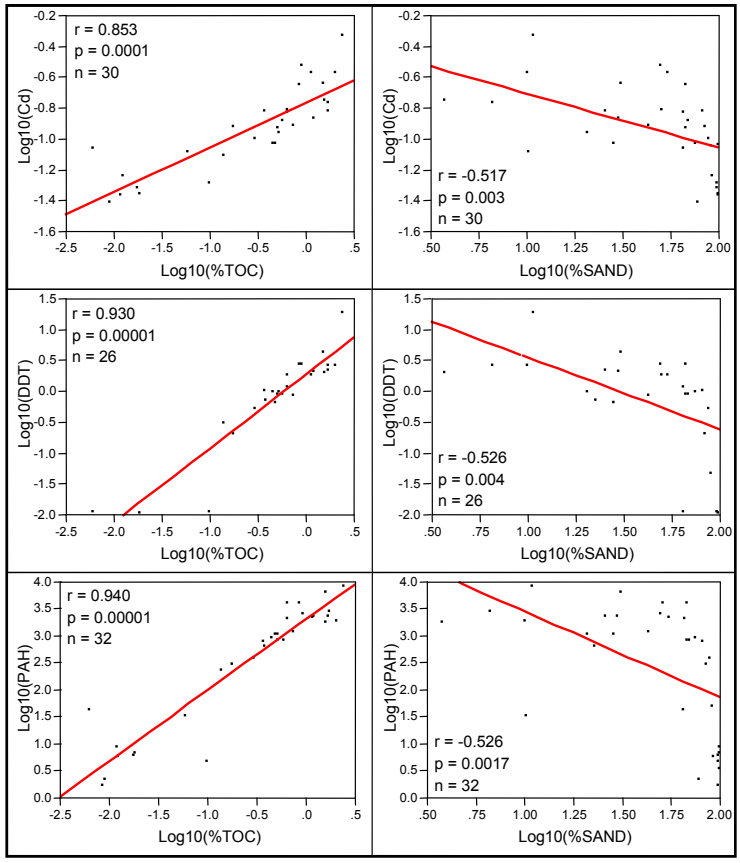

Figure 2.3.2. Correlation of $\log_{10}$ normalized cadmium, total DDT, and PAHs with percent sand and percent organic carbon in sediment within Boston Harbor and Massachusetts Bay. Source: Bioeffects 2004. (r=Spearman correlation; p=probabiliby; n=number of samples).

Table 2.3.1. Metal and organic contaminant concentrations among strata, 2004 Bioeffects. A, B, C, D, and E are Duncan groupings with ANOVA. Sites with different letters are significantly different (A>B>C>D>E). * p=0.01-0.05; **p<=0.01; CDANE = chlordanes and other cyclodienes. See Table 2.1 for Site abbreviations.

Metal Contaminants											
Site	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Se	Sb	Zn
BH (N=6)	A**	AB**	A**	A**	A**	A	A**	A**	A	A**	A**
MB (N=7)	BC**	AB**	B**	A**	BC**	A	AB**	BC**	A	A**	AB**
ABB (N=5)	BC**	AB**	B**	A**	BC**	A	AB**	BC**	A	AB**	AB**
D (N=5)	C**	A**	B**	A**	B**	A	A**	AB**	A	A**	A**
CC (N=5)	B**	BC**	B**	A**	C**	A	B**	CD**	A	BC**	BC**
SB (N=5)	D**	C**	C**	B**	D**	A	C**	D**	A	C**	C**

Organic contaminants								
Site	MIREX	CDANE	DDT	PCB	HCH	BT	PAH	LMW	HMW
BH (N=6)	A	B**	A*	A**	A*	A**	A**	A**	A**
MB (N=7)	A	B**	A*	B**	AB*	B**	BC**	AB**	BC**
ABB (N=5)	A	B**	A*	B**	AB*	B**	BC**	AB**	BC**
D (N=5)	A	AB**	A*	B**	AB*	B**	AB**	A**	AB**
CC (N=5)	A	B**	A*	B**	AB*	B**	C**	B**	C**
SB (N=5)	A	C**	B*	C**	B*	B**	D**	C**	D**

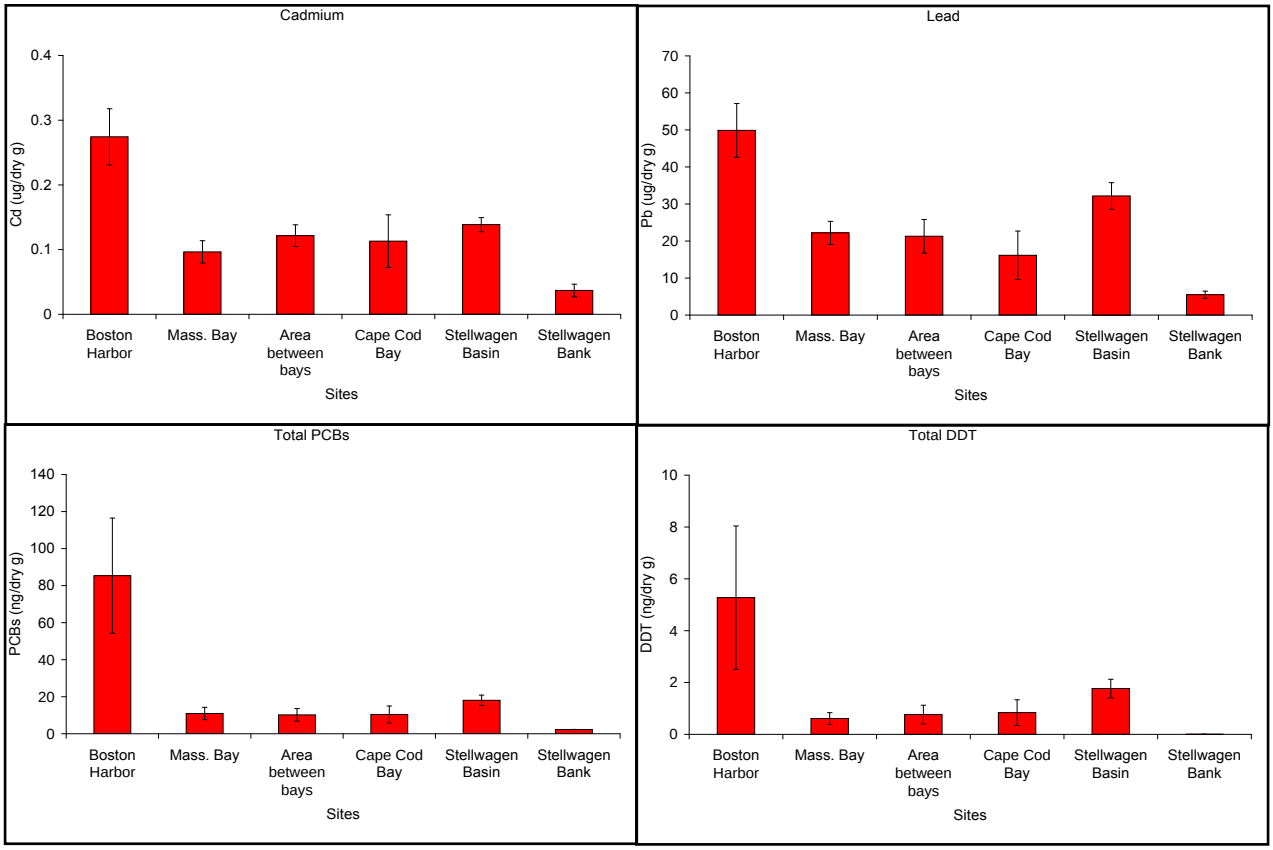

Figure 2.3.3. Concentration of select metals (Cd and Pb) and organics (total PCBs and DDT) in sediments within Massachusetts Bay. Source: NS&T Bioeffects, 2004.

Table 2.3.2. Metal and organic contaminant concentrations among strata, Benthic Surveillance (1984-1991). A, B, C, D, and E are Duncan groupings with ANOVA. Sites with different letters are significantly different (A>B>C>D>E). ND= No Data. * p=0.01-0.05; **p<=0.01; CDANE = chlordanes and other cyclodienes.

	Metal contaminants										
Site	**Ag**	**As**	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Se**	**Sb**	**Zn**
BOSPR (N= 10)	A**	A**	B**	B**	A**	AB**	A**	A**	AB**	A**	A**
BOSDI (N= 9)	B**	A**	BC**	C**	AB**	B**	A**	A**	B**	B**	A**
BOSQB (N= 6)	A**	A**	BC**	B**	A**	A**	A**	A**	AB**	A**	A**
BOSHB (N= 3)	AB**	A**	C**	BC**	AB**	B**	A**	A**	AB**	ND	A**
SALFP (N= 15)	C**	A**	A**	A**	B**	AB**	A**	A**	A**	B**	A**
MASPE (N= 3)	D**	B**	D**	D**	C**	C**	B**	B**	C**	ND	B**

	Organic contaminants						
Site	**MIREX**	**CDANE**	**DDT**	**PCB**	**PAH**	**LMW**	**HMW**
BOSPR (N= 10)	A	A	A*	A**	A**	A**	A**
BOSDI (N= 9)	A	A	B*	A**	AB**	AB**	A**
BOSQB (N= 6)	A	A	A*	A**	A**	AB**	A**
BOSHB (N= 3)	ND	A	B*	A**	B**	B**	B**
SALFP (N= 15)	A	A	A*	A**	AB**	AB**	AB**
MASPE (N= 3)	ND	ND	ND	B**	C**	C**	C**

all located along the shoreline, but the data do illustrate regional trends. In general, stations within Boston Harbor exhibited higher contaminant concentrations than outside the Harbor. There are exceptions to this general conclusion however. Concentrations of some of the trace elements are as high at Cape Ann as elsewhere. Arsenic is consistently higher at Cape Ann than at other stations. Whether this is due to oceanographic circulation phenomena, uptake from algae, or pollution from sources further up the coast is unknown. Concentrations of As are higher at Cape Ann than the geometric mean of reported values, but are below apparent toxic concentrations (Neff, 1997). Most anthropogenic contaminants were consistently lower at Cape Ann than at Boston Harbor stations however.

The Brewster Island (BHBI) station at the mouth of Boston Harbor shows elevated concentrations relative to more remote stations (Table 2.3.3). This indicates evidence of a gradient of contaminant concentration from inshore to offshore. This suggests an export of contaminants from Boston Harbor eastward toward Stellwagen Bank and southward toward Cape Cod Bay via suspended sediments and/or the water column. Thus, contamination derived from the harbor area diffuses out to Massachusetts Bay, regardless of where the POTW outfall is located. The rate at which contaminants are

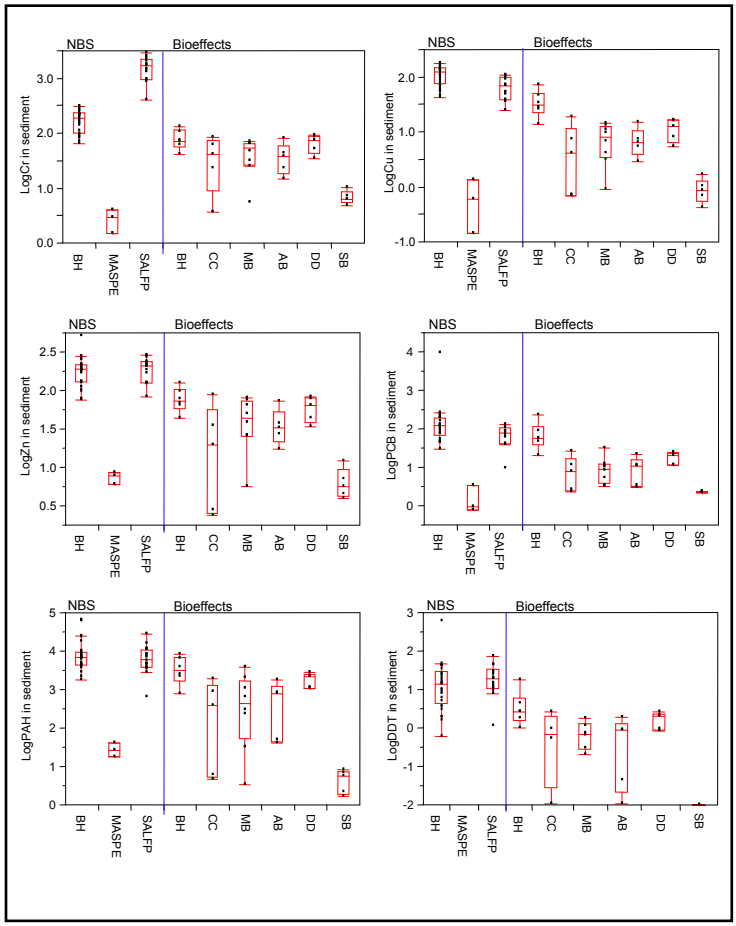

Figure 2.3.4. Sediment contaminants within strata. Source: National Benthic Surveillance (1984-1991) and Bioeffects (2004).

Table 2.3.3. Metal and organic contaminant concentrations among strata, Mussel Watch. A, B, C, D, and E are Duncan groupings with ANOVA. Sites with different letters are significantly different (A>B>C>D>E). * p=0.01-0.05; **p<=0.01; CDANE = chlordanes and other cyclodienes.

Metal contaminants											
Site	**Ag**	**As**	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Se**	**Sb**	**Zn**
BHDB (n=9)	AB**	BC**	A**	A**	A**	CD**	AB**	A**	A	A	AB**
BHDI (n=10)	ABC**	C**	C**	AB**	B**	BC**	BC**	CD**	A	A	B**
BHBI (n=11)	BC**	B**	AB**	A**	B**	A**	AB**	BC**	A	A	A**
BHHB (n=10)	A**	BC**	BC**	AB**	AB**	AB**	AB**	AB**	A	A	AB**
CAGH (n=10)	C**	A**	ABC**	AB**	C**	CD**	A**	E**	A	A	B**
DBCI (n=10)	AB**	BC**	D**	B**	C**	D**	C**	DE**	A	A	C**

Organic contaminants									
Site	**MIREX**	**CDANE**	**DDT**	**PCB**	**HCH**	**BT**	**PAH**	**LMW**	**HMW**
BHDB (n=9)	AB**	A**	A**	A**	A	A**	A**	A**	A**
BHDI (n=10)	B**	AB**	AB**	B**	A	AB**	A**	A**	A**
BHBI (n=11)	A**	B**	BC**	B**	A	B**	B**	AB**	B**
BHHB (n=10)	AB**	AB**	AB**	B**	A	B**	C**	B**	C**
CAGH (n=10)	B**	D**	D**	D**	A	C**	D**	C**	D**
DBCI (n=10)	C**	C**	C**	C**	A	C**	D**	C**	D**

transported to the open Bay may be impacted by the location of outfalls, but not the ultimate fate. Improvements in effluent treatment appear to have been effective at minimizing the impact, at least in the short term. The Box-plots of the MW data (1988-2003) illustrate that variability and concentrations at the remote sites at Cape Ann (CAGH) and Duxbury Bay (DBCI) were consistently lower than Boston Harbor stations, and the Brewster Island station (BHBI) at the mouth of Boston Harbor shows elevated concentrations relative to more remote stations (Figure 2.3.6).

The Benthic Surveillance data show similar patterns of spatial distributions based on contaminant concentrations in winter flounder liver. That is, fish collected in the vicinity of Boston Harbor specifically around Deer Island Flats (DI) had consistently higher contaminant concentrations than those from Massachusetts Bay near the new sewer outfall (Figure 2.3.7). The percent lipid content was also higher in the livers of fish from Deer Island (mean = 64.4% dry wt, SD = 5.5) than offshore (mean = 38% dry wt., SD = 2.5). Whether this is a reflection of fish age and/or diet, or some other factor is not known. Males at the Deer Island site tended to accumulate higher concentrations of chlorinated contaminants than females, but the lipid content of the sexes overlapped.

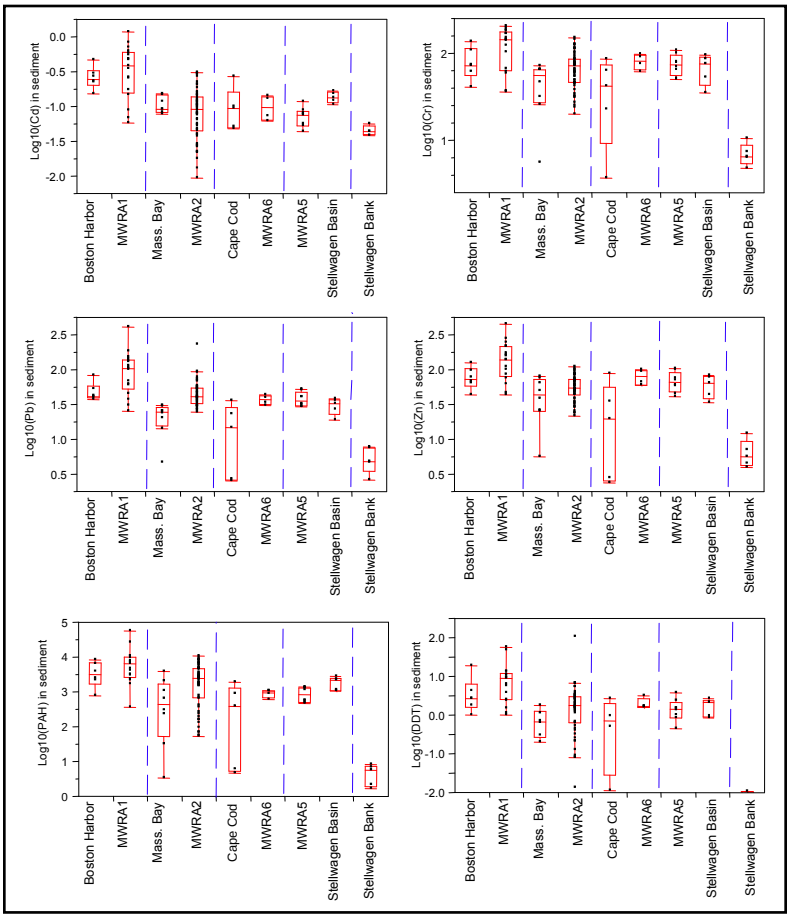

Figure 2.3.5. Variability among contaminant concentration of paired strata. Source: MWRA (2000-2004) and NS&T Bioeffects (2004).

Overall, tissue contaminant concentrations were higher in organisms collected in and around Boston Harbor than those from remote sites, with intermediate concentrations in the mid-Bay area between the harbor and Stellwagen Bank. These observations also suggest that export from Boston Harbor is a source of contamination for Massachusetts Bay and possibly for Stellwagen Bank.

Temporal Contaminant Assessment

The primary objective of the 2004 study was to characterize the current magnitude and extent of contamination in the Boston Harbor/Massachusetts & Cape Cod Bay system. Sampling was also designed for the data to be comparable to past NBS sampling efforts (1984-1991) in the region and limited temporal contrasts are possible. Data for sediment contaminant concentrations from the older NBS data base within and around Boston Harbor are too variable from year to year for statistically significant regression trends to be evident. Within the range of variability, the data indicated either static or slowly declining levels, depending on the specific chemical. When data from 2004 are combined with the historic data, regression analyses do show significant declines in metals and organic contaminants (except mirex) (Figure 2.3.8). These overall decreasing trends of anthropogenic contaminants in sediment are evidence that environmental conditions in Boston Harbor are improving. Bothner *et al.*, (2005) have also found decreasing trends in metals concentrations in Boston Harbor, which the authors attributed to decreasing discharges from the MWRA treatment plants.

Temporal trends in tissue body burden from Mussel Watch data are highly variable over time, and patterns are site specific. There were no statistically significant declines for any contaminant. For most trace elements the variability is so high, trends are not evident. Lead residue, which is considered a success story for pollution control due to it's removal from gasoline, while lower than observed in the 1980s, still shows high variability over time (Figure 2.3.9). Other trace elements such as Hg and Cd do not appear to have declined over time,

while Se appears to be increasing significantly. Of the organic contaminants with sufficient temporal data, PCBs and DDT do appear to have declined following drastic historical reduction in production and use, but tissue residues in Boston Harbor are still elevated relative to Cape Ann and Duxbury Bay (Figure 2.3.10). Total PAH residues are not greatly improved from historical concentrations. Low weight PAHs (indicative of fuel spills) have declined more than high weight PAHs (indicative of pyrogenic sources), but neither were statistically significant declines. Similar temporal trends were observed using the MWRA tissue liver chemistry data. Although this has limited direct application to Stellwagen Bank NMS as the stations are all located along the coastline, the data do illustrate temporal variation with regional trends implications (Long *et al.,*1996).

For comparative purposes, representative sites (DI = Deer Island flats, OF = Outfall Sites and ECCB = Eastern Cape Cod Bay) from the MWRA data were used for trend assessment using the fish liver chemistry data (1996-2003). Results show temporal trends that are generally similar to those indicated by the MW data set (Figure 2.3.11).

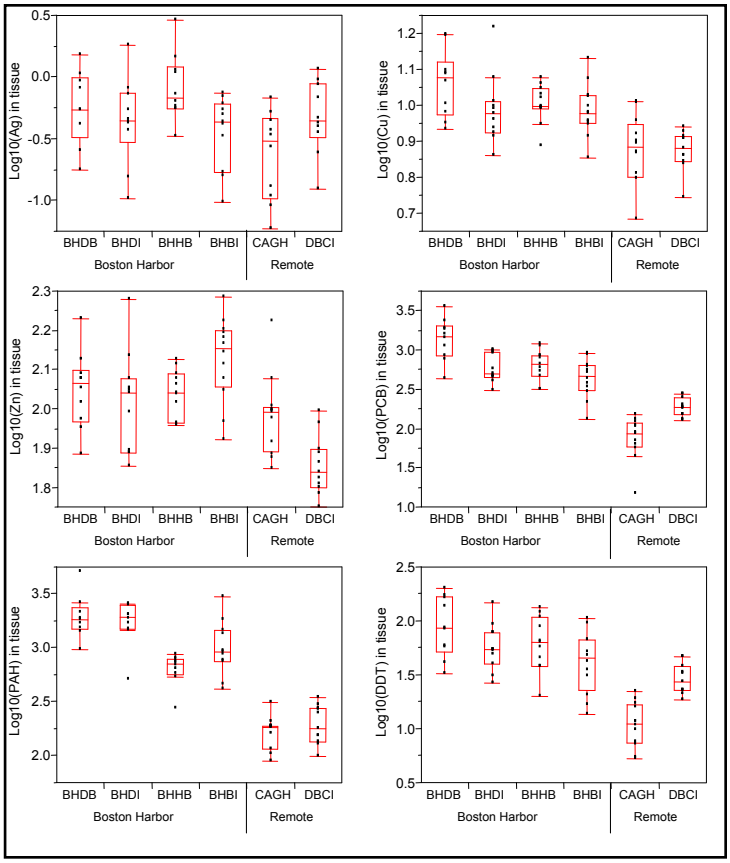

Figure 2.3.6. Tissue contaminant concentration in blue mussels (*Mytilus edulis*) at Mussel Watch sample sites (1988-2003).

Overall, persistent, chlorinated compounds that have been banned for decades show slowly declining concentrations. This attests to their persistence in the environment and that there are still large reservoirs in the watershed and sediment deposits within the region

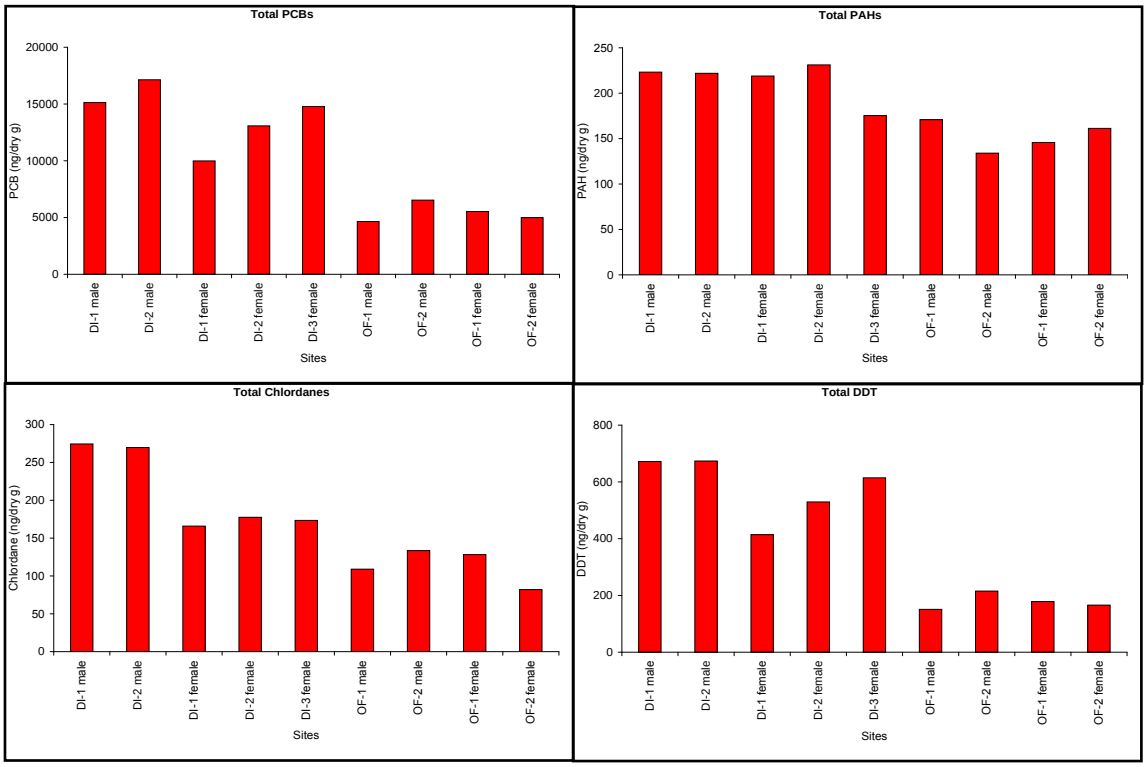

Figure 2.3.7. Concentration of organic contaminants found in winter flounder (*Pleuronectes americanus*) liver samples from Deer Island (DI) in Boston Harbor and the new sewage outfall (OF) in Massachusetts Bay.

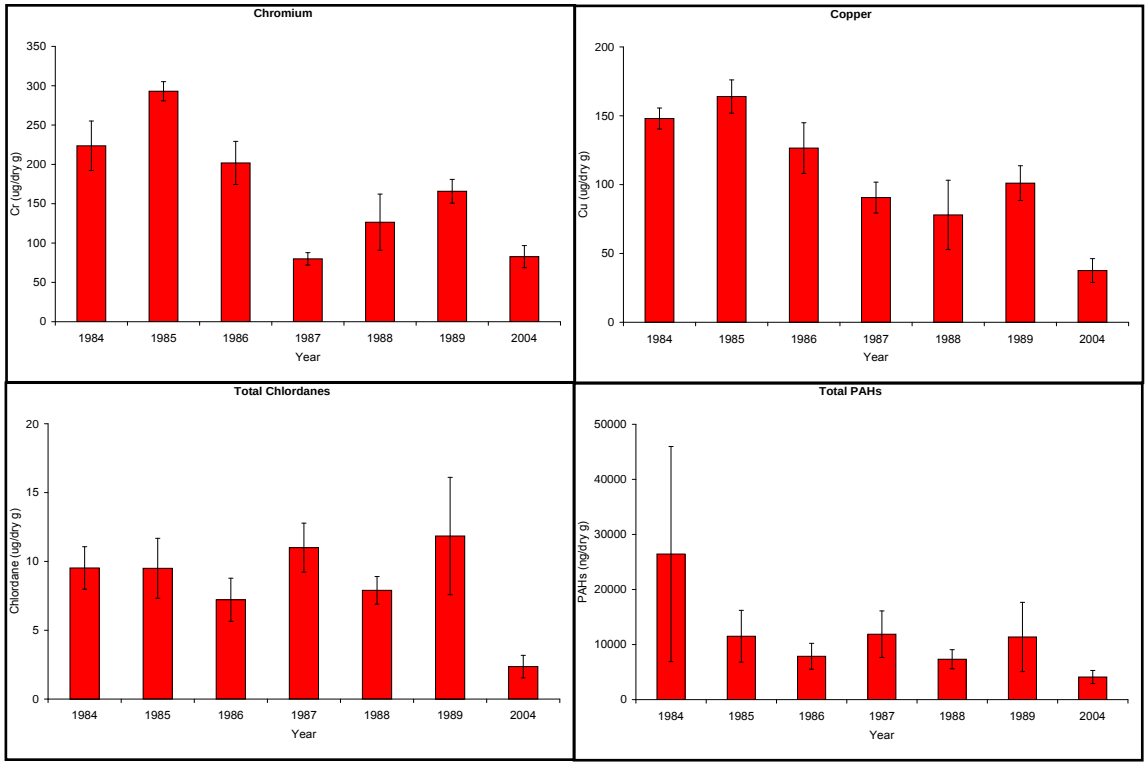

Figure 2.3.8. Temporal variation of select contaminant (Cr, Cu, Chlordanes, and PAHs) concentrations in Boston Harbor sediments. Source: Benthic Surveillance (1981-1991) and Bioeffects (2004).

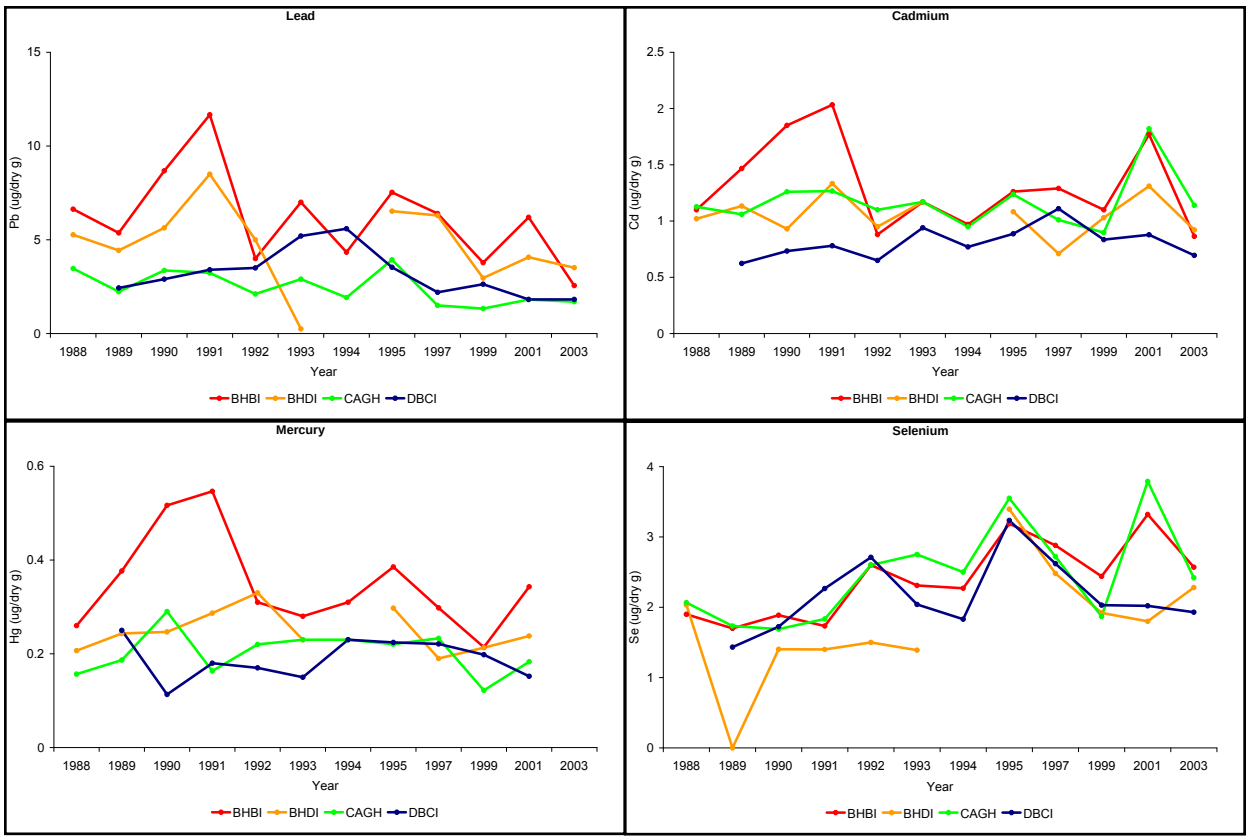

Figure 2.3.9. Temporal variation of selected metal concentrations (Cd, Hg, Pb and Se) found in blue mussel (*Mytilus edulis*) tissue collected in Massachusetts Bay. Source: Mussels Watch Project.

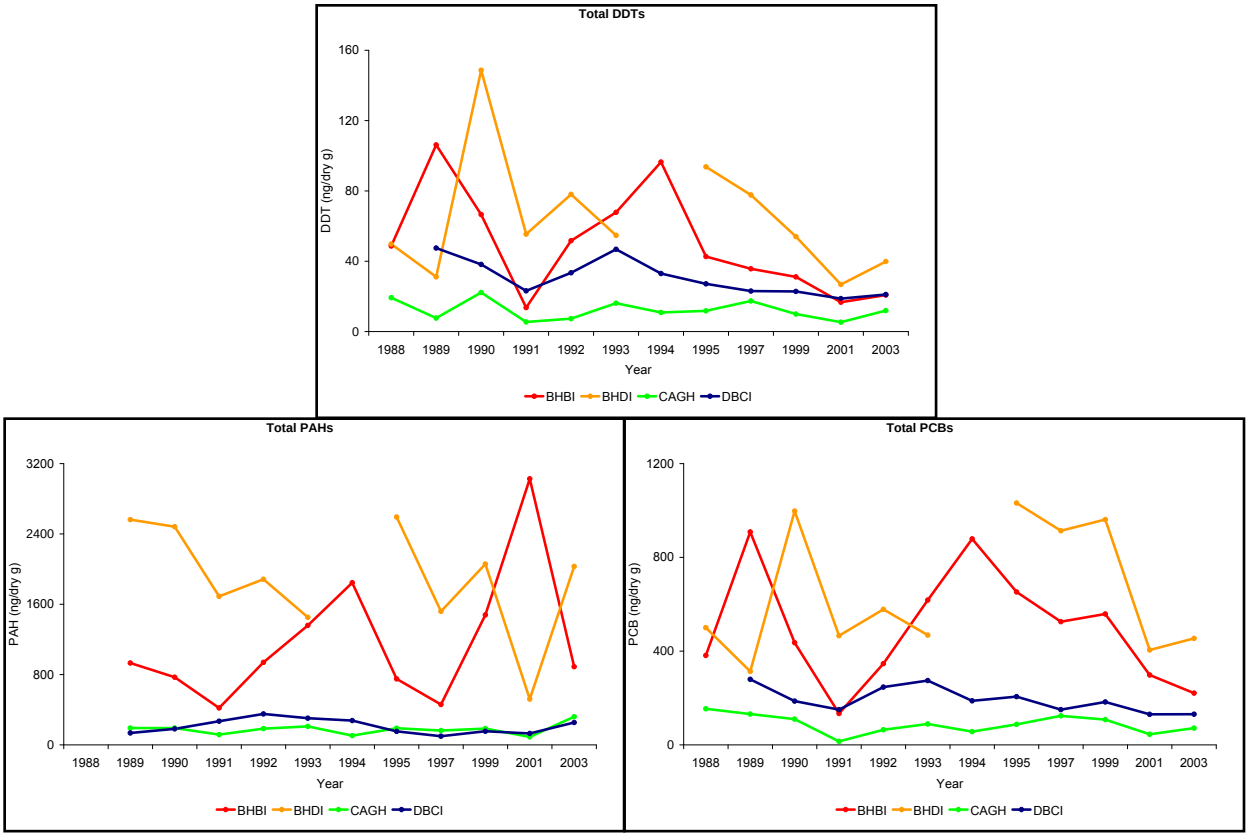

Figure 2.3.10. Temporal variation of select organic concentration (DDT, PAHs, and PCBs) found in blue mussel (*Mytilus edulis*) tissue collected in Massachusetts Bay. Source: Mussel Watch Project.

that continue to release contaminants to the wider environment. Other contaminants do not show declining concentrations, and this is probably the reflection of a balance between pollution control measures and releases due to increasing population pressure.

Benthic Community Assessment

The nodal analysis subdivides the habitats into three major zones. These appear to be driven by the species' preference for sediment grain size, with salinity and depth as secondary factors. The three nodes were sand banks (including all Stellwagen Bank stations), harbor, and deeper open water sites including both the deep areas of Stellwagen Basin and surrounding areas in Massachusetts and Cape Cod Bays (Figure 2.3.12). The sand bank node sites were characterized by coarse grained sediment with very low organic matter content. They were located on Stellwagen Bank and around the perimeter of the study area in relatively shallow, high energy environments, including the Benthic Surveillance control site at Plymouth. The harbor zone is exclusively made up of the Boston Harbor stations, including the Deer Island Flats site. No stations outside of Boston Harbor clustered in this group. The last zone is comprised of the remaining stations in Massachusetts and Cape Cod Bays and the deep stations in Stellwagen Basin. While these include stations outside of the deep basin, they were generally deeper than the sand bank stations, and had finer grained sediment with higher organic carbon content than the sandy areas. The sampling strategy employed by MWRA is more intensely focused on the area immediately surrounding the outfall and employs a fundamentally different approach than used in the NOAA study. However, the benthic community analysis conducted by the MWRA (Maciolek *et al.,* 2005) also concluded that the substantial differences between community groups was related primarily to grain size.

The sand node was inhabited by a mixed group of species (group A), some of which were cosmopolitan species occurring in stations of all three nodes, and a core group of species found almost nowhere else (Figure 2.3.13). The dominant species (in terms of abundance) in each node are listed in Table 2.3.4. Similarly, the muddy harbor node contained a core group of species (group B) found nowhere else, and species found at a few sites in Massachusetts and Cape Cod Bays. Only five harbor species were found in the sand node, and generally at very low abundance. The bulk of the species (group C) were found in the deep node. Most of these species were widely

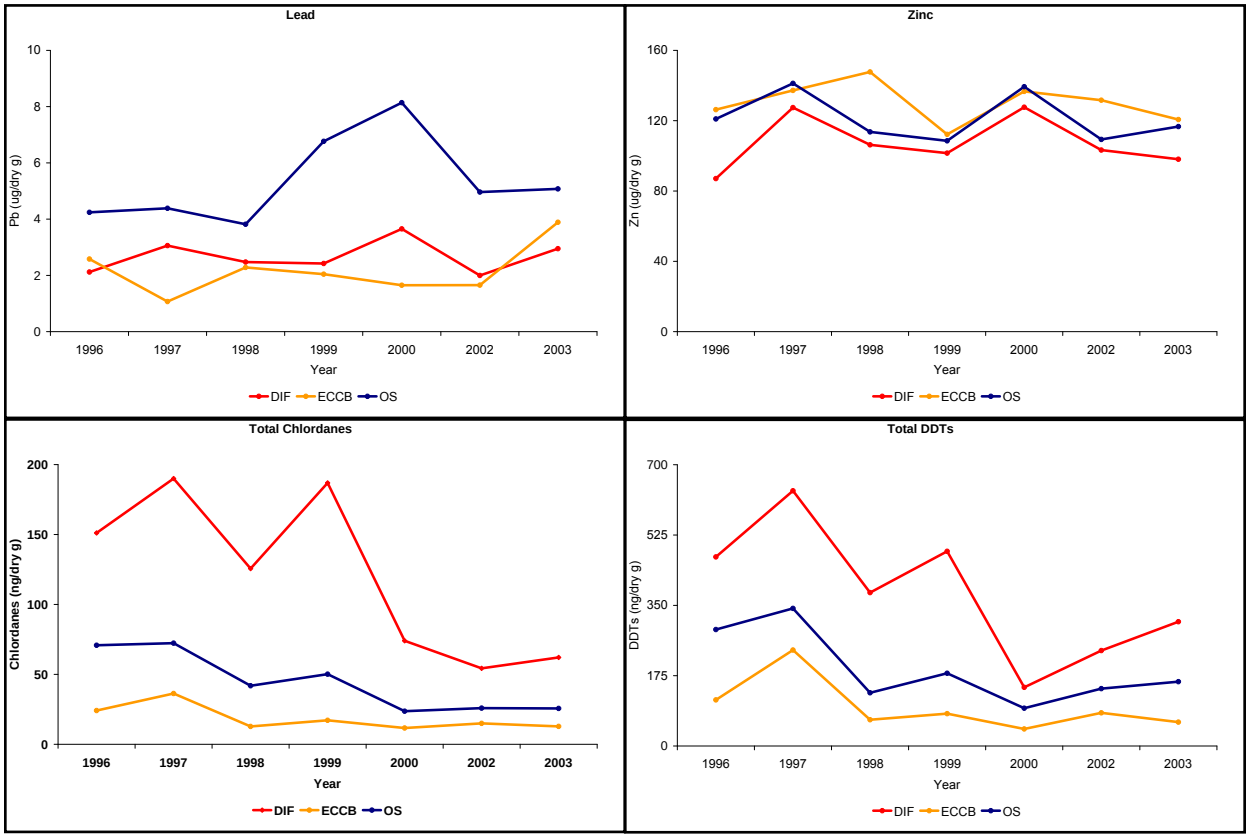

Figure 2.3.11. Temporal variation of lead, zinc, total Chlordanes, and DDT concentrations in winter flounder (*Pleuronectes americanus*) liver samples. Source: MWRA.

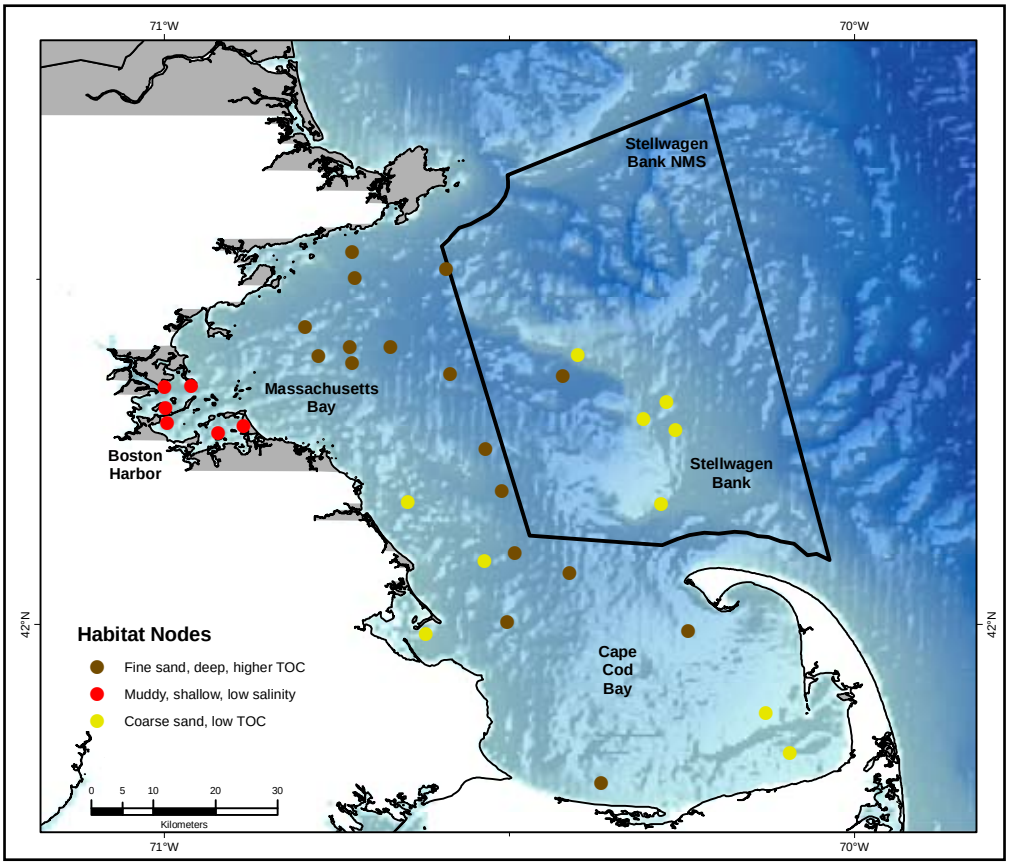

Figure 2.3.12. Location of sites representative of three major habitat nodes in the Boston Harbor/Massachusetts Bay region.

distributed among all the sites within this node. What they seem to have in common is that they were rarely found in the harbor or sand nodes. Within this species cluster is a subset of species that were found in all node sites, and again, species with more limited distribution within the node (groups c1 and c2). These latter species were rarely found in the deepest stations in Stellwagen Basin, but were distributed around the perimeter of the Basin. They were found in areas with low organic carbon in the sediment. The benthic monitoring program conducted by the MWRA has noted dramatic shifts in species dominance over time, which may be related to the patterns observed here. The NOAA sampling strategy was designed to enable a synoptic view on a broad geographic scale. A more detailed analysis of species specific distributions would be necessary to understand what processes that this snapshot of the benthic community has captured. The MWRA has also observed subsets of species associations within particular habitats. A fourth group of species (group D) appears in the species cluster that does not appear to associate with any particular habitat except that they were rarely found in the deep areas of Stellwagen

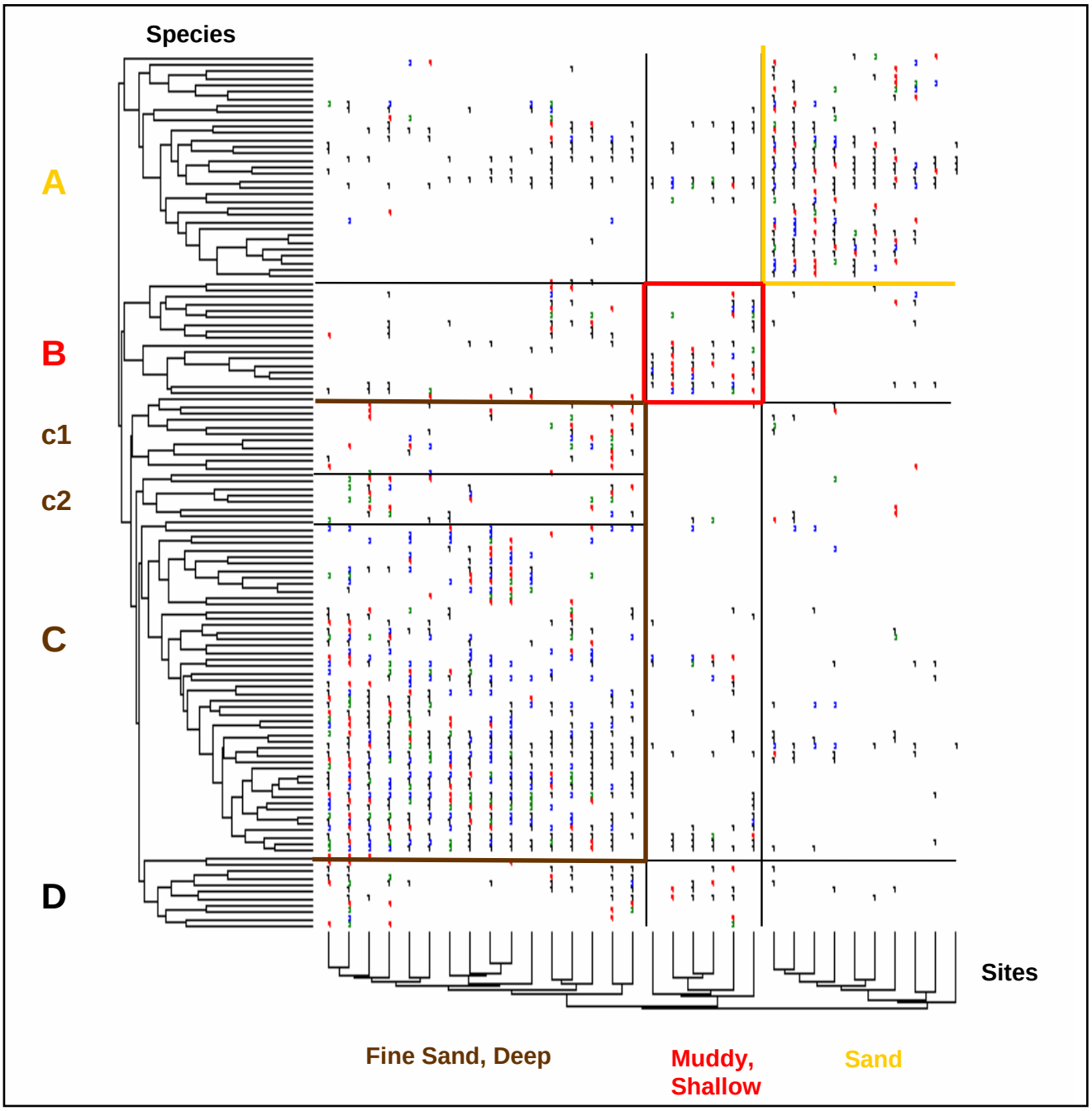

Figure 2.3.13. Nodal analysis displaying species clusters and site clusters for benthic community assessment in Massachusetts Bay and vicinity. Color indicates species specific relative abundance in 25% increments: black=low, blue-medium-low, green=medium-high, and red=high.

Basin or the shallow sand node. All species used in the analyses are listed, by node, in Appendix 7. The order of the species list is the same as the order in Figure 2.3.13.

The average number of species in the Boston Harbor stratum was consistently lower than all other strata (Table 2.3.5). The average number of species found on Stellwagen Bank was also relatively low, but this was due to the higher variability between individual stations in this stratum than in the other strata. Stations SB2 and SB3 had only 15 and 6 species, respectively. Low species diversity in coastal sand banks is not unusual and may be related to limited resources and/or a physically dynamic habitat that limits the number of species capable of thriving there (Hartwell and Hameedi, in press). Species diversity followed the same pattern. Average abundance was not low in the Boston Harbor stratum. However, this is due to the extreme abundance of a single Spionid polychaete species (*Polydora cornuta*) which was found at a density of over 35,000/m^2 at station BH3. Some Spionid worms (such as *P. cornuta*) are commonly associated with pollution tolerance in estuarine settings (Llanso *et al.,* 2002). *P. cornuta* was the dominant species at five of the six stations in Boston Harbor (including Deer Island Flats). Excluding this species from station BH3, the average abundance in the Boston Harbor stratum was 8,760/m^2. The Deer Island Flats station exhibits similar numbers compared to the other Boston Harbor stations. Average abundance at Stellwagen Bank stations was also relatively low, again due to high variability. Abundance was highest in the two southern strata. Diversity was relatively high in all the open water areas away from Boston and Stellwagen Bank. The occurrence of rare and unique species (those species found at only one or two sites) was highly variable, with no apparent pattern. The reference site at Plymouth was noteworthy, as half of all species found there were in this category. Eight of these twelve species were unique to that site (found nowhere else in the entire study area). While the location is relatively pristine, in terms of benthic community assessment, it would not be a valuable reference site for the open water habitats, as it has an unusual species composition by comparison. It was one of only a few stations that were not dominated by polychaete species.

Table 2.3.4. List of numerically dominant species in each node identified in the cluster analyses. # Sites is the number of stations the species was found in the entire data set.

Node	Taxa	# Sites
	Spio limicola	15
	Tubificidae (LPIL)	23
	Samythella sp. A	17
	Enchytraeidae (LPIL)	9
	Maldanidae (LPIL)	24
	Cirratulidae (LPIL)	23
	Euchone incolor	8
	Rhynchocoela (LPIL)	19
	Parapionosyllis longicirrata	8
Sand	*Exogone hebes*	13
	Polydora cornuta	5
	Tubificidae (LPIL)	23
	Samythella sp. A	17
	Maldanidae (LPIL)	24
	Prionospio steenstrupi	15
	Cirratulidae (LPIL)	23
	Eteone longa	6
	Euchone incolor	8
	Exogone hebes	13
Harbor	*Aricidea catherinae*	13
	Spio limicola	15
	Tubificidae (LPIL)	23
	Samythella sp. A	17
	Enchytraeidae (LPIL)	9
	Maldanidae (LPIL)	24
	Prionospio steenstrupi	15
	Cirratulidae (LPIL)	23
	Eteone longa	6
	Euchone incolor	8
Deep	Rhynchocoela (LPIL)	19

Fish Histopathology

At Deer Island flats 42 winter flounder; 14 males and 28 females were captured and necropsied. At the new outfall site 32 fish were captured and necropsied; 16 males and 16 females.

Hepatic lesions of toxicological significance (i.e. toxicopathic) that were diagnosed included hydropic vacuolation (centrotubular, tubular and focal types), and putatively preneoplastic foci of cellular alteration (specifically, eosinophilic foci) (Table 2.3.6). Hydropic vacuolation of biliary epithelial cells and hepatocytes, which is considered an effective histopathologic biomarker of chemical contaminant exposure in winter flounder (Moore *et al.,* 1996, 1997, 2005; Johnson *et al.,* 1992b, 1993; Myers *et al.,* 1999; Myers and Fournie, 2002) was detected in 14.3% of flounder from the Deer Island site, and was completely absent in flounder from the new outfall site (Table 2.3.7). In contrast, eosinophilic foci were detected in only a single fish from the new outfall site (3.2%), and were absent in fish from Deer Island. Other lesions detected in the liver that were not considered of toxicological significance

Table 2.3.5. Benthic community parameters in sediment samples from Boston Harbor and Massachusetts Bay.

Order	LABEL	AREA	# Species	Stratum Mean	#/m²	Stratum Mean	Diversity	Stratum Mean	Evenness	Stratum Mean	# Rare & Unique	% Rare & Unique	Stratum Mean
1	BH2	Boston Harbor	14		1,625		1.84		0.70		1	7.1	
2	BH3	Boston Harbor	28		54,375		1.21		0.36		6	21.4	
3	BH4	Boston Harbor	23		7,025		1.87		0.60		1	4.3	
4	BH5	Boston Harbor	28		3,850		2.63		0.79		1	3.6	
5	BHa2	Boston Harbor	21	22.8	12,750	15,925	1.56	1.8	0.51	0.6	1	4.8	8.3
6	DI	Boston Harbor DI	34		14,100		1.66		0.47		2	5.9	
7	MB2	Massachusetts Bay	60		16,200		2.75		0.67		6	10.0	
8	MBa1	Massachusetts Bay	47		12,000		2.17		0.56		7	14.9	
9	MBa3	Massachusetts Bay	45		2,225		3.45		0.91		9	20.0	
10	MBa10	Massachusetts Bay	52		15,175		2.67		0.68		3	5.8	
11	MBa11	Massachusetts Bay	64	53.6	5,550	10,230	3.47	2.9	0.83	0.7	13	20.3	14.2
12	D1	Stellwagen Basin 200ft	44		6,550		3.14		0.83		2	4.5	
13	D2	Stellwagen Basin 200ft	46		13,200		2.72		0.71		1	2.2	
14	D3	Stellwagen Basin 200ft	47		13,700		2.82		0.73		5	10.6	
15	D4	Stellwagen Basin 200ft	35		6,675		2.64		0.74		3	8.6	
16	D5	Stellwagen Basin 200ft	43	43.0	7,725	9,570	3.05	2.9	0.81	0.8	4	9.3	7.0
17	SB1	Stellwagen Bank 120ft	36		7,325		2.80		0.78		2	5.6	
18	SB2	Stellwagen Bank 120ft	15		4,325		1.97		0.73		0	0.0	
19	SB3	Stellwagen Bank 120ft	6		325		1.67		5.00		1	16.7	
20	SB4	Stellwagen Bank 120ft	29		7,750		2.13		0.63		9	31.0	
21	SB5	Stellwagen Bank 120ft	39	25.0	12,950	6,535	2.63	2.2	0.72	1.6	10	25.6	15.8
22	ABB1	Area Between Bays	50		22,300		2.43		0.62		0	0.0	
23	ABB3	Area Between Bays	63		26,775		2.75		0.66		4	6.3	
24	ABB5	Area Between Bays	52		18,075		2.87		0.73		6	11.5	
25	ABBa1	Area Between Bays	35		12,275		2.73		0.77		1	2.9	
26	ABBa5	Area Between Bays	34	46.8	10,050	17,895	2.75	2.7	0.78	0.7	4	11.8	6.5
27	CC1	Cape Cod Bay	28		3,800		2.58		0.78		6	21.4	
28	CC3	Cape Cod Bay	40		37,600		2.29		0.62		11	27.5	
29	CC4	Cape Cod Bay	58		15,875		2.90		0.71		7	12.1	
30	CC5	Cape Cod Bay	44		19,050		2.19		0.58		1	2.3	
31	CCa5	Cape Cod Bay	57	45.4	12,525	17,770	3.20	2.6	0.79	0.7	7	12.3	15.1
32	MASPE	Reference	25		6,225		2.36		0.73		12	48.0	

Table 2.3.6. Histological lesions assessed in winter flounder (*Pleuronectes americanus*) from Boston Harbor and Massachusetts Bay.

Parameter	Description
Liver epithelial neoplasms	Incidence of epithelial lesions
Liver mesenchymal neoplasms	Incidence of mesenchymal lesions
All types of liver neoplasms	Includes both epithelial and mesenchymal: Epithelial (liver cell adenoma, cholangioma, hepatocellular, carcinoma, cholangiocellular, carcinoma, mixed hepatobiliary carcinoma, biliary cystadenoma, biliary cystadenocarcinoma, pancreatic acinar cell adenoma, pancreatic ductal adenoma pancreatic cystadenoma, pancreatic acinar cell carcinoma, pancreatic adenocarcinoma); Mesenchymal (hemangioma, hemangioendothelioma, hemagiontothelial sarcoma, fibroma, fibrosarcoma, hemangiopericytoma, neurilemmona, neurofibroma, neurofibrosarcoma)
Hydropic vacuolation	Hepatocellular or biliary hydropic vacuolation (syn RAM cell areas, atypical cellular vacuolation)
Kidney neoplasms	Incidence of kidney neoplasms
Gross epidermal papilloma/abgioepithelial nodule	Incidence of gross epidermal papilloma/abgioepithelial nodule
Fin erosion	Incidence of fin erosion and associated lesions, including loss of fin, hemorrhagic fin tissue, fused rays, bent fin, exposed fin rays, fin ray blunting or retraction, and reflection of fin tissue back onto body sur-
All foci of cellular alteration.	Putative preneoplastic focal lesions (foci of cellular alteration, including clear cell focus, eosinophilic focus, basophilic cell focus, and hyperplastic hepatocellular regeneration)
Liver, non-neoplastic proliferative lesions	Liver, non-neoplastic proliferative lesions (includes biliary hyperplasia, hep. regeneration, oval cell proliferation, cholangiofibrosis, increased mitotic index)
Specific degeneration/ necrosis	Specific degeneration/necrosis (includes hep. nuclear pleomorphism, hepatic megalocytosis)
Spongiosis hepatis	Spongiosis hepatis or cystic degeneration of hepatocellular parenchyma
Necrosis	Necrosis (NOT same as SDN), primarily includes hep. coagulative necrosis, biliary epithelial cell necrosis, hep. and biliary pyknosis, karyorrhexis)
Kidney, proliferative lesions	Kidney, proliferative lesions (includes multiple lesions including tubular regeneration, tubular hyperplasia, glomerular hypercellularity, proliferation of parietal and visceral layers of Bowman's capsule, other rarely encountered lesions)
Kidney necrosis	Kidney necrosis (includes a long list of multiple lesions, including mesangiolysis, tubular necrosis, hydropic degeneration of tubular epithelium, hyalinization of tubular epithelium, others)
Kidney, sclerotic/fibrotic conditions	Kidney, sclerotic/fibrotic conditions (includes mesangiosclerosis, hypermembranous tubules, hypermembraneous glomerular tuft, calcification, glomerulosclerosis, peritubular fibrosis, and fibrosis/fibroplasia of the interstitium)

included hepatocellular coagulative necrosis (7% at Deer Island, 0% at New Outfall); a Myxosporean infection of the biliary system, probably *Myxidium* spp. (4.8% at Deer Island, 0% at New Outfall), and infection by an unidentified nematode in the liver capsule (0% at Deer Island, 3.1% at New Outfall).

A comparison of the prevalences of hydropic vacuolation in the current study to historical values in winter flounder from Deer Island Flats (Johnson *et al.,* 1992b, 1993; Moore *et al.,* 1996, 2005) clearly shows a continuing decrease in the prevalence of this lesion since monitoring began in 1987 (Table 2.3.7). These decreases in lesion prevalence are consistent with an improvement in sewage effluent quality and toxicant reduction, by instituting primary and secondary treatment, and especially by relocation of the effluent outfall to the offshore site in 2000

Table 2.3.7. Histopathology assessment results from winter flounder (*Pleuronectes americanus*) captured within Boston Harbor and Massachusetts Bay, 1988-2004. ND=No Data.

Location	Year	# Fish	Liver epithelial neoplasms	Liver mesenchymal neoplasms	All types of liver neoplasms	Hydropic vacuolation	Kidney neoplasms	Gross epidermal papilloma/ angioepithelial nodule	Fin erosion
Deer Isl	2004	42	0.0	0.0	0.0	14.3	0.0	0.0	21.4
Outfall	2004	31	0.0	0.0	0.0	0.0	0.0	0.0	3.2
Deer Isl	1991	60	1.7	0.0	1.7	30.5	0.0	0.0	13.6
Deer Isl	1990	60	1.7	0.0	1.7	59.3	0.0	0.0	0.0
Deer Isl	1989	62	4.8	1.6	4.8	43.5	0.0	0.0	30.6
Deer Isl	1988	89	7.0	1.2	7.0	41.9	0.0	0.0	21.3
Mass Bay	1988	39	0.0	0.0	0.0	2.8	ND	0.0	25.6
Hull Bay	1992	60	0.0	0.0	0.0	26.3	0.0	0.0	0.0
Hull Bay	1990	59	0.0	0.0	0.0	19.0	0.0	0.0	3.4
Hull Bay	1989	60	8.3	0.0	8.3	33.3	0.0	0.0	11.7
Quincy Bay	1992	10	0.0	0.0	0.0	30.0	0.0	0.0	0.0
Quincy Bay	1991	10	0.0	0.0	0.0	30.0	0.0	0.0	50.0
Quincy Bay	1990	60	0.0	0.0	0.0	52.5	1.7	0.0	0.0
Quincy Bay	1989	61	1.6	0.0	1.6	36.1	0.0	0.0	21.3
Quincy Bay	1988	3	0.0	0.0	0.0	50.0	ND	0.0	33.3
Plymouth	1989	60	0.0	0.0	0.0	3.4	0.0	0.0	8.3
Plymouth	1988	22	0.0	0.0	0.0	0.0	ND	0.0	18.2

Table 2.3.7 (Continued). Histopathology assessment results from winter flounder (*Pleuronectes americanus*) captured within Boston Harbor and Massachusetts Bay, 1988-2004. ND=No Data.

Location	All foci of cellular alteration	Liver, non-neoplastic proliferative lesions	Specific degeneration/ necrosis	Spongiosis hepatis	Necrosis	Kidney, proliferative lesions	Kidney necrosis	Kidney, sclerotic/fibrotic conditions
Deer Isl	0.0	0.0	0.0	0.0	7.1	0.0	54.8	0.0
Outfall	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Deer Isl	5.1	18.6	1.7	0.0	16.9	0.0	3.4	0.0
Deer Isl	3.4	18.6	0.0	5.1	25.4	0.0	22.0	3.4
Deer Isl	3.2	9.7	1.6	0.0	4.8	0.0	4.8	4.8
Deer Isl	5.8	12.8	2.3	4.7	11.6	3.3	13.3	6.7
Mass Bay	0.0	0.0	0.0	0.0	0.0	ND	ND	ND
Hull Bay	5.3	8.8	0.0	1.8	15.8	0.0	1.7	0.0
Hull Bay	3.4	15.5	1.7	3.4	19.0	0.0	1.7	0.0
Hull Bay	1.7	5.0	1.7	3.3	16.7	0.0	5.0	3.3
Quincy Bay	0.0	30.0	0.0	0.0	0.0	0.0	0.0	0.0
Quincy Bay	10.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0
Quincy Bay	1.7	3.4	0.0	5.1	11.9	1.7	12.1	0.0
Quincy Bay	0.0	4.9	3.3	3.3	26.2	0.0	5.0	5.0
Quincy Bay	50.0	0.0	0.0	0.0	0.0	ND	ND	ND
Plymouth	1.7	0.0	1.7	0.0	12.1	0.0	1.7	0.0
Plymouth	0.0	0.0	0.0	0.0	5.0	ND	ND	ND

(Moore *et al.,* 1996, 2005). For example, winter flounder sampled from Deer Island Flats in 1987-1989 in the NBS showed an approximate prevalence of 45% (Johnson *et al.,* 1993), while the approximate annual prevalences for this lesion in winter flounder from Deer Island flats reported graphically by Moore *et al.,* (2005) are as follows: 78% (1987), 65% (1988), 40% (1989); 40% (1990); 55% (1991); 50% (1992); 55% (1993); 50% (1994), 40% (1995), 45% (1996), 50% (1997), 35% (1998), 30% (1999), 45% (2000), 48% (2001), 25% (2002), and 35% (2003). Unfortunately, since this lesion is statistically more common in older fish, it is not possible at present to accurately and directly compare the lesion prevalence detected in the present study to historical values, until age data is obtained for the flounder sampled in 2004. However, it is highly likely that the age-adjusted prevalence value obtained for the present study will further support a continuing reduction in hydropic vacuolation at the Deer Island flats site. The mean standard lengths of flounder from the Deer Island site for the years 1991-2003 (Moore *et al.,* 2005) ranged from 277-330 mm, as compared to 366 mm for the mean total length of flounder captured in the present study. Although the comparison of standard length to total length is not an ideal situation, it is likely that the mean standard length would be in the vicinity of 310-330 mm, which is well within the upper range of mean lengths represented in the fish sampled for previous years at Deer Island flats by Moore *et al.,* (2005).

The complete absence of hydropic vacuolation in flounder from the new outfall site was unexpected because this lesion type had been detected over time at relatively high prevalences at a nearby site (42.3861 N, 70.8306 W). Observed frequencies were 25-35% between 1991 and 1993, and 22% (1994), 15% (1995), 22% (1996), 21% (1997), 25% (1998), 25% (1999), 25% (2000), 5% (2001), 25% (2002), and 18% (2003) (Moore *et al.,* 1996, 2005). Additional data for this lesion type exists for the NBS site MASBS located at 42.3417 N, 70.7667 W (Figure 2.2.2) which is also relatively close to the new outfall site in the present study (Johnson *et al.,* 1992b, 1993). The prevalence of hydropic vacuolation at this site was 2.6% in 1988, based on a limited sample size of 39 fish (Johnson *et al.,* 1994). A reasonable explanation for the fact that no cases of hydropic vacuolation were detected at the new outfall site in the present study is the relatively small size (and age) of the fish captured and necropsied. The mean total length of flounder from the outfall site was only 272 mm (approximately corresponding to a mean standard length of 220-240 mm), almost 10 full centimeters smaller than the fish from Deer Island Flats, and far lower than the standard length range of fish sampled by Moore *et al.,* (2005) previously at the new outfall site (269-301 mm). Flounder migratory data indicates that larger, older fish move into inshore waters in April, and younger fish move in later and may remain further offshore (M. Hall, personal communication). This is consistent with the present observations.

The only potentially toxicopathic renal lesion detected was coagulative necrosis of the second proximal segment of the kidney nephrons, found at the very high and surprising prevalence of 54.7% at Deer Island. This lesion was not detected in fish from the new outfall site. Historical data on similar necrotic kidney lesions exists for winter flounder from Deer Island Flats for 1987-1989 (Johnson *et al.,* 1992a), where 4.1% of flounder were affected by one of several separate types of necrotic lesions. Later data from subsequent sampling years demonstrate highly variable rates of necrotic renal lesions. At this point, we have no reasonable explanation for the extremely high prevalence of this lesion type at Deer Island flats in the 2004 data.

Contaminant Conditions in Stellwagen Bank National Marine Sanctuary

The status and trends of trace elements and organic contaminants in Massachusetts Bay as whole were assessed with the objective of investigating export of contaminants to the system. The foregoing assessment was conducted using contaminant concentrations in both sediment and tissue (mussels and fish). The current status of chemical contaminants in the shallow portions of Stellwagen Bank is significantly lower than those of the other region of Massachusetts Bay including Cape Cod Bay. Boston Harbor is the most polluted zone of the Massachusetts Bay/Cape Cod system. Sediments in the deep areas in Stellwagen Basin are accumulating contaminants from a variety of sources. The temporal assessment revealed no statistically significant trends for trace metals and PAHs, while banned but persistent organic contaminants (DDTs and chlordanes) show very slow decreasing trends over the monitoring years. The persistence of some organic compounds at relatively high concentrations in Boston Harbor, implies that the Harbor may be a continuing source of contaminants to other areas of Massachusetts Bay. Data in the current study indicates that pollution impacts in the Stellwagen Bank National Marine Sanctuary appear minimal. There is no indication that relocation of the POTW effluent has had short term consequences on the magnitude of export of contaminants from Boston to Stellwagen Bank NMS. That is not to say that contaminant export from Boston is not occurring, only that it does not appear to have ac-

celerated. Discharge reductions from improved sewage treatment efficiencies implemented by the MWRA have definitely aided in this regard (Maciolek *et al.,* 2005).

The track of the sewage plume from the diffusers was studied in 2001 to verify dilution rates and fate of the discharge in the water column in different seasons (Hunt *et al.,* 2002a, b). The effluent remains below the surface, but spreads throughout the entire Massachusetts Bay. During typical summer conditions of relatively calm winds and stratified water column in Massachusetts Bay, local wind forcing will vary the direction of flow randomly during any given time. Effluent dilution rates, based on tracer dye studies, found initial mixing of the effluent was completed very close to the diffuser line. Dilution measured down field from the diffusers ranged between 80 and 105 fold. The plume remains trapped below the thermocline (~5 -10 m). During subsequent tidal excursions over a period of several days the plume spreads out into the Bay. During non-stratified conditions, the plume will reach to the surface. In the summer 2001 study, after two days the effluent had spread south to as close as 5 km offshore of Scituate, Mass, remaining at a depth between 10 and 23 meters, and had increased in area from about 1.6 km^2 to 20 km^2. This represents an additional ~1000-fold increase in dilution over the 48-hour period. In a tracking study performed in the spring season, results were similar except the net transport direction was to the north. The plume dimensions 24 hours after dye release in the summer were substantially larger than in the spring due to the local currents and shear at the time of the plume surveys.

Water quality characteristics measured from discrete samples collected during the diffuser survey found increases in metals, nutrients, and total suspended solids in the plume, relative to background levels. For example, copper concentrations after initial mixing were ~60% higher than background levels measured east and north of the diffuser system, but remained below water quality criteria. Ammonia and phosphate in the diluted effluent were ~ 5- and 1.5-fold over background levels, respectively. Total suspended solids increased as much as 1.2 fold in the core of the plume. In situ measurements of the particle field confirmed a localized increase in turbidity relative to background levels. In contrast, bacterial indicators were near or below the detection limits and did not display an increase relative to the background levels.

With regard to particulate matter deposition from the effluent plume, some increases in the percentages of fine-grained material have been observed at selected nearfield stations in the vicinity of the diffusers (Maciolek *et al.,* 2005). Large changes in concentrations of contaminants compared to baseline values in sediment in 2001 and 2002 have not been seen. Similarly, contaminant data in 2003 and 2004 for nearfield stations did not indicate an increase in contaminant concentrations. However, stations located within 2 km of the diffusers, showed elevated

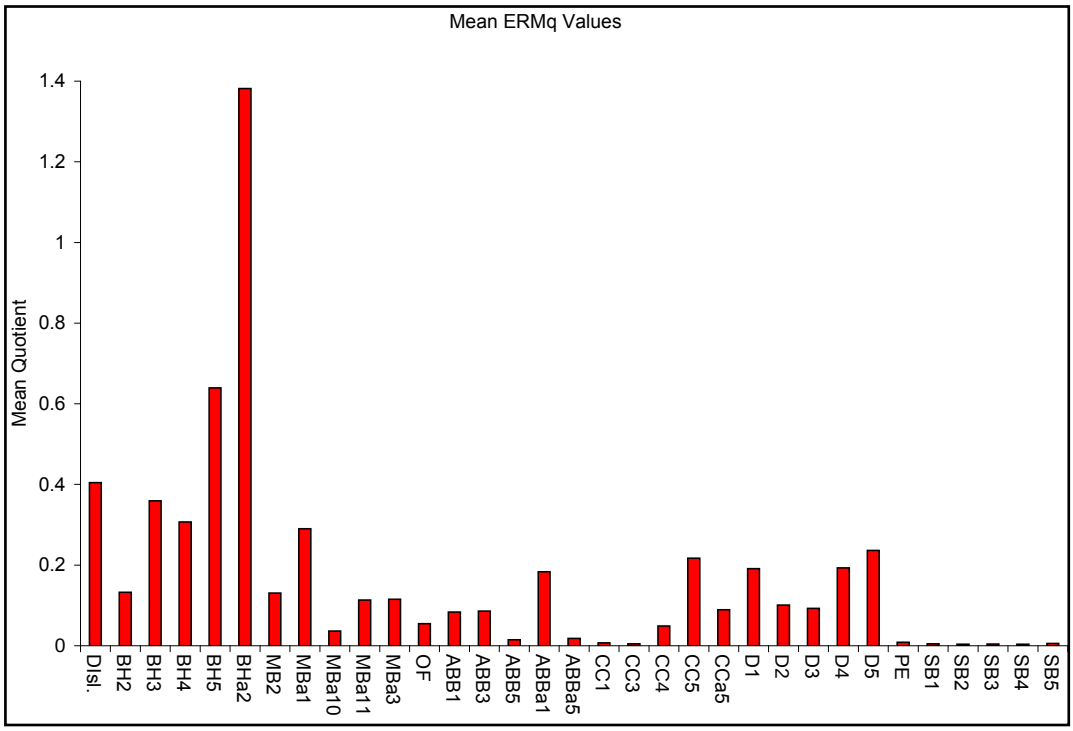

Figure 2.3.14. Mean ERM quotients for sampling stations in the Boston Harbor/Massachusetts Bay vicinity.

abundance of *C. perfringens*, indicating an effluent signal near the outfall.

Sediment contamination in Stellwagen Bank NMS is very low relative to the ERL and ERM sediment quality guidelines. Within the NS&T sampling scheme, the shallow areas on Stellwagen Bank showed five of the six lowest ERM quotients (ERMq) within the entire data set (Figure 2.3.14). Sediment stations in the deeper portions of Stellwagen Basin contained slightly elevated quotients. However, the highest ERMq in the deep stratum was only 0.24. Station D4 was within the Stellwagen Bank NMS boundaries and had an ERMq of 0.19. Station D3 on the northwestern edge of the Sanctuary had an ERMq of 0.09. Stations D4 and D3 had six and one ERL exceedances respectively. None of the shallow Stellwagen Bank stations exhibited any ERL exceedances (Table 2.3.8). Sampling stations in Cape Cod Bay and the region between there and Massachusetts Bay also exhibited very low contaminant levels. Only one station (CC5) exhibited an ERMq greater than 0.1. Stations CC5 and ABBa1 were the only stations to exceed any ERLs in these strata. These conditions are similar to those observed in NS&T Bioeffects studies in other near-coastal regions, for example in the vicinity of the mouths of Delaware and Chesapeake Bays (mean ERMq =0.016, S.D. =0.013) (Hartwell *et al*., 2001; Hartwell and Hameedi, in press). The Benthic Surveillance control site at the entrance to Duxbury Bay at Plymouth only had background trace levels (Table 2.3.8).

Table 2.3.8. Number of contaminants exceeding ERL and ERM thresholds in sediment samples from Boston Harbor and Massachusetts Bay.

Station	ERL Exceedances	ERM Exceedances
BH2	0	0
BH3	5	0
BH4	12	0
BH5	18	0
BHa2	16	1
DI	7	0
MB2	0	0
MBa1	7	0
MBa3	2	0
MBa10	0	0
MBa11	2	1
OF	0	0
D1	5	0
D2	0	0
D3	1	0
D4	6	0
D5	6	0
ABB1	0	0
ABB3	0	0
ABB5	0	0
ABBa1	4	0
ABBa5	0	0
CC1	0	0
CC3	0	0
CC4	0	0
CC5	4	0
CCa5	0	0
SB1	0	0
SB2	0	0
SB3	0	0
SB4	0	0
SB5	0	0
MASPE	0	0

Sediment contaminant concentrations at both shallow and deep sampling stations in Massachusetts Bay were higher on average than in the areas to the east and south, but the mean ERM quotients were not statistically higher (t=1.757, 24 df.). The ANOVA results from the spatial analysis clearly demonstrate that Boston Harbor is significantly more contaminated than all areas outside the harbor for most chemical parameters. Contaminant levels in sediments decrease offshore from Boston Harbor. However, elevated concentrations of contaminants occur in the small patches of fine sediments near the sewage outfall site and in the depositional areas of Stellwagen Basin and Cape Cod Bay. For example, the relatively high amounts of silver in Cape Cod Bay suggest preferential accumulation of sewage-associated contaminants in this region (USGS, 1998). Sediments in Massachusetts Bay have received inputs of contaminants from Boston Harbor for long periods of time (Werme and Hunt, 2005) through direct outflow and sediment transport out of Boston Harbor. Massachusetts Bay has also received contaminant loads via off-shore dumping grounds located northwest of the Stellwagen Bank NMS. Sediment transport in the region occurs primarily during storms. Typically, storm waves and northeast winds resuspend sediments, which are transported by shallow currents from western Massachusetts Bay toward Cape Cod Bay and by deeper currents to Stellwagen Basin (Werme and Hunt, 2005). Contaminants delivered to Massachusetts Bay from either Boston Harbor or the new POTW outfall will be subject to the same transport phenomena within the system and will accumulate in the deeper portions of Stellwagen Basin where currents seldom disturb bottom sediments.

2.4 SUMMARY AND APPLICATION TO WATER QUALITY MONITORING

The Stellwagen Bank NMS recently developed a water quality action plan in response to issues raised in a review of the Sanctuary management plan. The driving force behind the need for a water quality action plan was the concern that point and non-point sources of pollution have the potential to degrade the quality of the Sanctuary's water. Specifically, the four main issues were:

- No Existing Comprehensive Water Quality Plan
- Lack of Baseline Water Quality Data Including Toxins and Contaminants
- Appropriateness of Waste Water Discharge by Vessels in the Sanctuary
- Impacts of Municipal Sewage Outfalls and Other Waste Streams

Much of the pollution reaching the Sanctuary comes from non-point sources or from distant point sources. The Sanctuary is open to vessel traffic of all types, including container ships, liquefied natural gas (LNG) and oil tankers, barges, fishing vessels, and cruise liners. Shipping activities may result in a variety of chemical releases from discharges, spills and/or collisions, and the possibility of importation of invasive species. The Massachusetts Bay Disposal Site is located in Stellwagen Basin directly outside the Sanctuary's western boundary. Materials deemed free of hazardous materials by the U.S. Army Corps of Engineers (USACE) and the U.S. Environmental Protection Agency (EPA) may be dumped at this site, but historical dumping operations have included hazardous military and industrial wastes, and dredge spoil. The Massachusetts Water Resources Authority (MWRA) outfall discharges secondarily treated sewage effluent west of the Sanctuary. Several waste water treatment facilities discharge into Massachusetts Bay to the north and south of the Sanctuary also. Air pollution from power plants and industrial facilities and urban smog release a variety of chemicals over the Bay. Of concern are the cumulative impacts of multiple activities that may affect the living resources of the Sanctuary.

According to the Stellwagen Bank NMS Water Quality Action Plan, water quality monitoring and research has received relatively little attention to date. Sediments are a major sink for contaminants delivered to the Bay either from the water column or adsorbed onto fine particulate matter derived from point and non-point sources. Many organic pollutants and metals can persist in sediment depositional areas for decades. Accumulating contamination in the bottom sediments poses a threat to natural resources through biomagnifications in the food web. The NOAA assessment was designed to assess the magnitude and extent of sediment contamination and fish tissue accumulation in the Boston Harbor/Massachusetts/Cape Cod Bay system.

In 2004, metal and organic contaminant concentrations were found to be significantly higher in the sediments collected in and around Boston Harbor than all other areas. Intermediate concentrations were found in the middle and deeper areas of Massachusetts and Cape Cod Bays. The lowest sediment contaminant concentrations were consistently found in the Stellwagen Bank sites. Contaminant data from the 2004 sampling effort are consistent with historical data. In Boston Harbor, contaminant concentrations in the past were somewhat higher than current levels but there is large variability in the data. Within the range of variability, the data indicated either static or slowly declining levels, depending on the specific chemical. Although the data show some slight declines, there are no significant differences in concentration between the old and current sediment data as a whole. Data from offshore also indicated that there was little difference in contaminant concentrations over time in these areas. Within the limited time span of offshore POTW discharge, this suggests no pollution transfer from the opening of the new outfall, beyond that which was already being exported from Boston Harbor to Massachusetts Bay by existing physical transport processes.

Consistent with the sediment data, mussel tissue contaminant concentrations were higher from sites in the vicinity of Boston Harbor. The Brewster Island station at the mouth of Boston Harbor shows elevated concentrations relative to more remote stations, indicating evidence of a gradient of contaminant concentration from inshore to offshore. This suggests an export of contaminants from Boston Harbor eastward toward Stellwagen Bank and southward toward Cape Cod Bay via suspended sediments and/or the water column. Fish tissue show similar patterns of spatial distribution. Fish collected in the vicinity of Deer Island Flats had consistently higher contaminant concentrations than those from Massachusetts Bay near the new sewer outfall. Temporal trends in mussel and fish tissue body burdens are not strongly evident. Overall, persistent, chlorinated compounds that have been banned for decades show only slightly declining concentrations. This attests to their persistence in the environ-

ment and that there are still large reservoirs in the watershed and sediment deposits within the region that continue to release contaminants to the wider environment.

Histopathologic biomarkers of chemical contaminant exposure in winter flounder were detected in flounder from the Deer Island site, but were rare in flounder from the new outfall site. Comparison of the prevalence of lesions in the current study and historical values shows a continuing decrease at Deer Island. These decreases are consistent with an improvement in sewage effluent quality and toxicant reduction, and relocation of the effluent outfall to the offshore site in 2000. It may be that so few lesions were detected at the new outfall site in the present study due to the relatively young age of the fish captured there.

The benthic community analysis demonstrates three major habitat zones, driven by sediment grain size, with salinity and depth as secondary factors. Species diversity in the Boston Harbor stratum was consistently lower than all other strata. The average number of species found on Stellwagen Bank was also relatively low, due to the higher variability between individual stations. Average abundance for most species was low in Boston Harbor, but due to the extreme abundance of pollution tolerant species the overall abundance was not different than other areas. Diversity was relatively high in all the open water areas away from Boston and Stellwagen Bank.

Boston Harbor, Stellwagen Basin, and Cape Cod Bay are the long-term sinks for fine-grained sediments and associated contaminants from all sources in the region. Fine grained sediments accumulate in Boston Harbor because of its restricted flushing and low-wave climate. Bottom deposits on the inner shelf of the western shore of Massachusetts Bay are gravel, coarse sands, and bedrock. Fine sediments do not accumulate here because storm currents resuspend and displace them toward Cape Cod Bay and offshore into Stellwagen Basin where they settle to the bottom. Sediments that reach the sea floor in Cape Cod Bay or Stellwagen Basin are likely to remain there. They are low energy environments where fine-grained sediments can accumulate. Thus, once contaminants reach Stellwagen Basin or Cape Cod Bay, carried either by the mean flow or transported by storms, it is unlikely that they will be re-suspended and transported away again. Water quality monitoring plans should include assessment of sediment contamination and benthic community assessment within the Sanctuary. Coordinated efforts in collaboration with ongoing monitoring by the USGS and MWRA would be mutually beneficial. Specifically, fine grained sediments in Stellwagen Basin and possibly selected locations in Cape Cod Bay, should be monitored for contaminant accumulation and biological impact.

Critical habitats and food chains supporting many fish and wildlife species involve the benthic environment. Contaminants in the sediments often pose both ecological and human-health risks through degraded habitats, loss of fauna, biomagnification of contaminants, and human consumption of contaminated fish and wildlife. Thus, characterizing and delineating areas of sediment contamination and bioeffects are viewed as important goals of coastal resource management. Macrobenthic communities represent an important link to higher trophic levels for both planktonic and detritus-based food webs. They are a particularly important food source for juvenile fish and crustaceans. Benthic assemblages are composed of diverse taxa with a variety of reproductive modes, feeding guilds, life history characteristics, and physiological tolerances to environmental stressors, both natural and anthropogenic. Responses of some species (e.g. organisms that burrow in or feed on sediments) are indicative of changes in sediment quality. Benthic species composition, abundance, and biomass also are influenced by habitat conditions. Information on changes in benthic population and community parameters due to habitat characteristics can be useful for separating natural variation from changes associated with human activities. Furthermore, most benthic species have limited mobility and cannot physically avoid stressful environmental conditions. Benthic assemblages thus cannot avoid and must respond to a variety of stressors such as toxic contamination, eutrophication, sediment quality, and seasonal changes. Benthic community studies have a history of use in regional monitoring programs and have been proven to serve as an effective indicator for describing the extent and magnitude of pollution impacts in marine ecosystems, as well as for assessing the effectiveness of management actions.

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CHAPTER 3 - MARINE FISHES

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3.0 INTRODUCTION

The Gulf of Maine has a remarkable diversity of fish species. Despite the region being associated primarily with a few species of economic importance such as Atlantic cod, haddock, and bluefin tuna, the Gulf of Maine has 652 documented species of fish (Gulf of Maine Register of Marine Species at http://www.usm.maine.edu/gulfofmaine-census /Docs/About /GoMRMSClassification/ index.htm). The diversity of species in the Gulf of Maine region is due largely to the proximity of the boundary between Acadian and Virginian biogeographic regions and the seasonal shifts in temperature and productivity that facilitate the mix of species by northern and southern migrants, as well as on-shelf movements of slope and deep sea species. The Gulf of Maine is dominated by resident species while the Mid-Atlantic region is dominated by migrants that move north when conditions are favorable (i.e. warm water temperature). Further, the wide diversity of habitats and oceanographic conditions in the Gulf allows a diversity of fishes to occur in different places that meet their ecological requirements.

The initial exploration of the fish fauna of the Gulf region over 120 years ago was conducted by both fishermen and scientists (Goode, 1884, 1884-1887). Fishermen sought to make their living by exploiting the abundant and productive species that occurred in the Gulf, thereby contributing to the development of the coastal economies that the region is now noted for. Even then, fishermen recognized that patterns of diversity changed and shifted in particular places with seasons and over time and they used this knowledge in a practical way to govern where and when they fished (Rich, 1929). Thirty years (1975-2005) of fishery-independent trawl data, provided by the National Marine Fisheries Service's (NMFS) Northeast Fisheries Science Center, containing distribution and abundance of demersal fish species from the offshore regions of the Gulf of Maine were used to develop a preliminary biogeographic analysis of diversity patterns. Using these data, a regional scale analysis of fish diversity for the Gulf of Maine, and in particular Stellwagen Bank National Marine Sanctuary, was conducted by examining a variety of diversity metrics. Further, patterns of diversity at small spatial scales are examined using video transect data from discrete habitats within SBNMS. The distribution of ichthyoplankton within the Gulf of Maine are analyzed from data collected between 1977-1987. Finally, the distribution, patterns of dominance, and rarity of 16 species are described. Species were selected based on their ecological importance, current population status, or narrow habitat requirements.

3.1 FISH DIVERSITY

Regional scale (i.e. continental shelves) data about most marine fish is necessary to understanding even basic patterns of diversity. The National Marine Fisheries Service has compiled a robust regional scale dataset on fishes in the Gulf because of their economic importance. In particular, sample data derived from fishery independent trawl surveys can be useful for developing a fundamental understanding of how diversity within a particular major taxonomic group is distributed across wide geographic areas (Auster, 2002). However, due to the spatial scale at which trawl sampling operates (i.e. in the present case aggregates fishes across tows of 1.8 nm length), additional data that links individual animals to particular attributes of the underwater landscape are also needed to understand how diversity is distributed at local scales. Such information is critical for developing predictive models of how organisms will respond to variations in landscape and oceanographic conditions.

This chapter examines spatial and temporal patterns in the diversity of shelf fishes in the Gulf of Maine region (i.e. Gulf of Maine and Georges Bank) of the northwest Atlantic Ocean with particular reference to Stellwagen Bank National Marine Sanctuary (SBNMS). Regional scale patterns are examined shelf wide and take advantage of 30 years of fishery independent survey data. Small spatial scale comparisons (i.e. Stellwagen Bank National Marine Sanctuary (SBNMS)) are made using the same data set. Additional patterns in local scale patterns in diversity, at the spatial scale of particular habitat types, are described from video transect data collected during remotely operated vehicle (ROV) dives at SBNMS. The current study identifies patterns in space and their influence to the described diversity patterns.

Methods

Site Description

The Gulf of Maine and Georges Bank form a distinctive sub-region of the North American continental shelf in the northwest Atlantic Ocean (Sherman *et al*., 1996). The Gulf of Maine is bounded by Georges Bank to the south and is terrestrially bounded to the west and north. Water flows into the Gulf through the Northeast Channel and over the Scotian Shelf. The Gulf contains three major basins from 250-350 m deep which are bounded by topographic rises shallower than 100 m. The basins and other topographic lows generally contain mud habitats, while shallow slopes and rises are composed of coarser sediments from sand to gravel. The water column in the Gulf exhibits a three-layer stratification during summer, while the deepest two layers persist the remainder of the year. The major circulation pattern consists of a counterclockwise flow.

Georges Bank is a major topographic high along the shelf-slope boundary with a mean depth of approximately 50 m. The southern portion of the Bank grades into the continental slope and also contains a series of submarine canyons incised into the shelf and slope. A gravel pavement occurs on the northeast side of the Bank with coarse to fine sands across the remainder of the feature. Circulation is characterized as a clockwise gyre. The water column is generally well mixed and isothermal.

Stellwagen Bank National Marine Sanctuary encompasses all or part of several banks and basins in the western Gulf of Maine including Stellwagen Bank, Tillies Bank, the southwest part of Jeffreys Ledge, and Stellwagen Basin. Depths within SBNMS range from 20 m to 190 m below sea level. Stellwagen Bank, the major geologic feature within the Sanctuary, is a sandy and gravelly topographic high of glacial origin. It is approximately 15 km wide and 40 km long and trends northwest-southeast. Stellwagen Bank and other shallow bank features in the Sanctuary are isolated from sediment sources and are eroding. Tidal currents on the Bank are weak, reaching maximum speeds of only 20-30 cm/s. However, the Bank lies in the path of strong northeasterly storms. Currents generated by storm waves in the deep waters of the Gulf of Maine modify the seabed as they pass over this sill-like feature (Valentine and Schmuck., 1994). Nested within the landscape features of banks and basins, are seafloor habitats with a surface geology that include sand, gravelly sand, sand with shell deposits, mud, mud draped gravel, gravel pavement, partially buried boulders (in both mud and sand), piled boulder, and rock outcrop (Auster *et al,*. 1998; Valentine *et al.,* 2001). Boulder reefs are a seafloor feature distinguished by the composition of fish species. Boulder reefs are based on discrete features composed of boulder size (i.e. minimum diameter of 256 mm) rocks and are bounded by smaller gravel, sand or mud sediments (Auster and Lindholm, 2006).

SBNMS is currently managed as a multiple use site (USDOC, 1993) where recreational and commercial fishing activities are managed by a regional fishery management council such that regional regulations are applied within the Sanctuary (i.e. there are no special regulations protecting fish or fishery resources within the site). In December 1998, the Western Gulf of Maine closure was delineated by the New England Fishery Management Council and NOAA to conserve Atlantic cod and haddock populations. The boundaries of the closure include the eastern portion of SBNMS and significantly reduced fishing effort in the region.

Regional Scale Analyses

Spring and fall survey trawl data from the National Marine Fisheries Service (NMFS) Northeast Fisheries Science Center was used to quantify regional scale patterns in the diversity of fishes. Data were inclusive for the years 1975-2004. The survey strategy was designed to assess the population status of fishes of economic importance across the continental shelf from Cape Hatteras, North Carolina to Cape Sable, Nova Scotia (Grosslein, 1969; Doubleday, 1981). The survey has a stratified random design with strata based on temperature and depth. Each stratum is sampled by 1 tow per 680 km^2 conducted at randomly selected locations, with a minimum of five tows per stratum per survey. The tow period is 30 minutes from the period when the trawl sets on bottom to the time that hauling to the surface commences. In order to focus this analysis on the Gulf of Maine region, survey strata were parsed from the larger survey design based on approximate geographic boundaries delineated for the Gulf of Maine Large Marine Ecosystem (Sherman *et al*., 1996) such that the Gulf of Maine was bounded by Great South Channel to the southwest and the Scotian Shelf to the northeast. Numbers per species, rather than weight, was used as an index of abundance. A total of 26 strata were used in this analysis (Figure 3.1.1). Analyses were conducted on aggregate data across the time series as well as in 5 year time bins, for both spring and fall survey periods.

Stellwagen Bank National Marine Sanctuary (SBNMS) is the only National Marine Sanctuary designated within the Acadian biogeographic province of the United States. The boundaries of SBNMS are within a single sampling stratum (i.e. stratum 1260) of the NMFS trawl survey. Stratum 1260 includes Stellwagen Bank, Jeffreys Ledge, and Tillies Bank as major features, as well as a series of smaller banks and basins. The data set for stratum 1260 includes 353 tows. On average, 25 tows were conducted during each seasonal five-year trawl bin.

Although the boundaries of stratum 1260 extend beyond the limit of the Sanctuary, the patterns are indicative of those in the Sanctuary proper. Appendix 1 contains a list of species, common names, and summary statistics for all trawl samples collected at the regional scale and in stratum 1260.

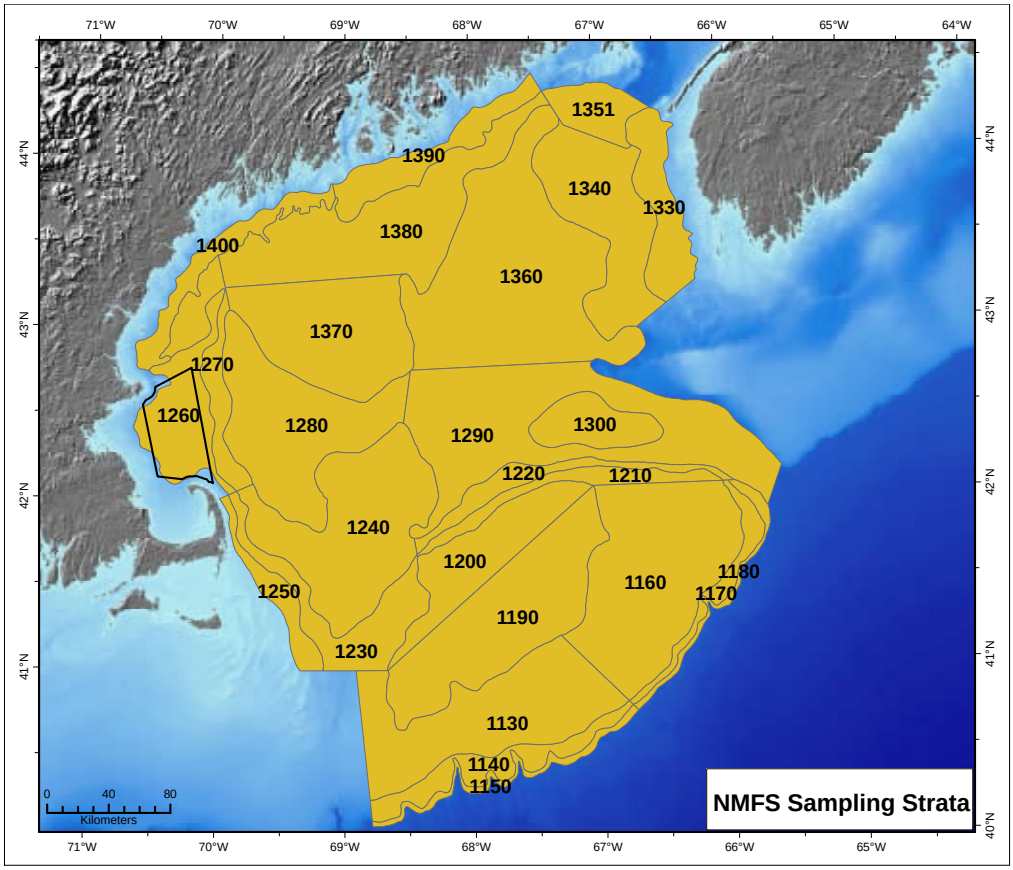

Figure 3.1.1. NMFS sampling strata for the Gulf of Maine sub-region.

For this analysis, six indicators of species diversity were calculated (Figure 3.2.2) for each survey strata within each season, and for each five year time period (i.e. species richness, Margalef's index, Shannon index, Simpson index, taxonomic diversity, and taxonomic distinctness) using the PRIMER software package version 5.2.8 (Clark and Warwick, 2001). The values for each stratum and index represent the mean of all samples for each time period. Data were delimited by quintile in order to differentiate broad spatial patterns of diversity (e.g. areas of low versus high diversity). Species richness is the simplest index and represents the total number of species from each sample. Margalef's index incorporates both species richness and the number of individuals in a sample and is a simple measure of the number of species per individual. The Shannon diversity index is a measure of both species richness and the number of individuals of each species in a sample (Note that this is different from Margalef's index in that Shannon links the numbers of individuals to each species). This index is most sensitive to changes in the number of rare species in a sample. The Simpson index is essentially an estimate of the probability that any two individuals drawn from a sample are members of the same species and is most sensitive to changes in the number and abundance of dominant species in a sample. The final two indices are based on the relatedness of species through links of a classification tree (i.e. number of links between species in a sample based on connections at generic, family, class levels etc.). Average taxonomic diversity is based on the average number of links between two individuals chosen at random from the sample. Average taxonomic distinctiveness, like the previous metric, is a distance measure through a classification tree but is based on average distances of random pairs of individuals that are not the same species. Both Clarke and Warwick (2001) and Magurran (2004) provide overviews of the range of diversity indices available and issues regarding interpretation.

Patterns of species rarity and dominance for SBNMS and the Gulf of Maine region were identified by listing the top 10 species in order of abundance as well as the 10 least abundant species (including ties), respec-

tively. Dominance curves were used to contrast patterns of cumulative species abundance across the entire time series. An additional analysis was undertaken to compare strata that contain the same approximate depth boundaries as stratum 1260. This analysis compares patterns of diversity between SBNMS and other strata with similar bathymetry within the region.

Species Richness – Total number of species

Margalef's Index

$D = (S-1)/\ln N$

N = the total number of individuals summed over all S species.

Shannon's Index

$H' = -\Sigma p_i \ln(p_i)$

p_i is the proportion of individuals found in the i^{th} species.

Simpson's Index

$1-(\Sigma(n/N)^2)$

n = total number of individuals of a particular species; N=total number of individuals for all species.

Taxonomic Diversity

$\Delta = 2 * \sum d_{ij}\, p_i p_j$

p_i and p_j are the proportions of the i^{th} and the j^{th} species, d_{ij} is the distance or dissimilarity between the i^{th} and j^{th} species. 5 levels of classification were used (Class, Order, Family, Genus, Species).

Taxonomic Distinctness

$\Delta^* = [\Sigma\Sigma_{i<j}\, \omega_{ij}\, x_i x_j]/[\Sigma\Sigma\, \delta_{i<j}\, x_i x_j]$

x_i is the abundance of the i^{th} of *s* species and ω_{ij} is the weight given to the path length linking species i and j. 5 levels of classification were used (Class, Order, Family, Genus, Species).

Figure 3.1.2. Formulas for diversity indices used to examine fish diversity within the Gulf of Maine sub-region.

Local Scale Analyses

Spatial patterns in the diversity of fishes at the local scale were investigated at SBNMS. Video transects were conducted to quantify fish abundance and diversity over a range of habitat types (i.e. mud, gravel-sand, boulder reefs) in summer 2000. During summer 2002, transects were conducted specifically in boulder reef habitats both inside and outside an area closed to fishing to contrast patterns in fish diversity based on variation in exploitation. Transects were conducted using the Kraken remotely operated vehicle (ROV).

Species-area and species-individual relationships were quantified for both sampling periods. The species-area curve is the cumulative relationship between area surveyed and where each new species appears along a transect. Area was calculated by estimating transect length from a series of navigation fixes (i.e. integrating global positioning data for the ship with slant-range and bearing of the ROV using an ultra-short baseline tracking system) and transect width (i.e. the mean value of path width measurements based on paired parallel lasers projected in the video field-of-view for calibration). The species-individual relationship is based on the accumulation of new species as the number of individuals observed increases along a transect. (Note that this relationship is area independent.) All species were identified from video imagery. Recording transects on video allowed replay of tapes and aided in identification of individuals observed only briefly or in distal parts of the field-of-view. Most transects were approximately 1 km in length. Shorter transects were the result of weather, vessel traffic, or the location of fixed fishing gear, that precluded the ROV from moving along the prescribed transect line. A preliminary exploration of the data demonstrated that log-log regressions provided the best fit to the data and are presented here.

Results

A total of 154 species of fishes were collected throughout the time series data used in this study and 68 in stratum 1260 (the proxy for SBNMS). This is in contrast to the total of 174 species for the Gulf of Maine overall and 66 species observed at SBNMS reported in a previous study (Auster, 2002). These fundamental differences can be attributed to the use of only fall and spring trawl data for the present study while Auster (2002) included available winter and summer survey data for an analysis that assessed patterns in diversity and community composition in aggregate across a 25 year time series. The slightly larger number of species at SBNMS can be attributed to sampling variation over the longer time series in the current study and the chance collection of rare species. The present study, in contrast to Auster (2002), examines variation in spatial patterns across the region in much finer detail.

Patterns across region in relation to SBNMS

Species Richness

Patterns of species richness across the Gulf of Maine and over time in each of the sample strata were variable (Figures 3.1.3 and 3.1.4). Slightly lower richness values overall were evident in spring than in fall. This pattern is attributed to colder temperatures in spring and a reduced number of southern migrants that draw from a more diverse species pool than do migrants from the north during this season.

SBNMS was always in the top two quintiles of all strata, suggesting that the site supports consistently diverse fauna (Figure 3.1.5). Species richness is highly sensitive to sample size and there was sampling effort variability among seasonal year-bins, however, this variability was not limited to the SBNMS nor any other sampling strata within the study area. Sample sites are selected randomly within all strata so the same sites are not re-sampled over time. Variation in sample location could contribute to variations in richness based on species associations with particular habitats (Auster *et al*., 1998, 2001). Given that the range of values represented within each of the top three quintiles is narrow, small differences in richness greatly affect membership within any of the top bins.

It is important to note that while richness values varied locally, this variation is attributed to shifts in the presence or absence of species that are generally occasional migrants (e.g. non-resident species with coastal, slope-deep sea, or more northern or southern distributions). There were no obvious local extinctions of resident species that could be identified by long-term absences across seasonal time bins.

Margalef's Index

Patterns of diversity calculated from Margalef's Diversity Index across the Gulf of Maine through the time-series are displayed in Figures 3.1.6 and 3.1.7 Considerable variability was observed throughout the study area during both seasons. Overall, fall indices were higher than in spring. The index was consistently low to moderate in the two strata comprising the shallower portion of Georges Bank (1190 and 1200; see Figure 3.1.1) and higher in the two deeper strata (1130, 1160). This region exhibited higher values during the fall, most notably within the last 15 years of the time-series. Strata 1240 was consistently in the top quintile during all year-bins during spring and three of the six fall year-bins.

During spring, Margalef's Index within SBNMS (strata 1260) was within the top two quintiles during three of the six year-bins (1975-79, 1990-94, 1995-99), the third quintile during 1985-89 and 2000-05, and in the lowest quintile during 1980-84. During Fall, the index was within the top two quintiles for five of the six year-bins (1980-2004) and within the third quintile during 1975-79. Mean diversity (across all year-bins) within SBNMS was moderate during spring compared to the rest of the study area and was in the top quintile for mean diversity during the fall (Figure 3.1.5).

This index most likely responded to natural variations in species richness and abundance in addition to the high degree of fishing mortality that varied across the time series. Since richness and evenness measures are independent in this index (i.e. abundance is not linked to individual species), it should track the loss of individual fishes from fishing mortality most tightly. While the variation over time at SBNMS, or other individual strata, does not mirror region-wide trends in fishing mortality, variation within strata over time may be illustrative of shifts in fishing effort and changes in the abundance and distribution of target species.

The index was also responsive to the number of rare species captured. The total list of rare species are displayed in Appendices 9-12. Rare species were identified for each seasonal year-bin, all strata combined, and compared with mean Margalef's diversity values for each seasonal year-bin. The mean number of rare species across all strata for each seasonal year-bin were positively correlated with mean Margalef's diversity values (Figure 3.1.8). Rare species were more frequently captured in sampling strata during the fall compared to spring.

Shannon's Index

Shannon's Index of diversity within the study area was variable during spring (Figure 3.1.9) and fall (3.1.10). Values were comparable between seasons, but on average were higher in the fall. The nearshore strata (1400) located along the northwestern portion of the Gulf of Maine was consistently high during spring and considerably lower during fall. The strata comprising Georges Bank exhibited no clear patterns during spring and fall. In gen-

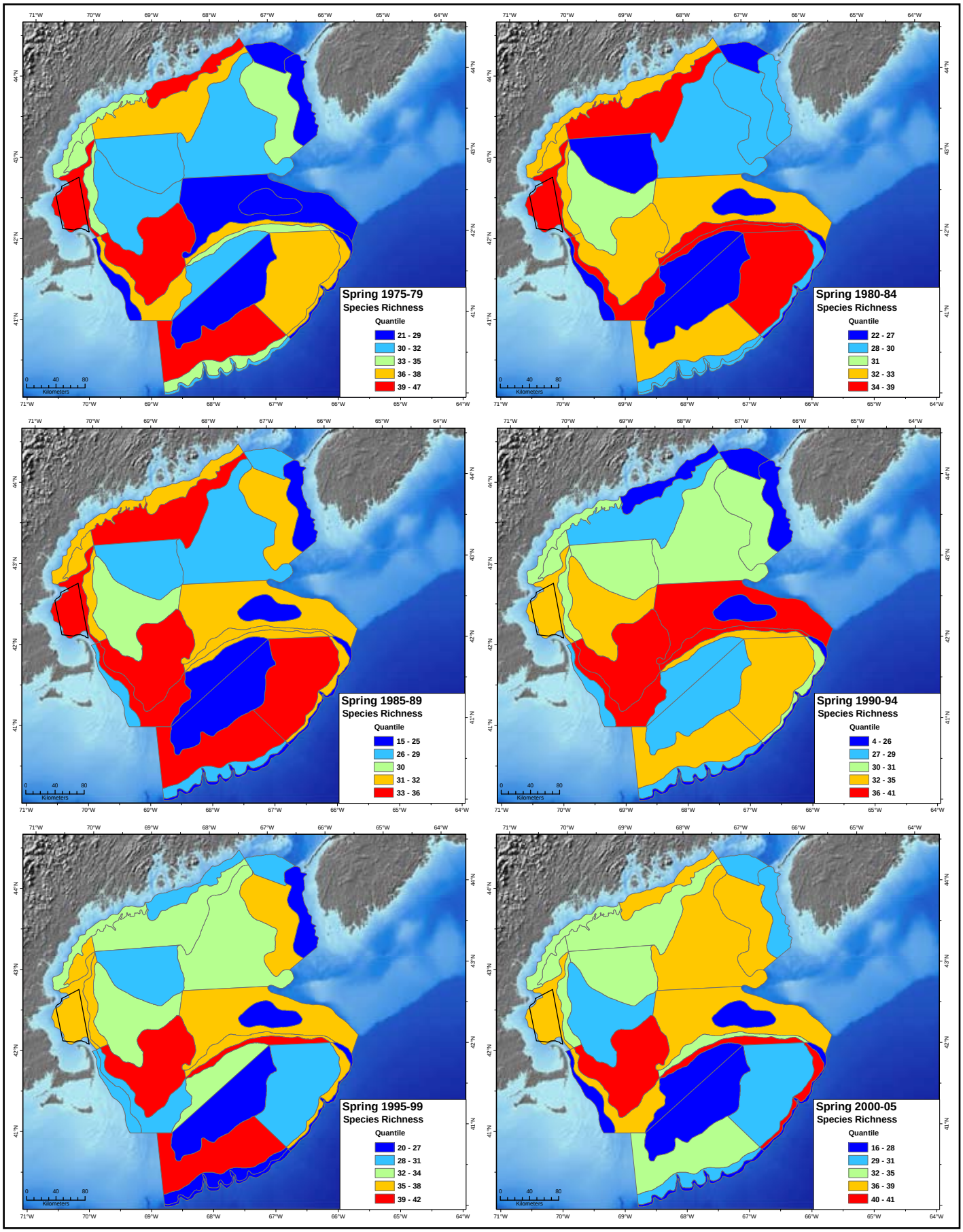

Figure 3.1.3. Species richness time-series (five year increments) within NMFS sampling strata, Spring 1975-2005.

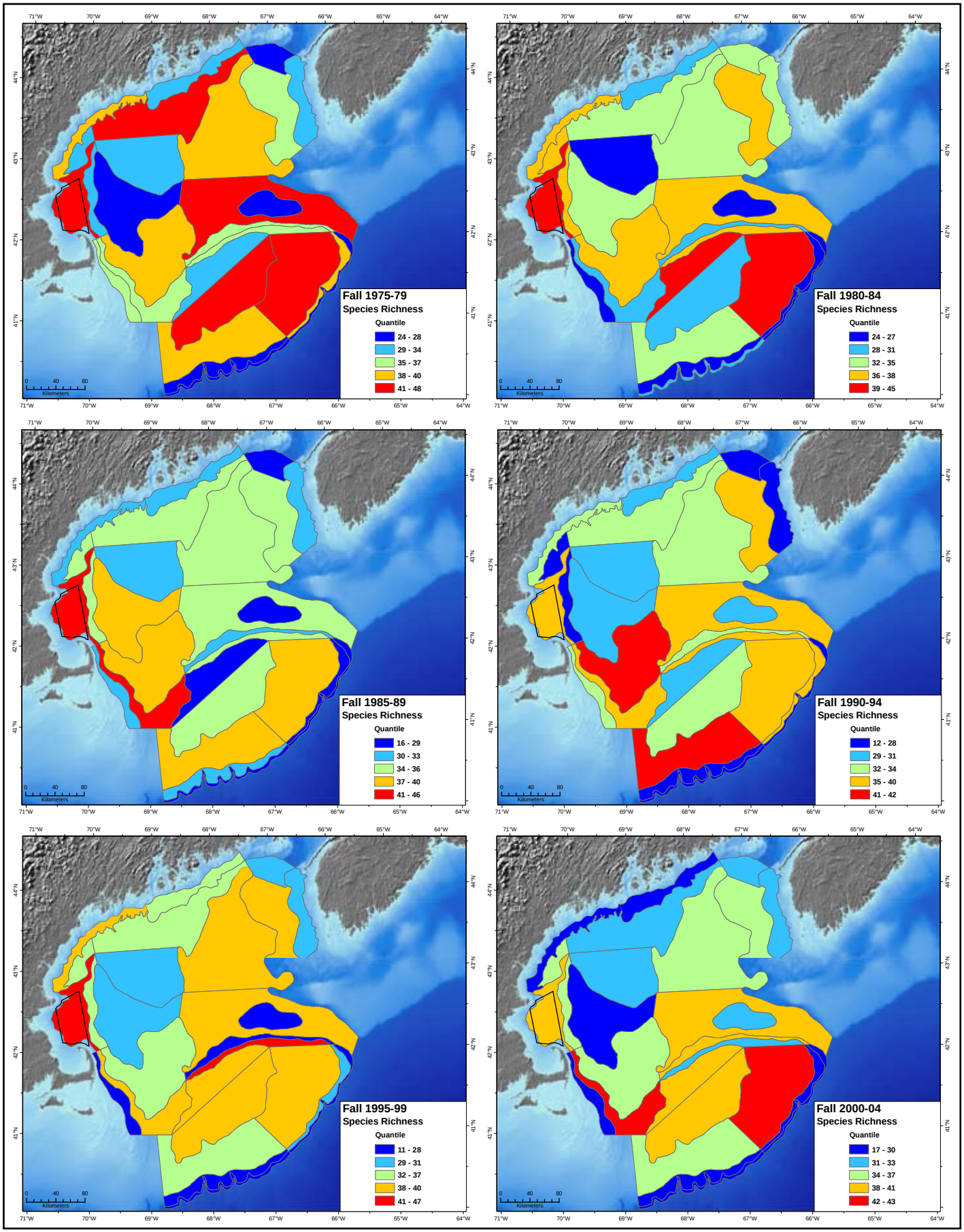

Figure 3.1.4. Species richness time-series (five year increments) within NMFS sampling strata, Fall 1975-2004.

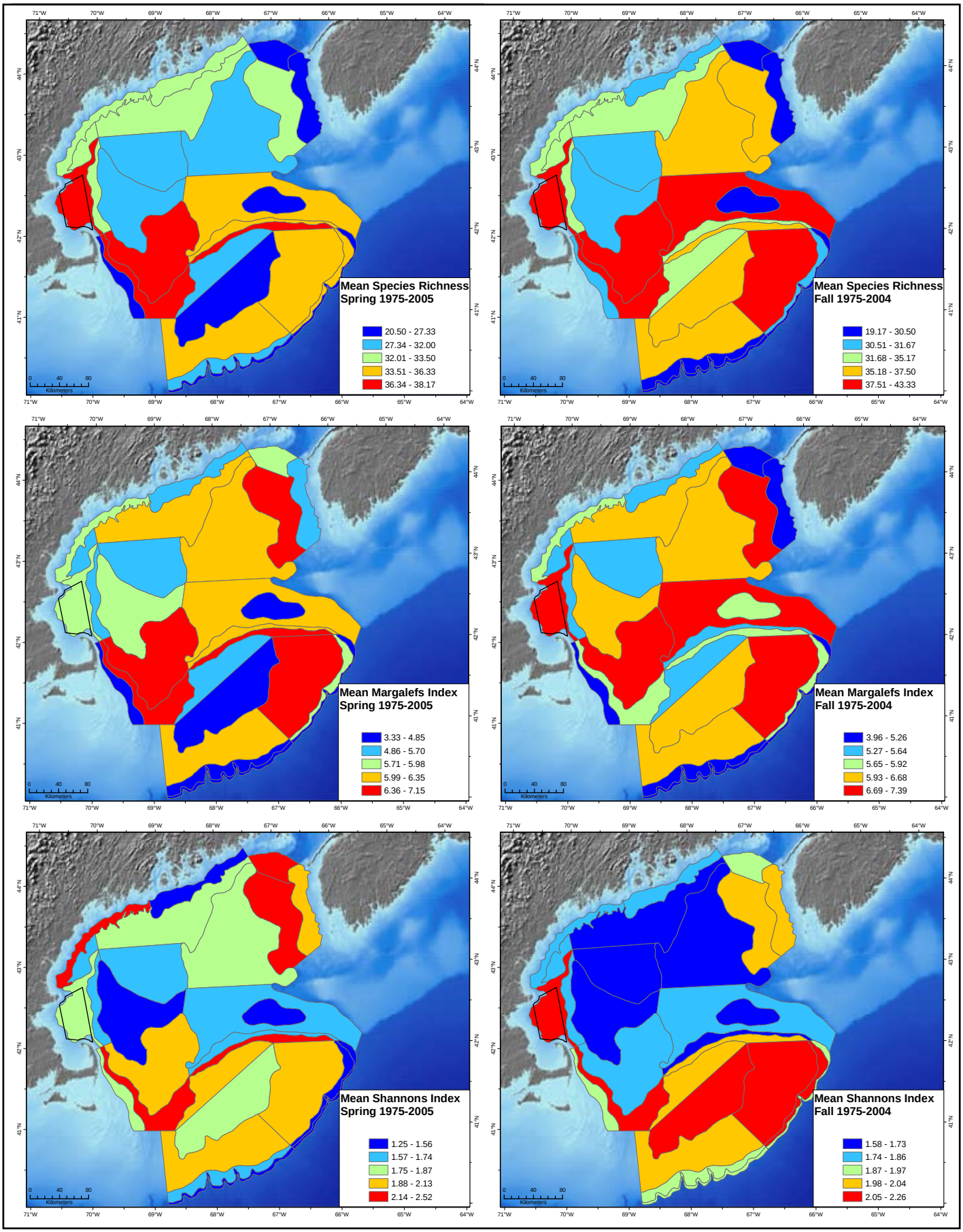

Figure 3.1.5. Seasonal mean diversity for sampling strata across all years.

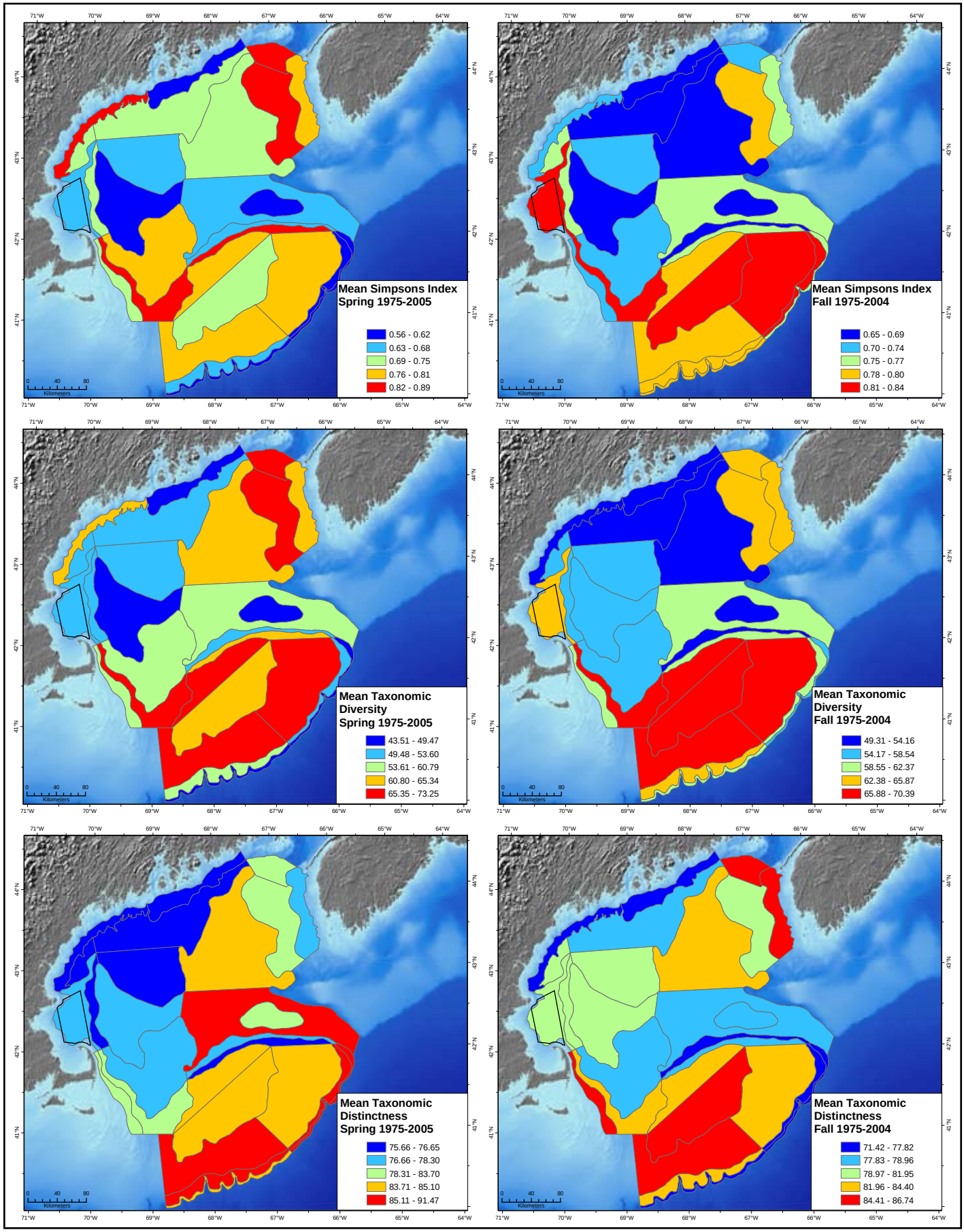

Figure 3.1.5. Continued. Seasonal mean diversity for sampling strata across all years.

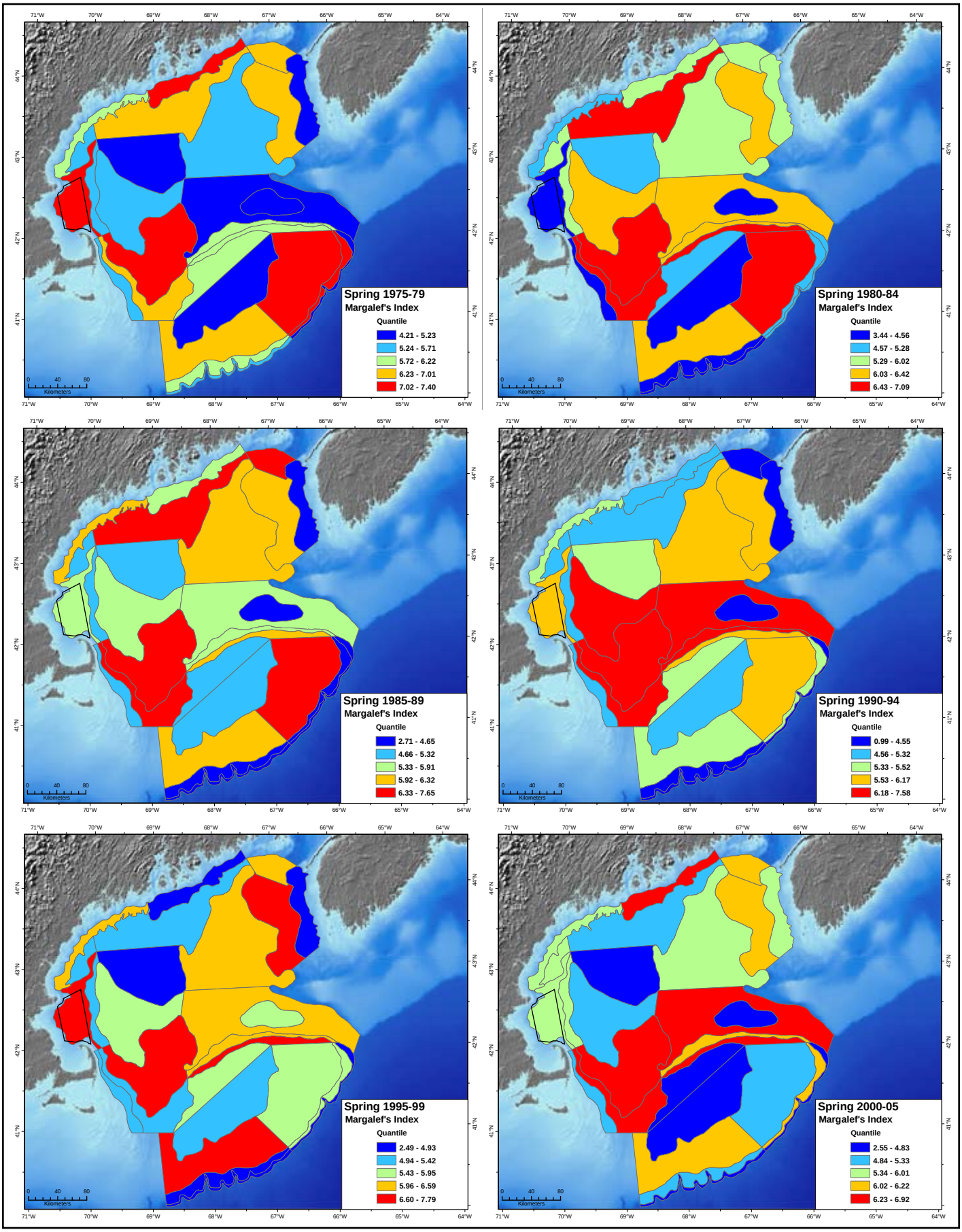

Figure 3.1.6. Margalef's diversity index time-series (five year increments) within NMFS sampling strata, Spring 1975-2005.

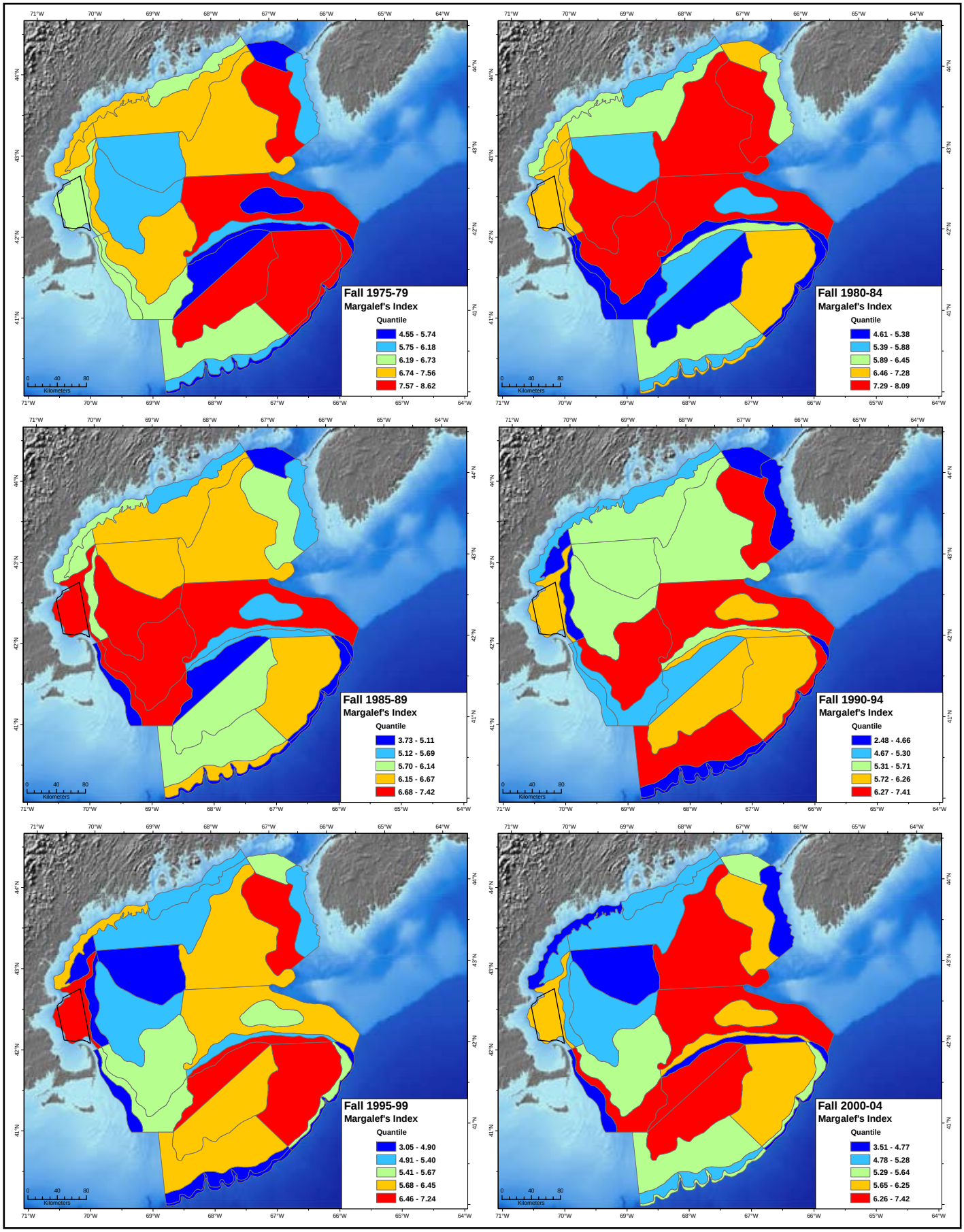

Figure 3.1.7. Margalef's diversity index time-series (five year increments) within NMFS sampling strata, Fall 1975-2004.

eral, the central portion of the Gulf of Maine (strata 1280, 1290, 1300, 1360, 1370) exhibited low diversity throughout the time-series during both spring and fall. For the most part these strata ranked in the lower two quintiles and diversity was infrequently ranked in the third quintile.

Within SBNMS, diversity ranked low between spring 1975-1989, but was in the top quintile during the past 15 years. Fall diversity values using Shannon's Index were moderate (third quintile) between 1975-1984 and increased in the remaining time-series with values in the top two quintiles. Mean diversity across the time-series within SBNMS was similar to the results of Margalef's Index, moderate in the spring and in the top quintile of all strata during the fall (Figure 3.1.5).

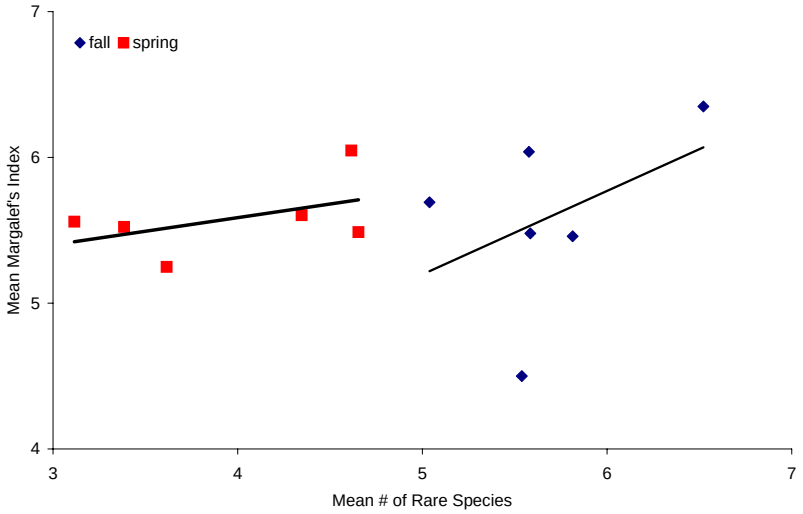

Figure 3.1.8. Mean number of rare species captured by NMFS trawls within seasonal year-bins regressed on mean values for Margalef's diversity index.

Diversity results using Shannon's index were sensitive to rare species. Rare species were enumerated within each strata for each seasonal year-bin and regressed on Shannon diversity values within each strata/seasonal year-bin. Diversity was positively correlated with number of rare species (Figure 3.1.11) and this pattern was more pronounced during fall.

Simpson's Index

Results for species diversity using Simpson's Index is displayed in Figures 3.1.12 and 3.1.13. Similar to the other indices, patterns of diversity were variable across the seasonal time-series. In general, the strata that comprise most of Georges Bank exhibited the most consistent patterns of high diversity.

Considerable variation was observed for Simpson's diversity within SBNMS. Diversity was low during the spring among all strata for the first 15 years of the time-series, then was ranked in the top quintile for the remaining 15 years. During the fall, diversity was low during 1975-1984, then ranked in the top two quintiles between 1985-2004. On average, Simpson's diversity index within SBNMS during spring ranked in the second lowest quintile compared to other strata within the study area and was in the highest quintile during fall (Figure 3.1.5).

The Simpson index was sensitive to species dominance. Abundant species (> 5% of the total abundance) were identified within each seasonal year-bin and regressed on Simpson diversity values (Figure 3.1.14). Strong positive correlations were observed during both seasons between the number of abundant species and diversity.

Taxonomic Diversity

Patterns of taxonomic diversity for the study area are displayed in Figures 3.1.15 and 3.1.16. As evidenced by other diversity indices, considerable variation in taxonomic diversity was observed within the Gulf of Maine. During spring, areas of highest taxonomic diversity generally occurred in the Georges Bank region and off the southwest coast of Nova Scotia. This pattern was also observed during fall.

Taxonomic diversity within SBNMS was low during the first 15 years of the spring time-series and increased during the last 15 years with diversity ranking in the second highest quintile compared to the other strata. During fall, diversity values were low within the Sanctuary during 1975-84 and increased to the second highest quintile during 1985-1994. Taxonomic diversity for the Sanctuary was in the highest quintile during 1995-2004.

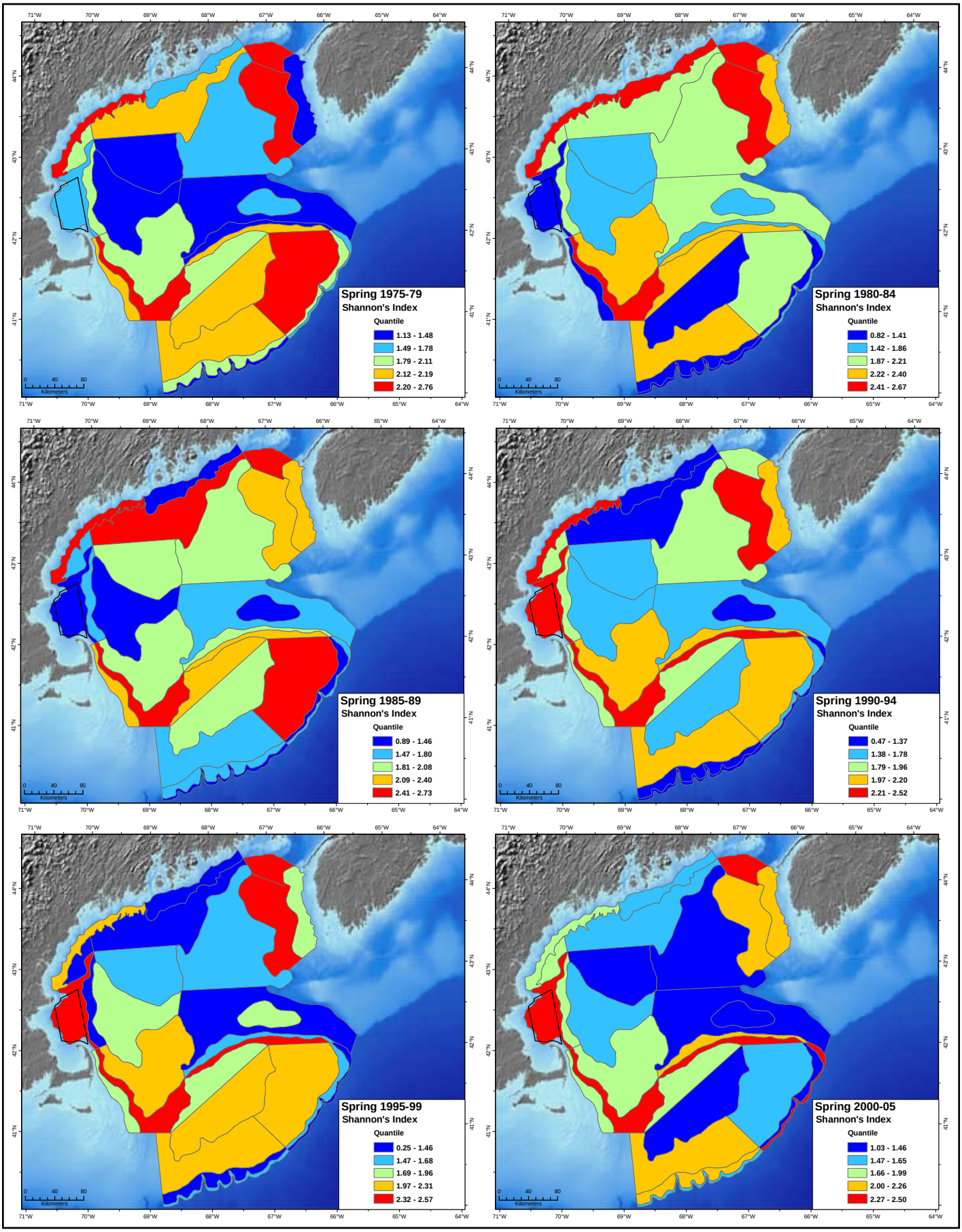

Figure 3.1.9. Shannon's diversity index time-series (five year increments) within NMFS sampling strata, Spring 1975-2005.

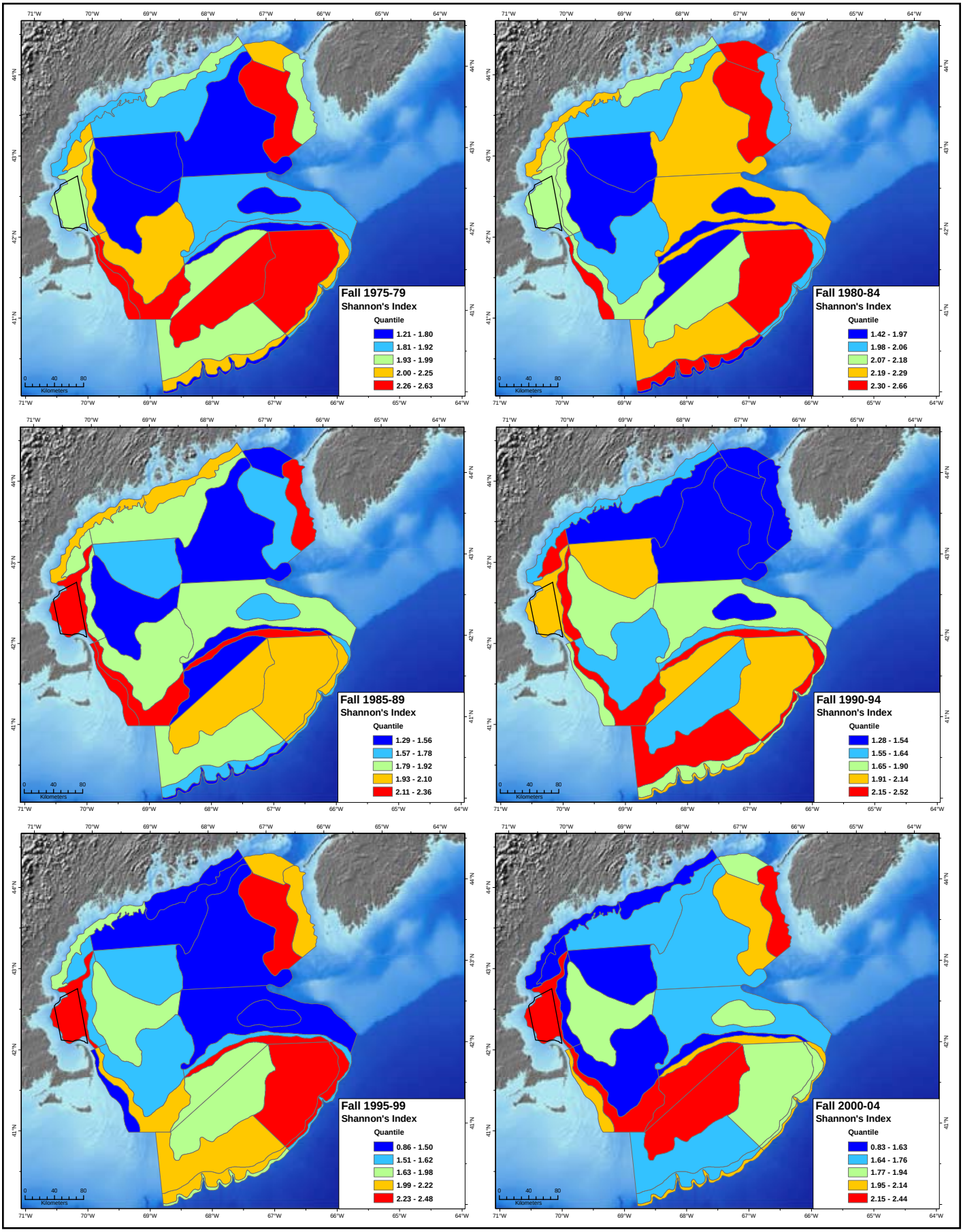

Figure 3.1.10. Shannon's diversity index time-series (five year increments) within NMFS sampling strata, Fall 1975-2004.

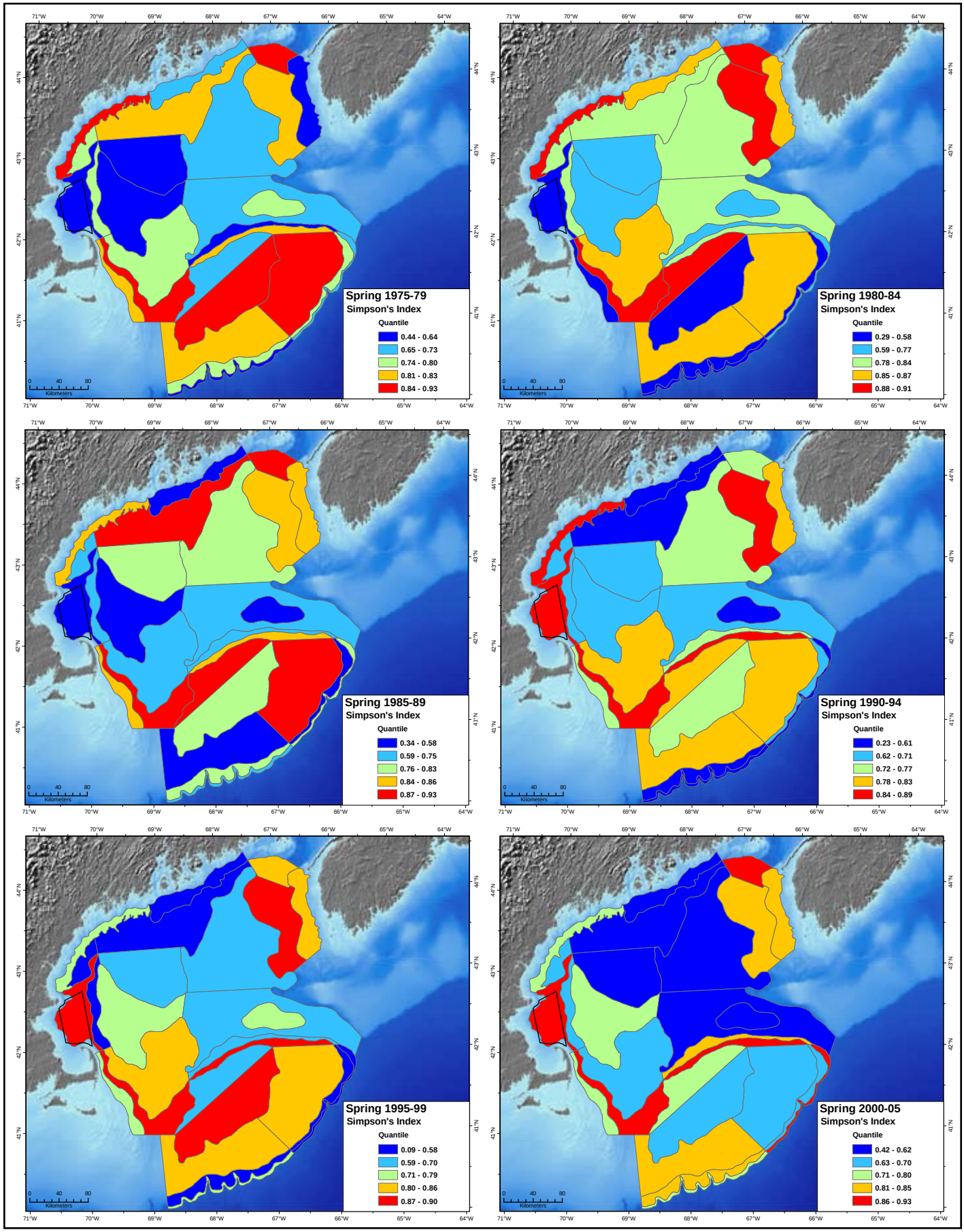

Figure 3.1.12. Simpson's diversity index time-series (five year increments) within NMFS sampling strata, Spring 1975-2005.

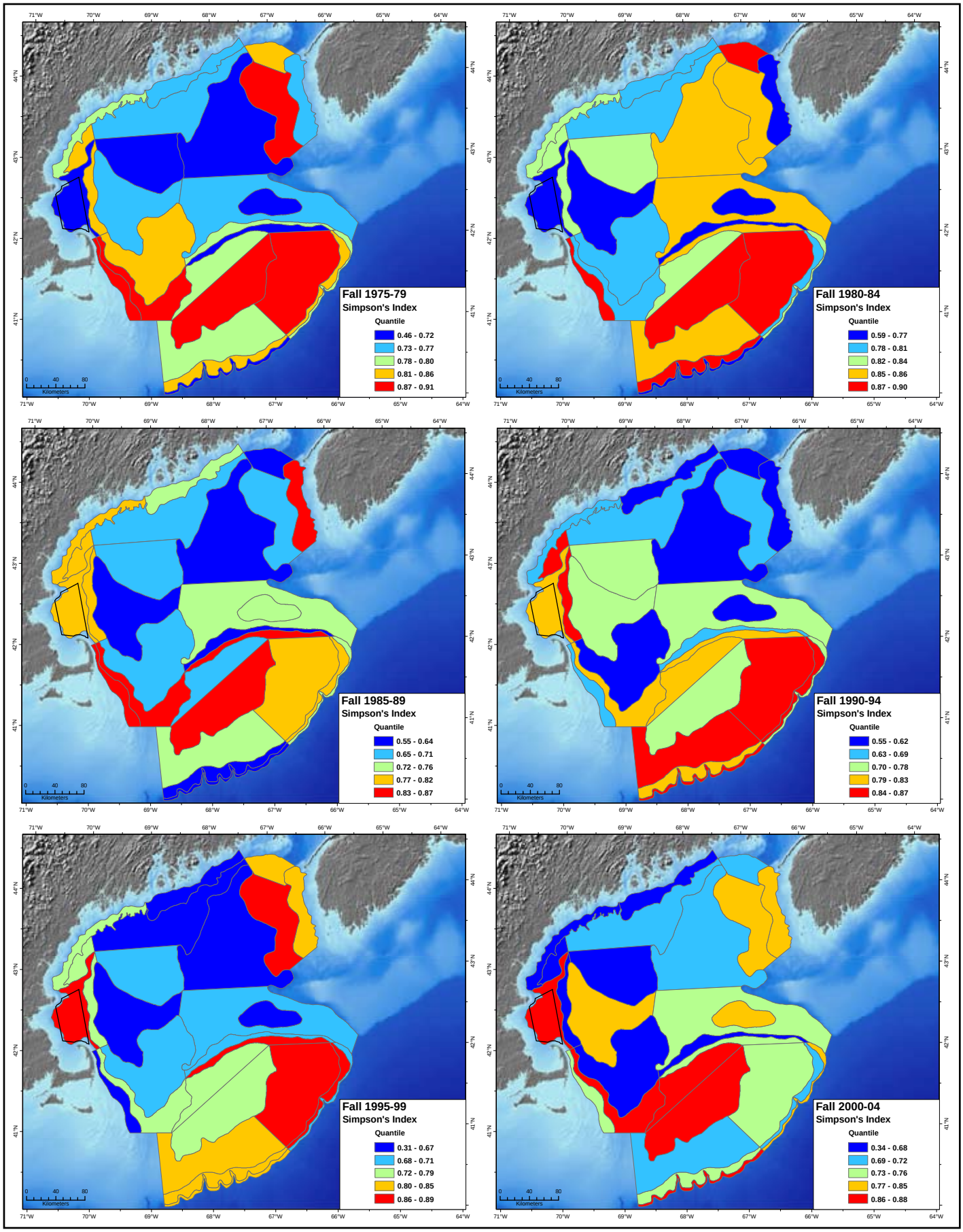

Figure 3.1.13. Simpson's diversity index time-series (five year increments) within NMFS sampling strata, Fall 1975-2004.

Mean seasonal taxonomic diversity within the Sanctuary was not considerably different between spring and fall, however, spring values ranked low in comparison to the remaining study area and were ranked within the second highest quintile during fall (Figure 3.1.5).

Taxonomic diversity was variable among strata through each seasonal time series and patterns through space and time. Some strata, such as 1160 , the eastern flank of Georges Bank) exhibited positive correlation between species richness and taxonomic diversity. In contrast, strata 1260 (the strata contained within SBNMS) had high species richness during spring 1975-1989, but low taxonomic diversity. Patterns of high taxonomic diversity are correlated with similar species compositions and similar relative abundances. For example, low taxonomic diversity was observed within strata 1260 during spring 1975-1989. While species composition was similar to many other strata, the low values result from the influence of high sand lance abundance which skewed evenness among species within the strata.

Taxonomic distinctness

Patterns of taxonomic distinctness were variable throughout the seasonal time-series. In general, Georges Bank exhibited some consistency for high values during spring and the deeper portions of the Gulf were relatively low (Figure 3.1.17). During fall (Figure 3.1.18), most of the western portion of the study area was low throughout the time-series, while the southern portion, including Georges Bank, exhibited high distinctness values.

Fall distinctness patterns within the Sanctuary ranked in the third quintile for all strata and progressively declined through the time-series. Spring values oscillated from high during 1975-79, low during 1990-94, and high again between 1995-2005. Overall, taxonomic distinctness values within the Sanctuary were the lowest diversity measurement among all the indices examined. On average, taxonomic distinctness was low in the spring and moderate during the fall (Figure 3.1.5).

Differences observed between low and high taxonomic distinctness occur between a small range (typically between 75-95) and small differences may affect membership within the quintile distribution. As such, patterns of taxo-

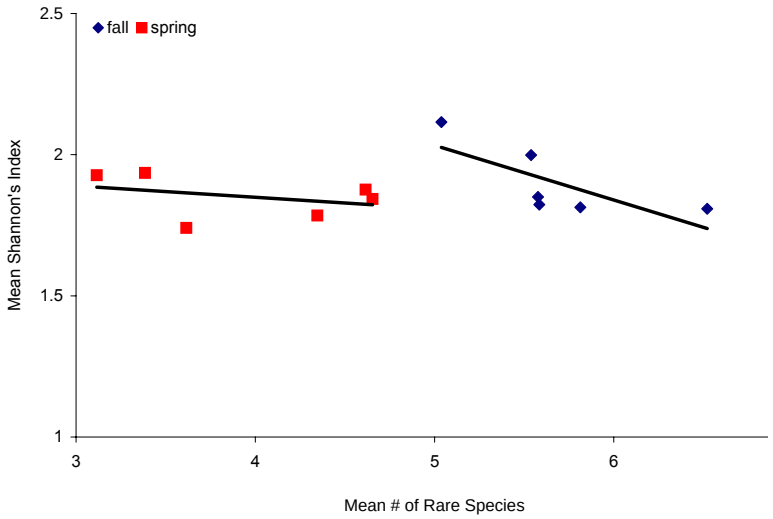

Figure 3.1.11. Mean number of rare species captured by NMFS trawls within seasonal year-bins regressed on mean values for Shannon's diversity index.

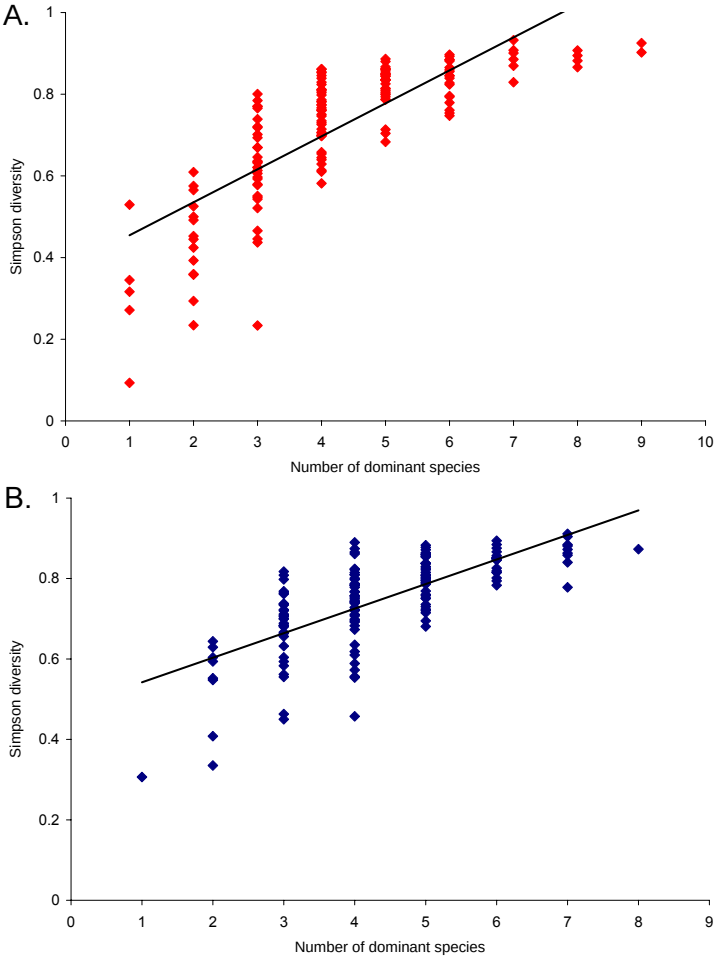

Figure 3.1.14. a)Number of abundant species (> 5% of total abundance) and b) Simpson diversity.

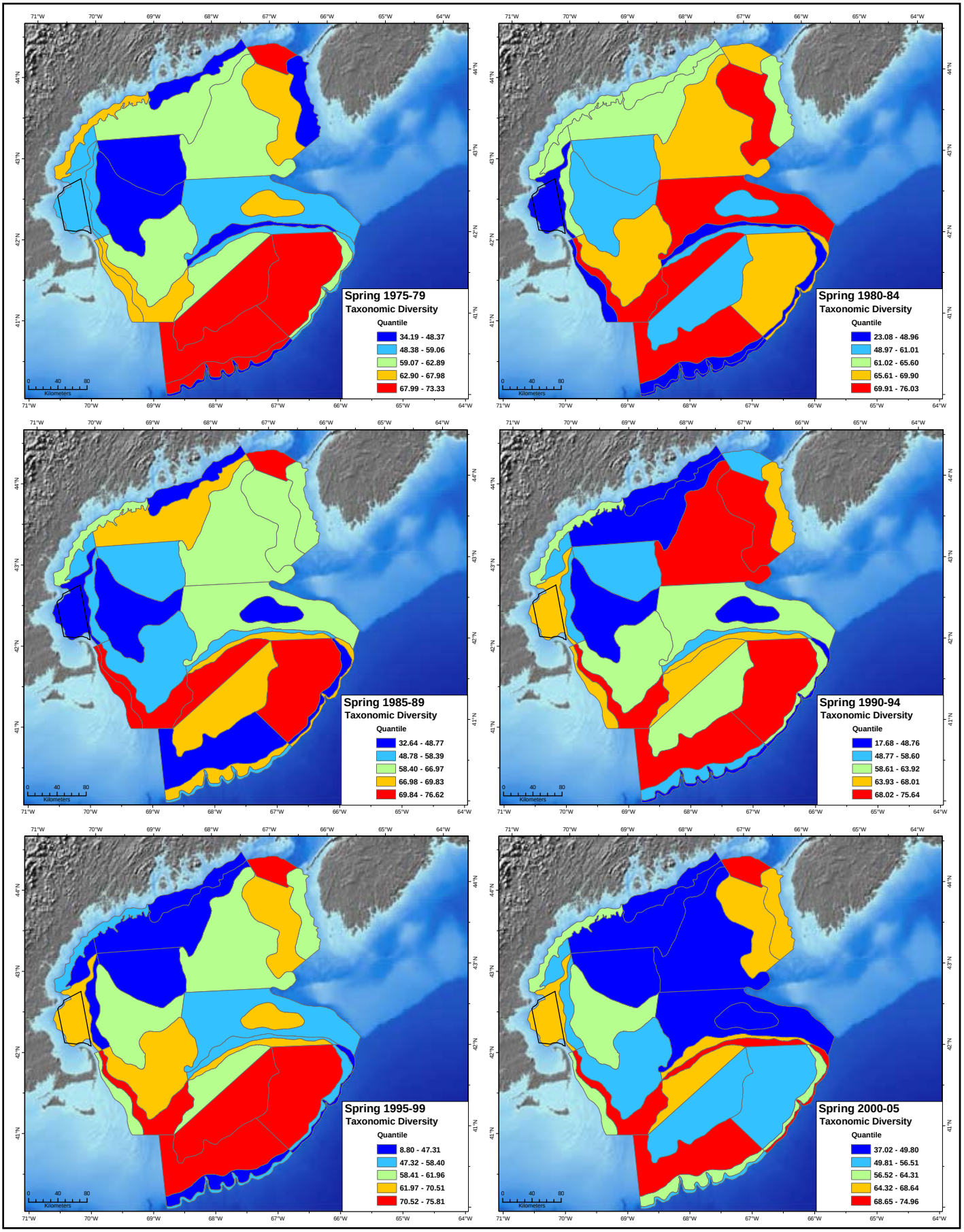

Figure 3.1.15. Taxonomic diversity time-series (five year increments) within NMFS sampling strata, Spring 1975-2005.

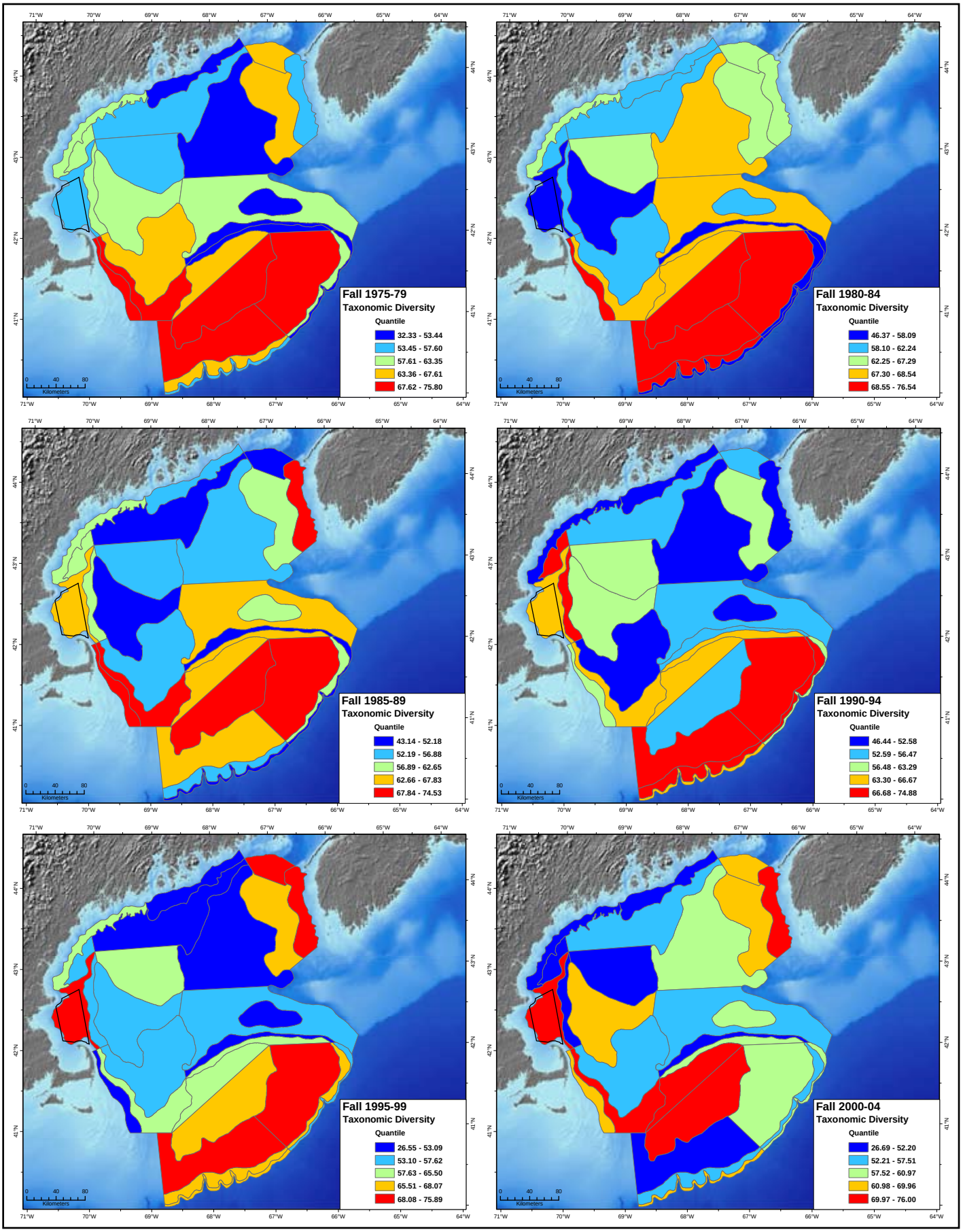

Figure 3.1.16. Taxonomic diversity time-series (five year increments) within NMFS sampling strata, Fall 1975-2004.

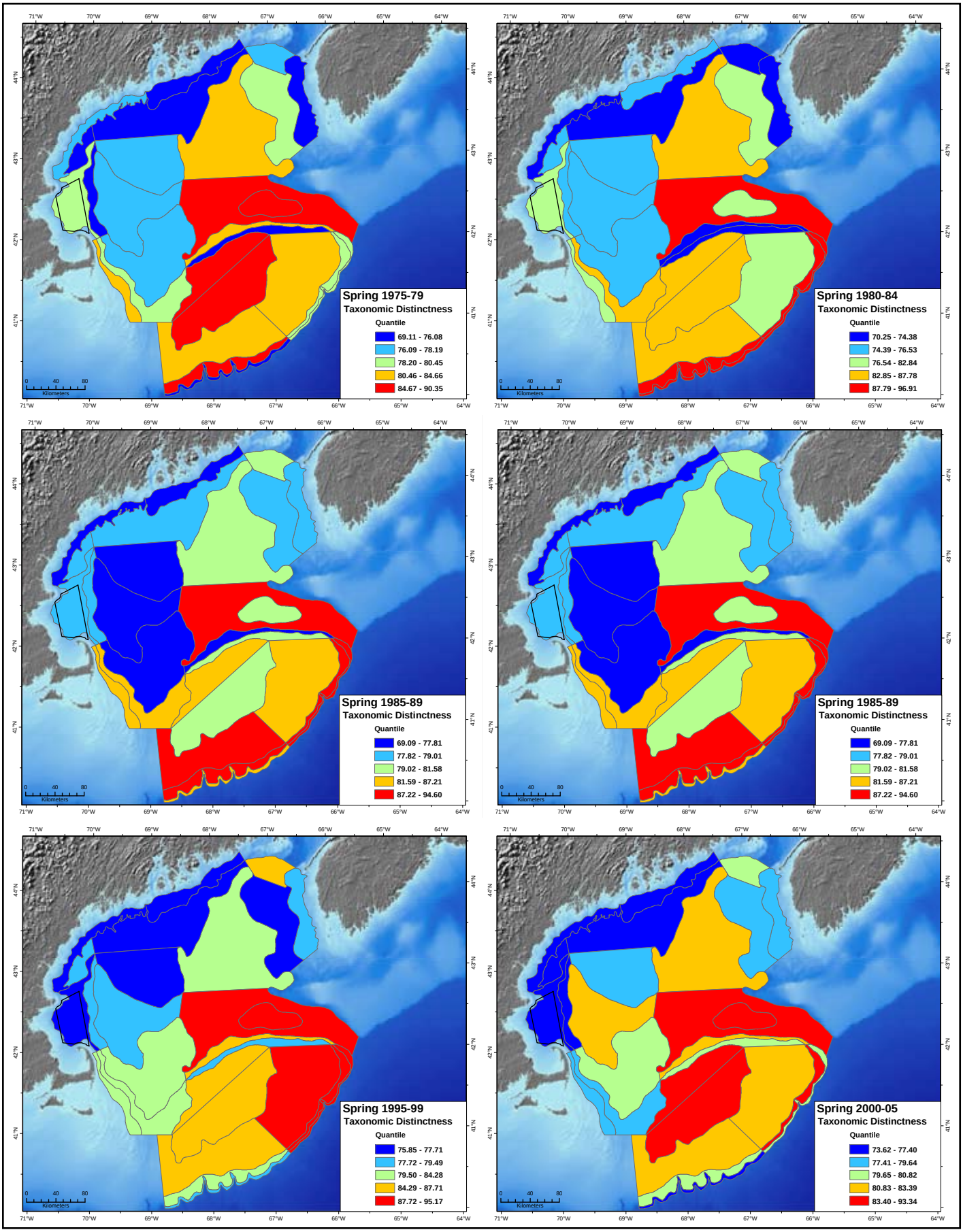

Figure 3.1.17. Taxonomic distinctness time-series (five year increments) within NMFS sampling strata, Spring 1975-2005.

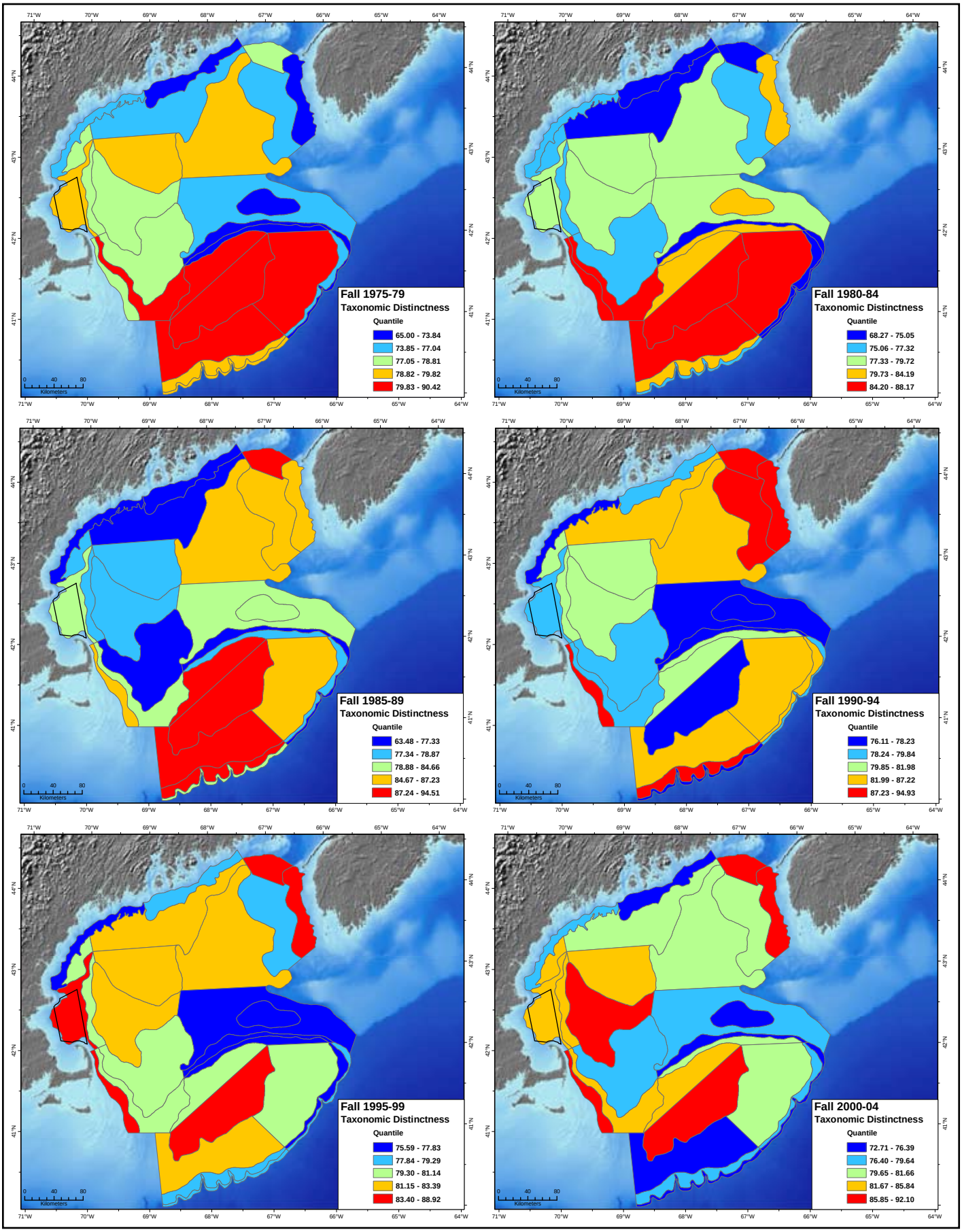

Figure 3.1.18. Taxonomic distinctness time-series (five year increments) within NMFS sampling strata, Fall 1975-2004.

nomic distinctness were consistently high in the strata around Georges Bank during both spring and fall. Little variability occurred within these strata, due in part to the small range of values classified into quintiles. Additional variability results from the influence of dominant species and their effect on community evenness within the strata, although its effect is not as strong as taxonomic diversity.

Patterns of dominance and rarity

Broad-scale comparison of species dominance within the Sanctuary and the Gulf overall exhibited similar trends. Overall, silver hake (*Merluccius bilinearis*) was the most abundant fish species within the study area during spring and fall (Table 3.1.1 and 3.1.2). During spring and fall, fishes dominant in the Gulf of Maine were also dominant in the Sanctuary, however the order of relative abundance shifted. Species composition during spring is comprised of mostly resident species, with some annual migrants present. Migrants were most prevalent during fall. Although the Sanctuary is much smaller in size compared to the rest of the study area, species accumulation curves were relatively similar (Figures 3.1.20, 3.1.21). Within the study area, typically 7-10 species comprised 90% of the numerical abundance of the fish community. Dominance curves for SBNMS and the larger Gulf region were similar for most seasonal year-bins (although species richness was significantly different based on area and sampling effort). An exception to this pattern occurred within Sanctuary samples conducted during spring and fall year-bins between 1975-1989. During these time periods, northern sand lance (*Ammodytes dubius*) dominated trawl abundance within the Sanctuary and alone comprised more than 50% of the total abundance. From a broad-scale perspective, species dominant within the Sanctuary were also dominant throughout the study area, although local and regional differences probably occur when examining data at a finer scale (i.e. habitat types).

The frequency of rare species was greater during fall than spring. As expected, rare species were less frequent within the Sanctuary during both seasons (Tables 3.1.3, 3.1.4) compared to the rest of the Gulf of Maine region (Tables 3.1.5, 3.1.6). Overall, rare species comprised 27% and 41% of spring and fall species composition, respectively, within the Sanctuary. In comparison, rare species comprised 71% and 77% of total species composition within the remainder of the study area. This is to be expected given the difference in area where the larger Gulf of Maine contains greater areas of habitats, including shelf/slope habitat where species composition can be substantially different than that in the Sanctuary. Northern and southern migrants are probably underrepresented in the smaller area of the Sanctuary in comparison to the rest of the Gulf of Maine.

SBNMS/Strata comparison

In order to contrast the uniqueness of SBNMS with other similar regions in the Gulf of Maine, diversity indices within the Sanctuary were compared with other strata that have similar bathymetric ranges (Figure 3.1.19). In general, comparison of diversity indices for the six strata yielded variable results. For some indices diversity patterns were quite similar (spring species richness, fall Shannon's Index) and little correlation among others (fall species richness, spring Margalef's Index). Overall, diversity indices within the Sanctuary were higher than or equal to most of the other strata (Figures 3.1.22, 3.1.23). Of all the strata, 1230 exhibited the most consistent pattern of high diversity index values. The high abundance of sand lance captured within the Sanctuary during spring 1980-1984 severely depressed those diversity index values that are sensitive to changes in dominance.

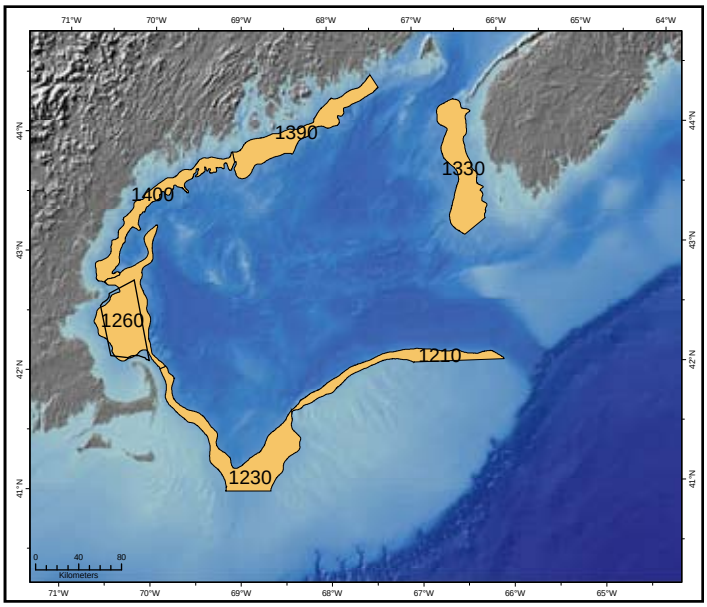

Figure 3.1.19. Strata used to compare diversity indices with SBNMS (strata 1260).

Patterns in species regional and local accumulation curves

There was no obvious effect of strata size on species richness based on the dominance curves (Appendix 14-15). This suggests that differences between strata are the result of factors other than sample size, such as habitat variability and patchiness, spatial varia-

Table 3.1.1. Dominant species within SBNMS and the Gulf of Maine trawl samples, spring 1975-2005. Numbers indicate abundance ranging from 1 (highest) to 10 (lowest).

SBNMS Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-05
Alosa pseudoharengus	Annual Migrant	-	-		-	-	10
Ammodytes dubius	Resident	1	1	1	4	-	-
Clupea harengus	Resident	9	3	2	1	9	4
Gadus morhua	Resident	7	4	6	8	3	5
Glyptocephalus cynoglossus	Estuarine/Coastal	6	7	-	-	-	-
Hippoglossoides platessoides	Resident	2	2	3	3	1	2
Leucoraja ocellata	Resident	-	-	8	-	-	-
Limanda ferruginea	Resident	-	-	10	6	-	9
Lumpenus maculatus	Resident	10	5	-	-	8	-
Macrozoarces americanus	Resident	-	10	4	9	6	-
Melanogrammus aeglefinus	Resident	5	8	-	-	2	6
Merluccius bilinearis	Resident	3	-	9	5	5	8
Myoxocephalus octodecemspinosus	Resident	-	-	5	2	4	1
Pollachius virens	Resident	-	-	7	10	10	-
Pseudopleuronectes americanus	Resident	-	-		-	-	7
Sebastes fasciatus	Resident	4	-	-	7	-	3
Squalus acanthias	Resident	-	6	-	-	-	-
Ulvaria subbifurcata	Estuarine/Coastal	-	9	-	-	-	-
Urophycis chuss	Resident	8	-	-	-	7	-
Gulf of Maine Species	**Residency Code**	**75-79**	**80-84**	**85-89**	**90-94**	**95-99**	**00-05**
Alosa pseudoharengus	Annual Migrant	-	-	-	-	-	9
Ammodytes dubius	Resident	3	1	7	-	-	-
Clupea harengus	Resident	7	8	3	3	4	5
Gadus morhua	Resident	-	10	-	-	-	-
Hippoglossoides platessoides	Resident	6	5	-	-	-	-
Leucoraja erinacea	Resident	8	7	8	5	9	10
Leucoraja ocellata	Resident	-	-	4	7	-	-
Macrozoarces americanus	Resident	-	-	-	9	-	-
Melanogrammus aeglefinus	Resident	2	4	10	10	10	3
Merluccius bilinearis	Resident	1	3	2	1	1	1
Myoxocephalus octodecemspinosus	Resident	-	-	5	4	5	7
Peprilus triacanthus	Annual Migrant	-	-	-	-	8	-
Scomber scombrus	Annual Migrant	-	-	-	-	7	4
Scophthalmus aquosus	Resident	10	-	-	-	-	-
Sebastes fasciatus	Resident	4	9	9	6	2	2
Squalus acanthias	Resident	5	2	1	2	3	6
Urophycis chuss	Resident	9	6	6	8	6	8

Table 3.1.2. Dominant species within SBNMS and the Gulf of Maine trawl samples, fall 1975-2005. Numbers indicate abundance ranging from 1 (highest) to 10 (lowest).

SBNMS Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-04
Alosa pseudoharengus	Annual Migrant	-	5	8	-	-	-
Ammodytes dubius	Resident	1	1	-	-	-	-
Clupea harengus	Resident	-	10	1	1	4	4
Gadus morhua	Resident	5	6	5	7	-	9
Glyptocephalus cynoglossus	Estuarine/Coastal	7	-	-	-	-	-
Hippoglossoides platessoides	Resident	2	2	2	2	3	3
Limanda ferruginea	Resident	9	9	-	8	10	-
Melanogrammus aeglefinus	Resident	4	7	-	-	8	5
Merluccius bilinearis	Resident	3	3	6	3	5	6
Myoxocephalus octodecemspinosus	Resident	-	8	4	4	7	8
Pollachius virens	Resident	-	-	10	10	6	10
Scomber scombrus	Annual Migrant	-	-	3	-	-	-
Sebastes fasciatus	Resident	10	-	7	6	2	2
Squalus acanthias	Resident	6	-	9	9	1	1
Urophycis chuss	Resident	8	4	-	5	9	7

Gulf of Maine Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-04
Ammodytes dubius	Resident	-	6	-	-	-	-
Clupea harengus	Resident	-	-	4	4	3	2
Etrumeus teres	Southern Migrant	-	-	-	-	-	10
Hippoglossoides platessoides	Resident	8	8	-	8	10	-
Leucoraja erinacea	Resident	9	9	-	-	-	-
Leucoraja ocellata	Resident	-	-	10	10	-	-
Melanogrammus aeglefinus	Resident	2	4	8	-	8	4
Merluccius bilinearis	Resident	1	1	1	1	2	1
Myoxocephalus octodecemspinosus	Resident	7	7	6	5	7	8
Peprilus triacanthus	Annual Migrant	5	2	3	3	1	6
Scomber scombrus	Annual Migrant	-	-	-	-	9	9
Sebastes fasciatus	Resident	4	10	7	7	5	3
Squalus acanthias	Resident	3	3	2	2	4	5
Urophycis chuss	Resident	6	5	5	6	6	7
Urophycis tenuis	Resident	10	-	9	9	-	-

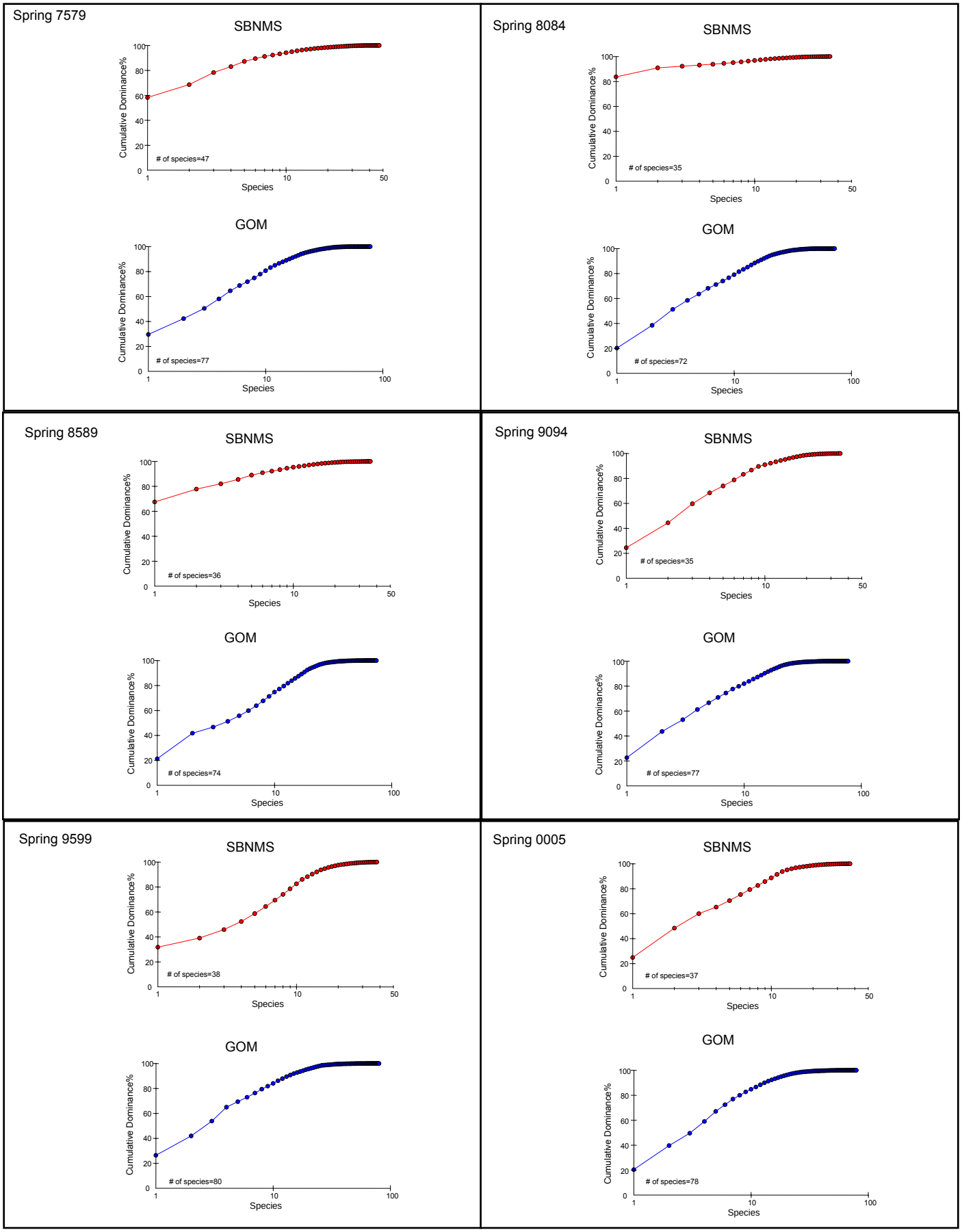

Figure 3.1.20. Species accumulation curves for trawl samples collected within SBNMS compared with the Gulf of Maine region, spring 1975-2005.

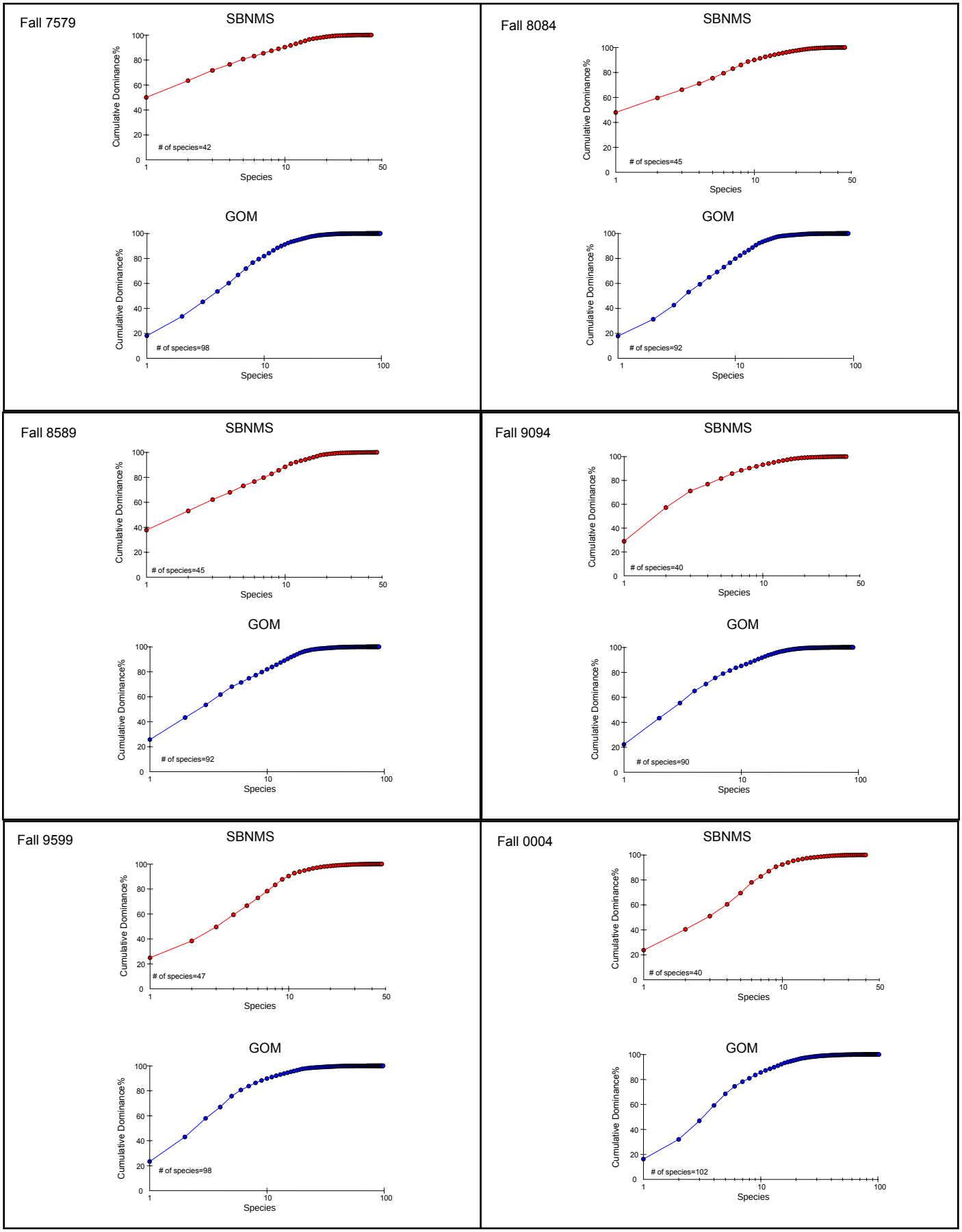

Figure 3.1.21. Species accumulation curves for trawl samples collected within SBNMS compared with the Gulf of Maine region, fall 1975-2004.

Table 3.1.3. Rare species captured in NMFS trawl samples within SBNMS, spring 1975-2005. Species are ranked from 1 (most rare)-10 (least rare). Residency code is the residency classification (Auster, 2002) * species not found in species list compiled by Auster, 2002.

SBNMS Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-05
Alosa aestivalis	Annual Migrant	-	-	5	4	-	-
Alosa sapidissima	Annual Migrant	1	7	1	4	1	-
Amblyraja radiata	Resident	-	-	-	10	-	9
Ammodytes americanus	Resident	-	-	-	-	-	10
Ammodytes dubius	Resident	-	-	-	-	10	2
Anarhichas lupus	Resident	-	-	-	7	10	6
Apeltes quadracus	Estuarine/Coastal	1	-	-	-	-	-
Aspidophoroides monopterygius	Resident	-	-	7	-	8	3
Brosme brosme	Resident	7	4	2	2	-	1
Cryptacanthodes maculatus	Resident	3	2	-	1	-	1
Cyclopterus lumpus	Resident	1	-	2	2	2	-
Enchelyopus cimbrius	Resident	-	-	4	-	7	7
Eumicrotremus spinosus	Western Migrant	1	-	-	-	-	-
Glyptocephalus cynoglossus	Resident	-	-	9	3	2	-
Helicolenus dactylopterus	Slope/ Mesopelagic	9	-	-	-	-	-
Hippoglossus hippoglossus	Resident	5	-	-	-	-	-
**Lepophidium profundorum*	Southern Migrant	-	-	3	-	-	-
Leucoraja erinacea	Resident	6	-	8	-	-	-
Leucoraja ocellata	Resident	-	8	-	-	4	8
**Liparis inquilinus*	Resident	-	-	2	-	-	-
Lophius americanus	Resident	-	5	1	-	3	4
Lumpenus lumpretaeformis	Resident	8	-	-	-	3	-
Lumpenus maculatus	Resident	-	-	-	-	-	8
Lycenchelys verrilli	Slope/ Mesopelagic	3	-	-	-	-	-
Malacoraja senta	Resident	-	4	4	-	-	4
Melanogrammus aeglefinus	Resident	-	-	-	9	-	-
Melanostigma atlanticum	Slope/ Mesopelagic	1	-	-	-	5	1
Morone saxatilis	Annual Migrant	-	-	-	-	1	-
Myoxocephalus aenaeus	Estuarine/Coastal	2	-	-	1	-	1
Myxine glutinosa	Resident	-	1	-	-	9	-
Paralichthys oblongus	Resident	-	6	6	8	-	-
Pollachius virens	Resident	-	10	-	-	-	-
**Reinhardtius hippoglossoides*	Northern Migrant	-	-	-	-	1	-
Scomber scombrus	Annual Migrant	-	-	-	-	2	1
Scophthalmus aquosus	Resident	4	-	10	5	1	5
Tautogolabrus adspersus	Resident	3	3	6	6	-	-
Triglops murrayi	Resident	10	5	-	1	-	-
Ulvaria subbifurcata	Estuarine/Coastal	-	-	3	1	-	-
Urophycis tenuis	Resident	-	9	-	7	6	6

Table 3.1.4. Rare species captured in NMFS trawl samples within SBNMS, fall 1975-2004. Species are ranked from 1 (most rare)-10 (least rare). Residency code is the residency classification described in Auster, 2002. * not found in species list compiled by Auster, 2002.

SBNMS Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-04
Alosa aestivalis	Annual Migrant	8	8	7	1	2	-
Alosa pseudoharengus	Annual Migrant	-	-	-	7	-	-
Alosa sapidissima	Annual Migrant	2	6	6	-	8	5
Amblyraja radiata	Resident	-	-	-	-	-	10
Ammodytes dubius	Resident	-	-	1	-	-	-
Anarhichas lupus	Resident	-	-	8	-	5	7
Ariomma bondi	Southern Migrant	-	-	-	1	-	-
**Artediellus spp.*	?	-	4	5	8	2	4
Aspidophoroides monopterygius	Resident	6	6	4	10	8	1
Brevoortia tyrannus	Annual Migrant	-	1	-	2	-	-
Brosme brosme	Resident	7	2	3	1	1	3
Centropristis striata	Southern Migrant	1	-	2	-	1	-
Citharichthys arctifrons	Resident	-	-	-	-	1	-
Cryptacanthodes maculatus	Resident	-	3	2	8	2	4
Cyclopterus lumpus	Resident	3	-	1	-	2	-
Enchelyopus cimbrius	Resident	-	-	-	-	6	8
Gasterosteus aculeatus	Estuarine/Coastal	1	-	2	2	-	2
Glyptocephalus cynoglossus	Resident	-	-	10	-	10	-
Hippoglossus hippoglossus	Resident	4	1	1	-	3	-
Lepophidium profundorum	Resident	-	-	1	-	-	-
Leucoraja erinacea	Resident	-	-	5	-	4	-
Leucoraja ocellata	Resident	-	5	-	8	9	2
Lophius americanus	Resident	10	9	4	-	7	-
Lumpenus lumpretaeformis	Resident	-	1	-	-	1	-
Lumpenus maculatus	Resident	3	-	1	1	5	-
Lycenchelys verrilli	Southern Migrant	-	-	3	-	-	-
Malacoraja senta	Resident	5	2	2	4	4	-
Maurolicus weitzmani	Slo/Meso	1	-	-	8	8	9
Melanostigma atlanticum	Slo/Meso	-	-	-	-	2	1
Merluccius albidus	Slo/Meso	-	-	-	-	-	2
Myxine glutinosa	Resident	-	7	1	5	1	1
Nemichthys scolopaceus	Slo/Meso	2	-	-	-	-	-
Paralichthys oblongus	Resident	6	10	9	6	-	6
Peprilus triacanthus	Annual Migrant	-	-	-	4	-	-
**Pomatomus saltatrix*	Estuarine/Coastal	-	-	-	-	-	2
Prionotus carolinus	Resident	-	3	-	-	-	-
Psuedopleuronectes americanus	Resident	7	-	10	-	-	-
Petromyzon marinus	Resident	-	-	-	-	1	-
Scomber scombrus	Annual Migrant	-	-	-	4	-	7
Scomberesox saurus	Annual Migrant	1	-	1	-	-	-
Scophthalmus aquosus	Resident	-	2	-	3	4	1
Stenotomus chrysops	Southern Migrant	-	3	-	-	-	-
Syngnathus fuscus	Estuarine/Coastal	-	3	-	-	-	-
Tautogolabrus adspersus	Resident	5	-	5	1	7	-
Triglops murrayi	Resident	3	-	3	6	1	1
Ulvaria subbifurcata	Estuarine/Coastal	-	2	1	-	-	-
Urophycis regia	Southern Migrant	9	1	-	-	-	-

Table 3.1.5. Rare species captured in NMFS trawl samples within the Gulf of Maine, spring 1975-2005. Species are ranked from 1 (most rare)-10 (least rare). Residency code is the residency classification (Auster, 2002) * species not found in species list compiled by Auster, 2002.

Gulf of Maine Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-05
Anchoa hepsetus	Southern Migrant	-	-	-	-	1	-
Antigonia capros	Southern Migrant/Slope/Mesopelagic	-	-	1	-	-	-
Arctozenus rissoi	Slope/Mesopelagic	-	-	-	-	1	1
Argentina striata	Southern Migrant	-	-	-	2	-	3
Centropristis striata	Southern Migrant	-	-	-	1	-	-
**Ceratoscopelus maderensis*	Slope/Mesopelagic		4				
Chauliodus sloani	Slope/Mesopelagic	-	-	-	-	1	-
Chaunax stigmaeus	Slope/Mesopelagic	-	-	1	-	-	-
Chlorophthalmus agassizi	Slope/Mesopelagic		6		3	7	7
Coelorhynchus carminatus	Slope/Mesopelagic	-	1	-	-	-	-
**Conger oceanicus*	Resident	2	1	3	2	4	1
Cryptacanthodes maculatus	Resident	9		9			10
Cyclopterus lumpus	Resident	10			7	9	
Dipturus laevis	Resident	7	2	4	10	-	-
Epigonus pandionis	Southern Migrant	-	-	-	-	-	1
Etropus microstomus	Southern Migrant	-	-	1	1	2	-
Eumicrotremus spinosus	Western Migrant	1	-	-	-	-	-
Foetorepus agassizi	Southern Migrant	-	-	-	-	5	5
Gasterosteus aculeatus	Estuarine/Coastal	-	-	2	2	1	1
Hyperoglyphe perciformis	Resident	1	-	-	-	-	-
Leucoraja garmani	Southern Migrant	-	-	-	-	1	-
Liparis atlanticus	Resident		9	5		10	
**Liparis inquilinus*	Resident	3	-	1	-	-	-
Lopholatilus chamaeleonticeps	Slope/Mesopelagic	1	-	-	-	-	1
Lumpenus lumpretaeformis	Resident				4	8	
Lycenchelys verrilli	Slope/Mesopelagic		8	2	3	6	9
Macrourus berglax	Slope/Mesopelagic	1	-	-	-	-	-
Malacocephalus occidentalis	Slope/Mesopelagic	-	-	-	-	1	-
**Mallotus villosus*	Northern Migrant	6	4				
Maurolicus weitzmani	Slope/Mesopelagic		4				
Menidia menidia	Estuarine/Coastal	-	-	2	2	-	-
Merluccius albidus	Slope/Mesopelagic	-	-	-	10	4	4
Monolene sessilicauda	Slope/Mesopelagic	-	-	-	-	-	1
Mustelus canis	Southern Migrant	-	-	1	-	-	-
Myoxocephalus aenaeus	Estuarine/Coastal	2	-	7	-	-	-
Myoxocephalus scorpius	Resident	3	-	-	-	-	5
Myxine glutinosa	Resident			8	9		
**Nemichthys scolopaceus*	Slope/Mesopelagic	-	1	-	1	5	5
Nezuia bairdi	Slope/Mesopelagic	2	-	-	-	-	-
**Ogcocephalus corniger*	Southern Migrant	5					
Ogcocephalus nasutus	Southern Migrant	1	-	-	1	-	-
Ophichthus cruentifer	Southern Migrant	-	-	-	1	-	-
Othropristis chrysoptera	Southern Migrant	-	1	-	-	-	-
Osmerus mordax	Estuarine/Coastal	-	10	1	-	-	-

Table 3.1.5. Continued.

Gulf of Maine Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-05
Paralepis coregonoides	Slope/Mesopelagic	-	-	-	2	-	-
Parasudis truculenta	Slope/Mesopelagic	-	-	1	1	1	-
Peristedion miniatum	Slope/Mesopelagic	2	-	-	-	1	7
Petromyzon marinus	Resident	6	1	1	8	4	6
Pholis gunnellus	Estuarine/Coastal	6	3	6	1	4	2
**Polyipnus clarus*	Slope/Mesopelagic	-	-	1	-	-	-
Prionotus carolinus	Resident	3	8			7	
**Reinhardtius hippoglossoides*	Northern Migrant	-	-	1	-	1	10
Selar crumenophthalmus	Southern Migrant					2	
Simenchelys parasiticus	Slope/Mesopelagic			2			
Stenotomus chrysops	Southern Migrant	-	-	-	1	-	-
**Sternoptychidae*	Slope/Mesopelagic		7			3	
**Stomias boa*	Slope/Mesopelagic	-	-	-	1	-	-
**Symphurus plagiusa*	Southern Migrant	-	-	1	-	1	-
Syngnathus fuscus	Estuarine/Coastal	1	1	-	7	5	5
Tautoga onitis	Estuarine/Coastal	4		2			
Torpedo nobiliana	Southern Migrant	2	1	-	-	-	-
Trichiurus lepturus	Slope/Mesopelagic	-	1	-	-	-	-
Ulvaria subbifurcata	Estuarine/Coastal				6		
**Urophycis chesteri*	Slope/Mesopelagic			10		8	
Urophycis regia	Southern Migrant	8	5				
**Zenopsis conchifera*	Slope/Mesopelagic	1	-	-	5	1	8

Table 3.1.6. Rare species captured in NMFS trawl samples within the Gulf of Maine, fall 1975-2004. Species are ranked from 1 (most rare)-10 (least rare). Residency code is the residency classification described in Auster, 2002. * not found in species list compiled by Auster, 2002.

Gulf of Maine							
Species	**Residency Code**	**75-79**	**80-84**	**85-89**	**90-94**	**95-99**	**00-04**
Acipenser oxyrhynchus	Annual Migrant	-	-	-	-	-	-
**Alosa mediocris*	Resident	5	1	-	-	-	-
Aluterus schoepfi	Southern Migrant	-	-	1	-	-	-
Ammodytes americanus	Resident	-	-	-	-	-	5
Anarhichas lupus	Resident	-	-	-	-	-	8
Amchoa hepsetus	Southern Migrant	-	2	5	-	-	-
**Anchoa mitchilli*	Southern Migrant	6	-	1	2	7	1
Anguilla rostrata	Annual Migrant	-	-	-	-	-	-
**Antigonia capros*	Slope/Mesopelagic	-	-	-	-	-	-
Apeltes quadracus	Estuarine/Coastal	-	-	1	-	-	-
**Archosargus probatocephalus*	Southern Migrant	-	-	-	-	1	-
Arctozenus rissoi	Slope/Mesopelagic	-	2	-	5	-	1
Ariomma bondi	Southern Migrant	-	1	1	-	5	9
**Balistes capriscus*	Southern Migrant	-	1	-	-	-	3
Brevoortia tyrannus	Annual Migrant	3	-	4	-	-	-
**Caranx crysos*	Southern Migrant	1	-	-	2	-	-
**Centropristis ocyurus*	Southern Migrant	-	-	-	-	-	1
Centropristis striata	Southern Migrant	4	-	-	1	1	-
Chauliodus sloani	Slope/Mesopelagic	-	1	1	-	2	-
Chaunax stigmeus	Slope/Mesopelagic	-	-	-	1	-	-
Chlorophthalmus agassizi	Slope/Mesopelagic	-	-	4	5	-	-
**Conger oceanicus*	Resident	2	1	-	3	1	1
**Cookeolus japonicus*	Southern Migrant	-	-	-	-	-	1
Cryptacanthodes maculatus	Resident	5	10	-	-	-	-
**Cubiceps pauciradiatus*	Slope/Mesopelagic	-	-	-	3	-	-
Cyclopterus lumpus	Resident	-	-	9	8	10	-
Dactylopterus volitans	Southern Migrant	-	-	-	-	4	2
Decapterus macarellus	Southern Migrant	-	3	2	9	5	-
Decapterus punctatus	Southern Migrant	1	-	5	-	5	2
Dipturus laevis	Resident	-	2	6	-	-	-
Engraulis eurystole	Southern Migrant	-	8	6	-	-	-
Etropus microstomus	Southern Migrant	-	-	3	-	-	-
Etrumeus teres	Southern Migrant	-	4	8	-	1	-
**Fistularia petimba*	Southern Migrant	-	-	-	-	1	-
**Fistularia tabacaria*	Southern Migrant	-	1	-	-	-	-
Foetorepus agassizzi	Southern Migrant	-	-	1	-	-	7
Gasterosteus aculeatus	Estuarine/Coastal	4	-	-	-	-	-
**Hyporhamphus unifasciatus*	Southern Migrant	2	-	-	-	-	1
**Laemonema barbatulum*	Southern Migrant	-	-	-	-	-	1
Leucoraja garmani	Southern Migrant	-	-	-	-	-	1
Liparis atlanticus	Resident	9	8	1	-	-	3
Lumpenus lumpretaeformis	Resident	3	4	-	3	3	-
Lumpenus maculatus	Resident	1	5	-	-	-	-
Lycenchelys verrilli	Slope/Mesopelagic	2	2	5	-	1	4
Lycodes reticulatus	Western Migrant	1	-	-	-	-	-

Table 3.1.6. Continued.

Gulf of Maine Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-04
Macrorhamphosus scolopax	Slope/Mesopelagic	-	-	1	-	-	-
Malacocephalus occidentalis	Slope/Mesopelagic	-	-	-	-	-	3
Maurolicus weitzmani	Slope/Mesopelagic	-	9	-	-	-	-
Melanostigma atlanticum	Slope/Mesopelagic	8	-	-	-	-	-
**Menticirrhus saxatilis*	Southern Migrant	-	-	-	-	1	-
Merluccius albidus	Slope/Mesopelagic	-	-	-	10	6	8
Menidia menidia	Estuarine/Coastal	1	7	7	-	-	2
Monacanthus hispidus	Southern Migrant	5	5	2	8	2	2
**Monolene sessilicauda*	Slope/Mesopelagic	2	3	-	-	-	-
Morone saxatilis	Annual Migrant	-	-	-	2	-	-
Mustelis canis	Southern Migrant	3	6	4	-	8	-
Myoxocephalus aenaeus	Estuarine/Coastal	10	3	7	-	-	-
Myoxocephalus scorpius	Resident	2	-	-	-	9	-
Naucrates ductor	Southern Migrant	1	-	-	-	-	-
Nemichthys scolopaceus	Slope/Mesopelagic	-	-	-	-	1	1
Nezumia bairdi	Slope/Mesopelagic	-	1	1	7	4	4
Ophichthus cruentifer	Southern Migrant	1	1	3	7	-	-
**Ophidion selenops*	Southern Migrant	-	-	-	-	1	-
Opsanus tau	Southern Migrant	1	-	-	-	-	-
Osmerus mordax	Estuarine/Coastal	1	-	-	-	-	-
Peristedion miniatum	Slo/Meso	-	1	-	-	1	-
Petromyzon marinus	Resident	3	-	-	-	-	-
Pholis gunnellus	Estuarine/Coastal	3	2	-	3	2	6
**Polymetme thaeocoryla*	Slope/Mesopelagic	-	-	-	-	1	-
**Polyipnus clarus*	Slope/Mesopelagic	1	4	-	-	4	-
Priacanthus arenatus	Southern Migrant	-	1	-	-	-	10
Prionotus evolans	Southern Migrant	-	-	-	-	1	3
Pristigenys alta	Southern Migrant	-	-	1	-	-	-
**Reinhardtius hippoglossoides*	Northern Migrant	-	-	-	4	-	2
**Rhomboplites aurorubens*	Southern Migrant	-	-	-	-	3	-
Sarda sarda	Southern Migrant	-	-	-	1	2	-
**Scomber japonicus*	Southern Migrant	-	-	-	-	1	-
Scomberesox saurus	Annual Migrant	-	-	-	10	6	-
**Scyliorhinus retifer*	Southern Migrant	-	-	-	1	-	-
Selar crumenophthalmus	Southern Migrant	7	-	-	1	-	-
Selene setapinnis	Southern Migrant	2	-	-	-	-	-
Selene vomer	Southern Migrant	1	1	-	-	-	-
Seriola zonata	Southern Migrant	2	-	-	-	-	-
Simenchelys parasiticus	Slope/Mesopelagic	2	-	-	-	-	-
Sphoeroides maculatus	Southern Migrant	-	-	2	-	-	2
Syngnathus fuscus	Estuarine/Coastal	-	-	10	10	-	-
**Symphurus civitatus*	Slope/Mesopelagic	-	-	-	-	-	1
**Symphurus diomedianus*	Southern Migrant	-	-	-	1	-	-
**Symphurus plagiusa*	Southern Migrant	-	-	5	-	-	2

Table 3.1.6. Continued.

Gulf of Maine Species	Residency Code	75-79	80-84	85-89	90-94	95-99	00-04
Tautoga onitis	Estuarine/Coastal	-	1	3	4	1	1
Torpedo nobiliana	Southern Migrant	2	-	1	3	6	3
Trachurus lathami	Southern Migrant	1	8	3	2	2	4
**Urophycis chesteri*	Slope/Mesopelagic	-	-	-	-	8	-
Ulvaria subbifurcata	Estuarine/Coastal	10	-	-	6	2	6
**Zenopsis conchifera*	Slope/Mesopelagic	-	9	6	-	5	4

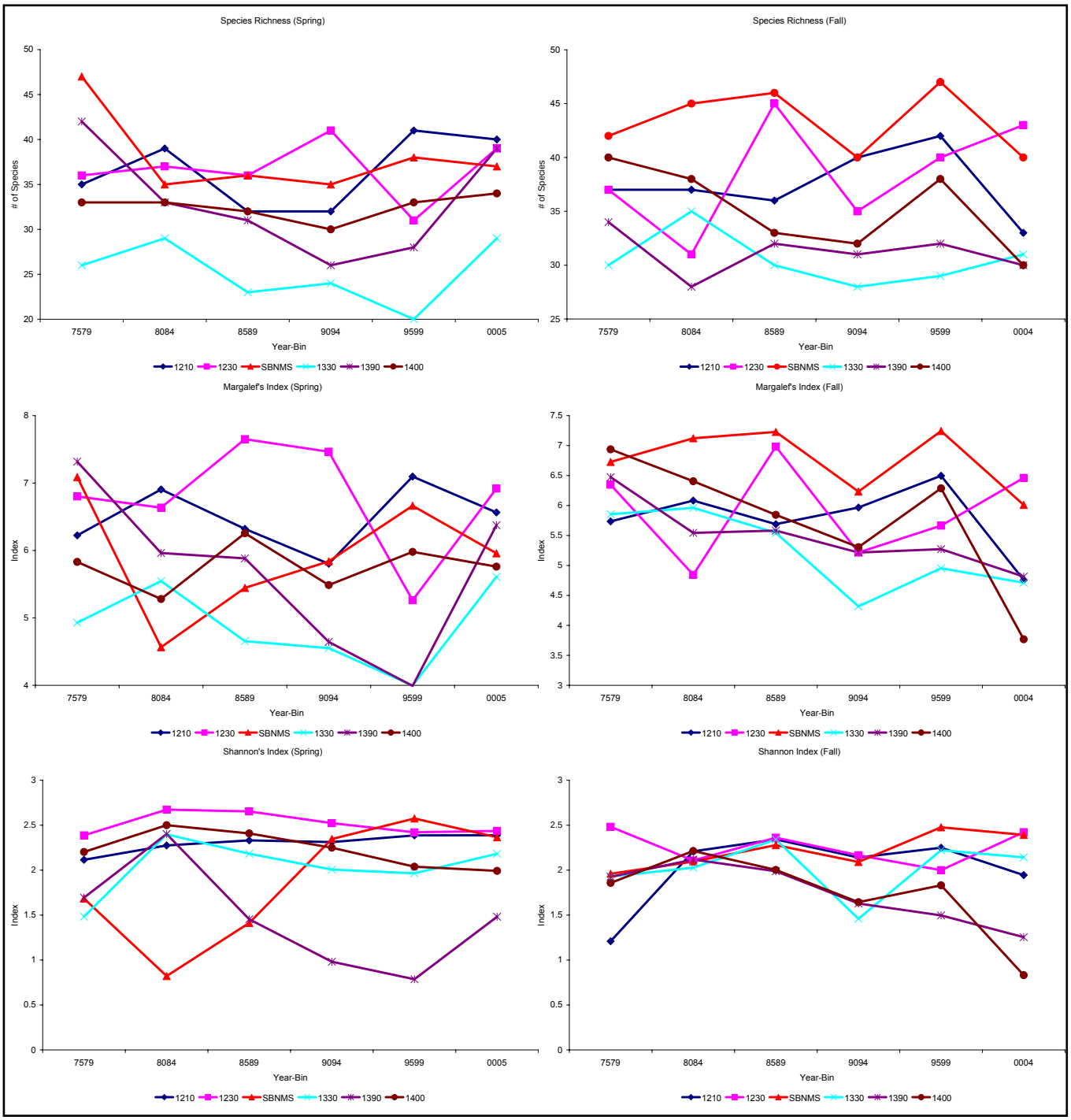

Figure 3.1.22. Diversity comparisons (species richness, Margalef and Shannon's Index) between SBNMS and other strata within the region with similar bathymetric profiles.

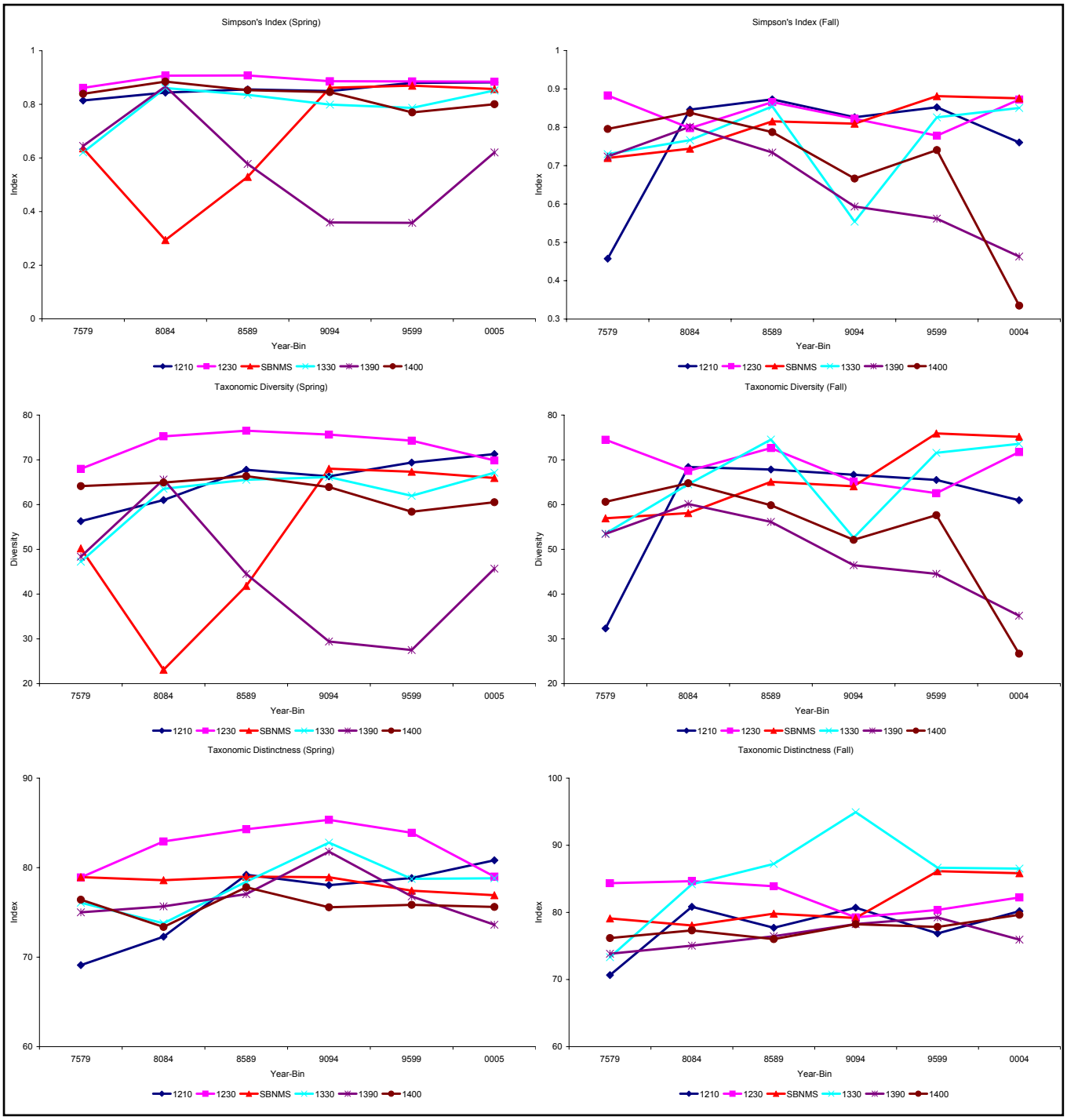

Figure 3.1.23. Diversity comparisons (Simpson's Index, taxonomic diversity and distinctness) between SBNMS and other strata within the region with similar bathymetric profiles.

tions in species distributions due to environmental factors, and other factors that mediate the distribution and abundance of particular taxa.

Patterns at the scale of habitat patches

At the scale of habitat patches (i.e. local scale), habitats with the highest spatial complexity (i.e. boulder reefs) did not necessarily support the highest levels of species richness (Figure 3.1.24). Note that the regression with the highest slope for both species-area and species- individual curves is for mud habitat (see Appendix 16 for species observed during ROV census). Further, regressions were not aggregated based on habitat type as would be expected if the level of spatial complexity solely mediated patterns of diversity. While different habitats in SBNMS exhibited unique species compositions or patterns of species dominance (Auster et al., 1998, 2001), no consis-

tent habitat related patterns in diversity metrics were found in this study. Contrasts in patterns in the distribution of fish diversity on boulder reefs in areas that were fished commercially with those that were closed to fishing (except for hook-and-line fishing) suggest that there was no significant responses in spatial patterns of diversity to closure after 6 years (Figure 3.1.25).

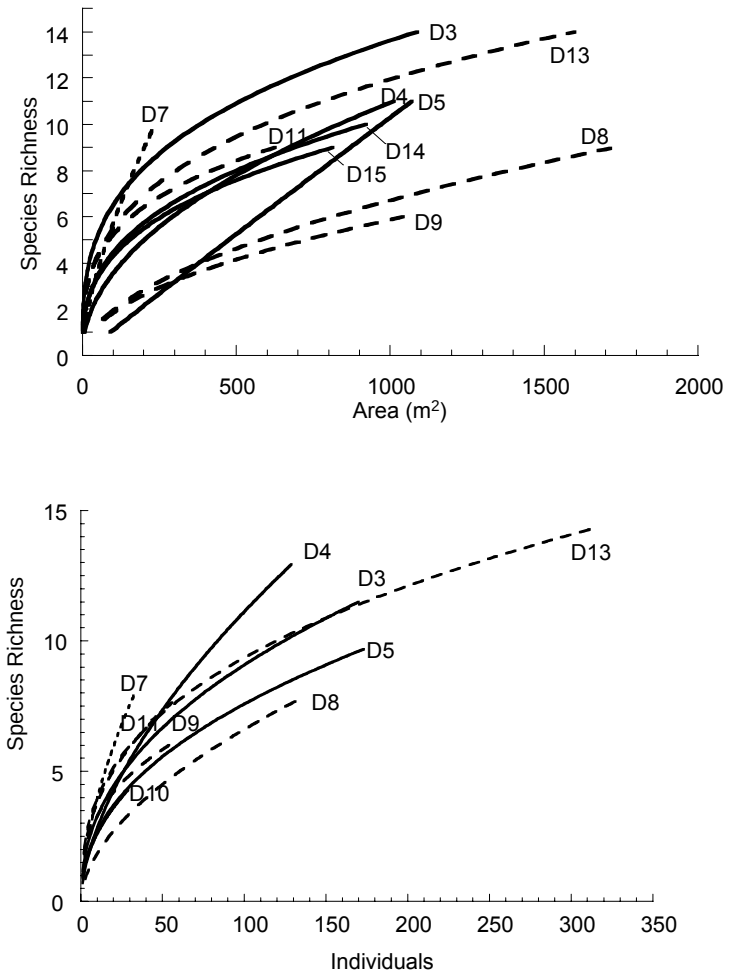

Figure 3.1.24. Species-area (top) and species-individual regressions (bottom) from video transects across a range of habitat types at SBNMS in 2000 (solid lines = boulder, long dashed lines = gravel, short dashed line = mud; labels on lines are dive numbers, see Appendix 9 for species composition data).

Discussion

Understanding how biological diversity is distributed within geographic regions and how it varies over time is fundamental to developing strategies for its conservation and sustainable use. Analyses of fish diversity at regional (based on fall and spring trawl sampling) and local spatial scales (based on video transects) in the Gulf of Maine illustrate the highly heterogenic distribution of fish species. A range of indices (i.e. species richness, Margalef's index, Shannon index, Simpson index, taxonomic diversity, taxonomic distinctness), each sensitive to different attributes of diversity (e.g. changes in dominant or rare species in a sample, taxonomic relatedness), produced patterns that illustrate the role that Stellwagen Bank National Marine Sanctuary (SBNMS) plays in representing the diversity of fishes in the Gulf of Maine. For example, regional patterns of species richness (based on species per tow) were highly dynamic over time (5 year time bins over a 30 year time series), but SBNMS was consistently in the top two quintiles of the distribution of sample strata. Variation in the values of both Shannon and Simpson indices , as well as the indices of taxonomic relatedness, over the time series may be in response to changes due to fishing in the abundance of both dominant and rare species. Video transects were used to compare patterns of diversity between habitat types (i.e. boulder reefs, gravel, sand, mud) within SBNMS using both species-area and species-individual relationships. Habitats with the highest spatial complexity (i.e. boulder reefs) did not necessarily support the highest level of fish diversity. The highest slope for both species-area and species-individual curves was for mud habitat. Patterns in the distribution of fish diversity on boulder reefs, in areas that were fished commercially (except for hook-and-line fishing) with those that are closed to fishing, suggest that there was no significant response to closure after six years. These patterns can be attributed to the low numbers of boulder reef species that are considered residents versus larger numbers that are either seasonal or transient (Auster and Lindholm 2006). Such behaviors could mediate the effects of fishing at individual reefs and patterns of diversity and abundance would shift at regional but not local scales.

Analysis of ECNASAP (East Coast of North America Strategic Assessment Project) data (Auster, unpublished) showed high species richness ringing the Gulf of Maine and Georges Bank, but high diversity samples across this geographic range did not occur in all years. ECNASAP samples (1970-1994) were single tows rather than aggregated to sampling strata. High diversity samples, defined as those in the top quintile of the distribution of diversity values, varied in temporal distribution depending upon the type of index. Samples with high species richness occurred across the entire time series but did not consistently cluster at SBNMS. Samples with high Shannon and Simpson diversity index values did not occur in all years and clustered around particular time frames, making them unsuitable to serve as indices to identify diversity hot-spots.

Fish sampled within the stratum that contains SBNMS during the 25 year time series included 66 of the 176 species sampled throughout the Gulf of Maine region (Auster, 2002). The most abundant species at SBNMS were also common elsewhere within the GOM (Table 3.1.7). Species not captured within SBNMS were generally annual migrants, occasional winter or summer migrants, or deep water species (Appendix 2 in Auster, 2002). Clearly the occurrence of rare species in the tows influenced the shift in spatial pattern of diversity as measured using high species richness versus a metric using both richness and numerical abundance.

Such a shift in pattern is illustrative of the problem associated with choosing indicators of diversity that may be used to identify sites for conservation of diversity and to develop management strategies. Hotspots of diversity have been used in both terrestrial and marine settings for locating target areas for conservation action. However, there has been some debate in the literature about the utility of various metrics and the implications of the resulting patterns in distribution to meet conservation goals.

Analysis of regional scale data is needed to correlate patterns of diversity with seafloor habitat features such as depth, sediment type, habitat heterogeneity. While depth correlations can be made across the region, habitat comparisons can only be conducted for points and grids where high-resolution seafloor sediment maps are available (Auster *et al*., 2001). Contrasts in spatial and temporal patterns of diversity are also needed to understand the responses inherent in the use of various metrics. For example, how many planning units (e.g., strata or cells) considered "hotspots" shift when contrasting maps produced using species richness versus other metrics that take both richness and evenness into account? Finally, understanding patterns of fish diversity within individual planning units (e.g. distribution of years, patterns of species accumulation curves) would assess the adequacy of sampling at particular spatial scales. Such understanding is critical for applying these types of analyses to real decision-making

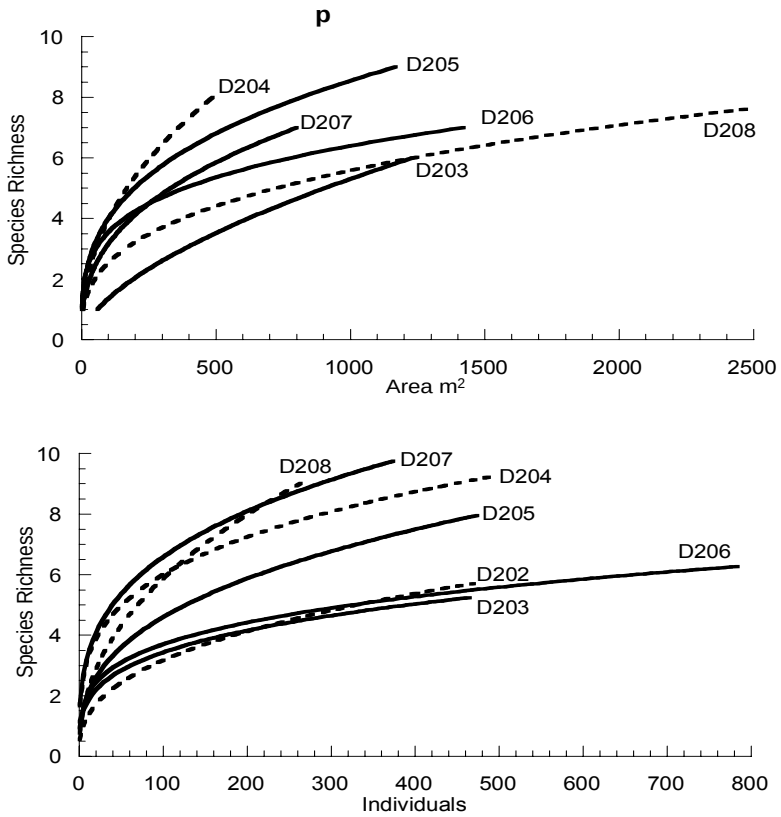

Figure 3.1.25. Species-area and species-individual regressions from video transects on boulder reefs inside and outside the Western Gulf of Maine closure in 2002 (dotted lines = outside closure; solid lines = inside closure; labels on lines are dive numbers). See Appendix 10 for species composition data. Species-area curves were not calculated for dive 202 due to navigational problems.

Table 3.1.7. Residency status of fishes collected at SBNMS compared with all species in the GOM sub-region. Quantities in columns two and three are numbers of species with percent of total in parentheses (e.g., 62% of species collected within SBNMS are resident to GOM, 28% of all species collected within the GOM are resident). The last column is the percent of species from GOM that occur in GOM within each residency category (e.g., 85% of GOM resident species occur within SBNMS). There was a total of 66 species in 388 tows at SBNMS and 108 other species from 9215 tows from all other areas in the GOM. (Table adapted from Auster, 2002.)

Residency Classification	SBNMS	Total Species Gulf of Maine	Category Comparisons
Resident	41 (62%)	48 (28%)	85
Annual migrant	7 (11%)	14 (8%)	50
Summer migrant	5 (8%)	50 (29%)	10
Winter migrant	1 (1%)	11 (6%)	9
Slope (epi or mesopelagic)	6 (9%)	39 (22%)	15
Coastal	6 (9%)	12 (7%)	50
Total Species	66	174	

focused on the conservation and sustainable use of biological diversity in the Gulf of Maine region in general and Stellwagen Bank National Marine Sanctuary in particular.

SBNMS contains a diverse and representative component of the Gulf of Maine fish community. However, based on the six measures of diversity used in this study, the site is not consistently a diversity hotspot. Hotspots for the entire region shifted in space and time with sites other then SBNMS exhibiting the same pattern. This may be a characteristic pattern found in outer continental shelf fish communities or may be limited to those regions and communities that have significant shifts in diversity and abundance due to seasonal migration. Studies to compare and contrast other outer continental shelf fish communities across a range of oceanographic and geographic settings will be needed to better understand the extent that such patterns can be generalized.

3.2 ICHTHYOPLANKTON

Data

The National Marine Fisheries Service's Northeast Fisheries Science Center conducted standardized ichthyoplankton surveys from 1977-1988 along the continental shelf between Cape Hatteras, North Carolina and Cape Sable, Nova Scotia. These data were collected as part of a comprehensive fisheries ecosystem study to identify changes in fish community structure and investigate recruitment mechanisms. During this time period 25,000 bongo samples were collected within this broad area. In this analysis, a subset of the data were used to model ichthyoplankton abundance and distribution within the Gulf of Maine from Cape Sable, Nova Scotia to southern Massachusetts. Overall, 6,406 samples were used to model abundance and distribution within a seasonal time series (Figure 3.2.1). Additionally, samples conducted within Stellwagen Bank National Marine Sanctuary were analyzed to determine species composition abundance within the Sanctuary.

Methods

Ichthyoplankton collection methods are fully described in Sibunka and Silverman, 1984, 1989. Ichthyoplankton data were binned into four seasonal (spring, summer, fall, and winter) and four three-year bins. Seasons were defined as: spring-March, April, May; summer-June, July, August; fall-September, October, November; and, winter-December, January, February. Years were grouped into 3-year bins: 1977-1979; 1980-1982; 1983-1985; and, 1986-1988. Samples were only available for spring 1988, thus the last year bin for summer, fall, and winter consists of samples from 1986-1987.

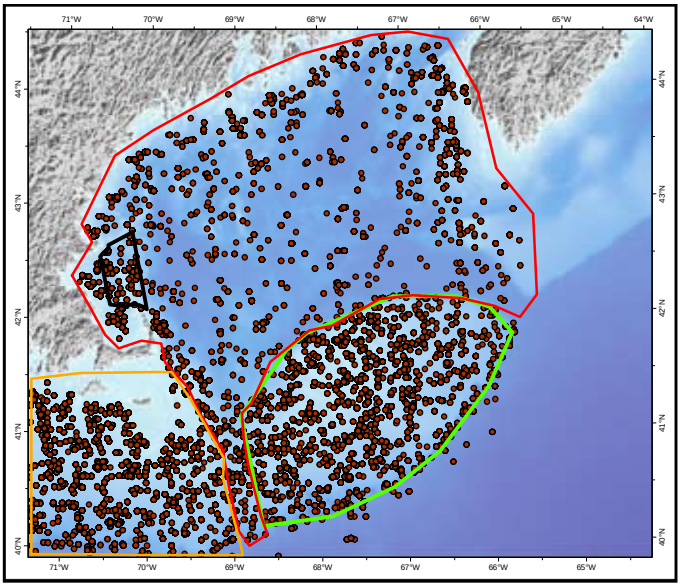

Figure 3.2.1. Ichthyoplankton samples within the Gulf of Maine, 1977-1988. Source: NEFSC-MARMAP. Regions indicated in colored polygons: red=GOM, Green=Georges Bank, black=SBNMS, and orange=southern New England.

Spatial and temporal patterns of ichthyoplankton were modeled using the same protocol as that of zooplankton described in Chapter 1 (See page 37). Binned data were log transformed and examined for autocorrelation then interpolated with kriging using ArcMap 9.1 Geostatistical Analyst Extension. Cross validation was conducted to assess model accuracy by regressing observed versus predicted values (See modeling statistics Table 3.2.1). Maps of the kriging standard error were also generated and used to exclude poorly interpolated areas within the analysis extent. Data with a standard error greater than 50% was removed from the interpolated map to depict only the most reliable model results.

Ichthyoplankton data were grouped into four regional categories to examine species composition and spatial patterns (southern New England, Georges Bank, SBNMS, and the Gulf of Maine). However, due to disproportionate sampling within the Sanctuary during all seasons comparison of species abundance and distribution patterns between the Sanctuary and other areas only support the analysis of general patterns.

Results

Seasonal patterns of ichthyoplankton abundance within the study area exhibited an increasing trend from spring to summer, followed by a decrease and marked variability through fall and winter (Figure 3.2.2). Spring samples displayed a consistent level of abundance for all year-bins, whereas abundance was higher during the summer, however, more variability was observed. Ichthyoplankton abundance was variable during the fall and winter with average abundance values lower than that observed during the spring. In general, model results for all seasons demonstrated highest ichthyoplankton abundance in areas southwest of Cape Sable, Georges Bank, southern New England, and Massachusetts Bay, including the Stellwagen Bank National Marine Sanctuary. The following text will describe model results for each season-year time series for the study area with emphasis on the ichthyoplankton species observed within the Stellwagen Bank NMS and other areas of high ichthyoplankton abundance

Table 3.2.1. Summary kriging statistics for NEFSC ichthyoplankton abundance.

Analysis	Sample size	Lag Size (km)	Number of Lags	Neighbors (total, minimum)	Cross Validation Prediction Map -r^2
spring 7779	617	20	12	10,5	0.58
spring 8082	572	20	12	10,5	0.52
spring 8385	442	20	12	10,5	0.6
spring 8688	355	20	12	10,5	0.42
spring all	1,986	20	12	10,5	0.56
summer 7779	387	25	12	10,5	0.55
summer 8082	378	25	12	10,5	0.46
summer 8385	376	20	12	10,5	0.36
summer 8687	360	15	12	10,5	0.17
summer all	1,501	30	12	10,5	0.33
fall 7779	479	25	12	10,5	0.31
fall 8082	360	25	12	10,5	0.47
fall 8385	482	20	12	10,5	0.51
fall 8687	434	20	12	10,5	0.35
fall all	1,755	20	12	10,5	0.41
winter 7779	222	30	12	10,5	0.47
winter 8082	306	30	12	10,5	0.56
winter 8385	413	30	12	10,5	0.51
winter 8688	223	20	12	10,5	0.71
winter all	1,164	25	12	10,5	0.52

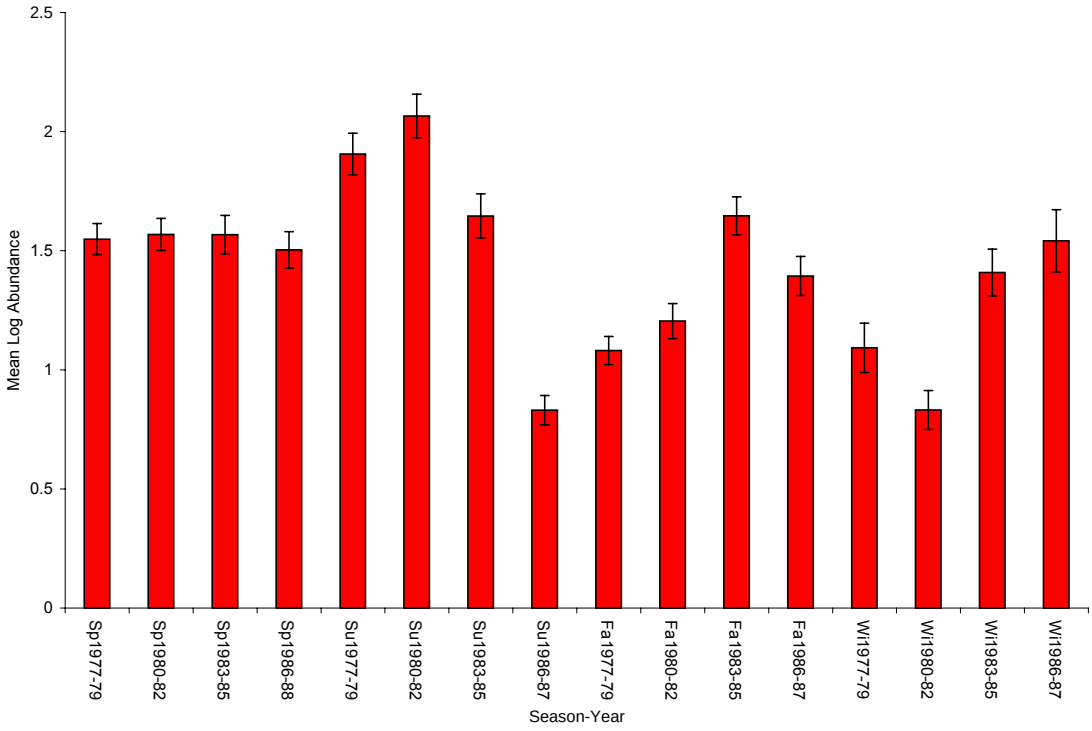

Figure 3.2.2. Overall ichthyoplankton abundance and standard error within study area by season-year.

(Georges Bank, southern New England). Model results were most reliable in the middle and southern portion of the study area where samples were most abundant. Standard error for model results was typically high in areas around Cape Sable and the northern and central Gulf of Maine and were removed from the map.

Spring

Spring samples (N=1,986) yielded 80 species of larval fishes. Ichthyoplankton abundance within the study area was highest during spring, specifically in areas over Georges Bank, southern New England, and, to a lesser extent, within eastern Massachusetts Bay (Figure 3.2.3). Mean abundance within the study area was consistent with little variability throughout the time series.

Spring ichthyoplankton samples were dominated by sand lance (*Ammodytes* spp.) which comprised 82% of the total abundance for (Table 3.2.2). Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) comprised 7.6% and 5.4%, respectively. Sand lance was the most abundant species in samples taken within Stellwagen Bank NMS, southern New England, and in the Gulf of Maine. Conversely, Atlantic cod and haddock were more abundant than sand lance over Georges Bank throughout this time period. Larvae from witch flounder (*Glyptocephalus cynoglossus*), winter flounder (*Pseudopleuronectes americanus*) and radiated shanny (*Ulvaria subbifurcata*) were also abundant within SBNMS. While Atlantic cod was one of the top 10 species in abundance within the Sanctuary, its abundance was significantly lower compared to other areas within the study area, but this may be attributed to reduced effort within the Sanctuary.

Table 3.2.2. Dominant species taken in ichthyoplankton samples within the Gulf of Maine, spring 1977-1988. Source: NEFSC MARMAP.

Location	Taxa	Mean Log Abundance	Location	Taxa	Mean Log Abundance
SBNMS	*Ammodytes* spp.	0.91	Southern NE	*Ammodytes* spp.	1.62
	Glyptocephalus cynoglossus	0.30		*Gadus morhua*	0.21
	Pseudopleuronectes americanus	0.20		*Melanogrammus aeglefinus*	0.16
	Ulvaria subbifurcata	0.20		*Limanda ferruginea*	0.13
	Scomber scombrus	0.10		*Myoxocephalus octodecemspinosus*	0.11
	Paralichthys dentatus	0.08		*Pollachius virens*	0.09
	Enchelyopus cimbrius	0.06		*Hippoglossoides platessoides*	0.08
	Lumpenus maculatus	0.06		*Pholis gunnellus*	0.08
	Gadus morhua	0.05		*Pseudopleuronectes americanus*	0.08
	Pholis gunnellus	0.05		*Merluccius albidus*	0.05
Georges Bank	*Gadus morhua*	0.77	Gulf of Maine	*Ammodytes* spp.	0.60
	Melanogrammus aeglefinus	0.61		*Gadus morhua*	0.17
	Ammodytes spp.	0.59		*Melanogrammus aeglefinus*	0.15
	Hippoglossoides platessoides	0.20		*Benthosema glaciale*	0.13
	Pollachius virens	0.14		*Sebastes* spp.	0.13
	Limanda ferruginea	0.12		*Pholis gunnellus*	0.12
	Sebastes spp.	0.11		*Pollachius virens*	0.09
	Pholis gunnellus	0.10		*Hippoglossoides platessoides*	0.08
	Pseudopleuronectes americanus	0.10		*Glyptocephalus cynoglossus*	0.05
	Benthosema glaciale	0.09		*Myoxocephalus octodecemspinosus*	0.04

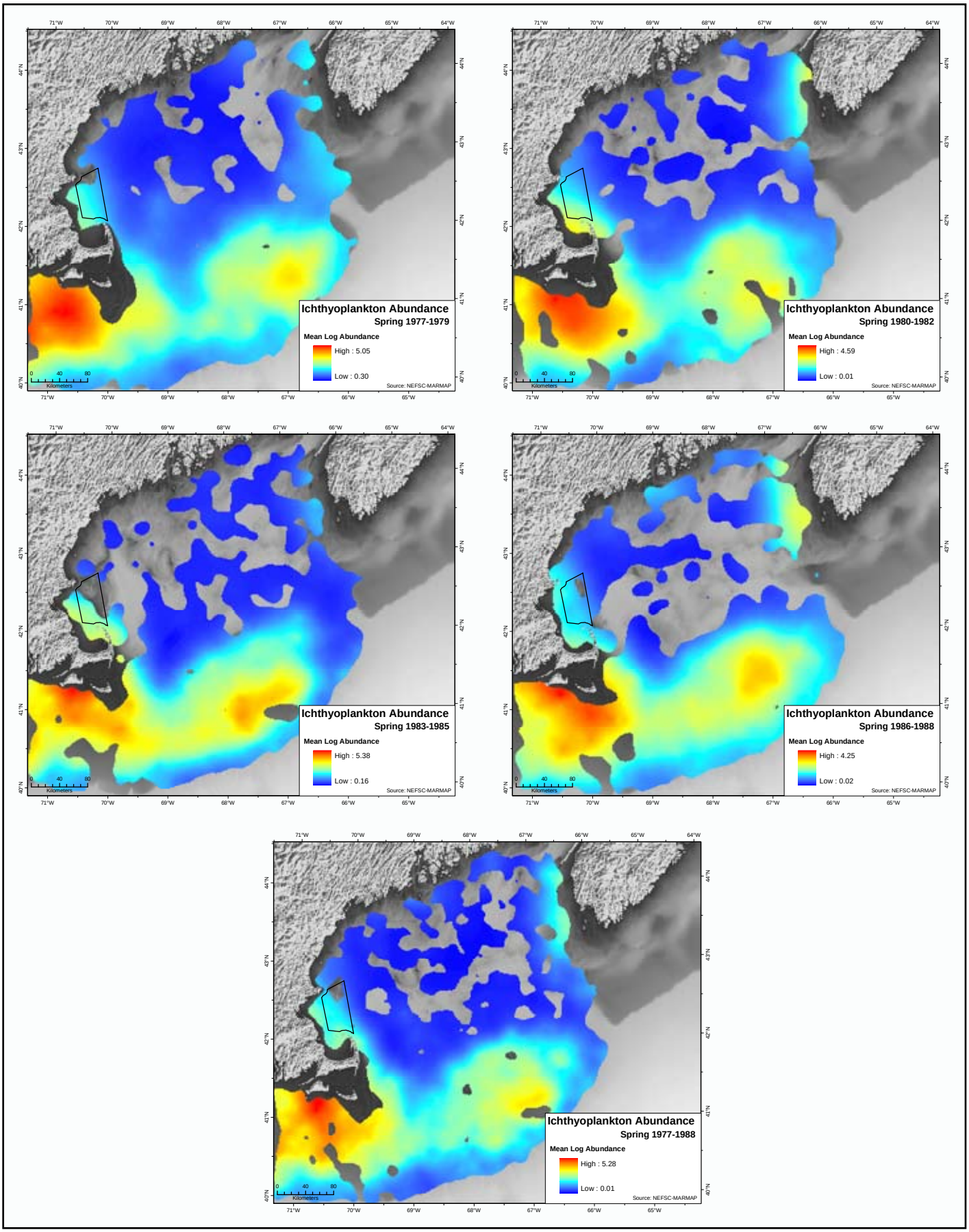

Figure 3.2.3. Predicted ichthyoplankton abundance during spring (1977-1988) within the Gulf of Maine. Data source: NEFSC MARMAP.

Summer

Sampling effort during summer was lower than spring (N=1,501) but yielded more larval fish species (89) than spring samples. Mean abundance was lower than that observed during spring with higher variability. Similar to that observed in spring, areas of peak abundance were in the same locations with highest abundance along an almost continuous band from Georges Bank through southern New England (Figure 3.2.4). Abundance was moderate within the Sanctuary, Massachusetts Bay, and off the western shore from Cape Ann north to Penobscot Bay. Model results indicate that the deeper portions of the central Gulf of Maine exhibit low ichthyoplankton abundance during summer.

Silver hake (*Merluccius bilinearis*) and hakes of the genus *Urophycis* were most abundant throughout the study area during summer. Yellowtail flounder (*Limanda ferruginea*) and windowpane flounder (*Scophthalmus aquosus*) were also abundant in the areas around Georges Bank and southern New England. Within the Sanctuary, larvae of four-beard rockling (*Enchelyopus cimbrius*), cunner (*Tautogolabrus adspersus*), Atlantic mackerel (*Scomber scombrus*), witch flounder (*Glyptocephalus cynoglossus*), and hakes (*Urophycis* and M*. bilinearis*) were most abundant during summer (Table 3.2.3). The most abundant species found within the Sanctuary were also abundant throughout the larger Gulf region.

Table 3.2.3. Dominant species taken in ichthyoplankton samples within the Gulf of Maine, summer 1977-1987. Data source: NEFSC MARMAP.

Location	Taxa	Mean Log Abundance	Location	Taxa	Mean Log Abundance
SBNMS	*Enchelyopus cimbrius*	0.82	Southern NE	*Merluccius bilinearis*	0.92
	Tautogolabrus adspersus	0.52		*Urophycis* spp.	0.87
	Scomber scombrus	0.48		*Peprilus triacanthus*	0.54
	Glyptocephalus cynoglossus	0.47		*Limanda ferruginea*	0.43
	Urophycis spp.	0.47		*Hippoglossina oblonga*	0.42
	Merluccius bilinearis	0.38		*Citharichthys arctifrons*	0.36
	Sebastes spp.	0.37		*Scomber scombrus*	0.33
	Gadus morhua	0.36		*Tautogolabrus adspersus*	0.23
	Limanda ferruginea	0.27		*Glyptocephalus cynoglossus*	0.23
	Hippoglossoides platessoides	0.20		*Scophthalmus aquosus*	0.17
Georges Bank	*Merluccius bilinearis*	1.02	Gulf of Maine	*Sebastes* spp.	0.64
	Scophthalmus aquosus	0.57		*Merluccius bilinearis*	0.25
	Urophycis spp.	0.57		*Urophycis* spp.	0.23
	Limanda ferruginea	0.51		*Enchelyopus cimbrius*	0.14
	Tautogolabrus adspersus	0.20		*Limanda ferruginea*	0.13
	Hippoglossina oblonga	0.17		*Tautogolabrus adspersus*	0.12
	Merluccius albidus	0.13		*Glyptocephalus cynoglossus*	0.11
	Peprilus triacanthus	0.12		*Scomber scombrus*	0.09
	Melanogrammus aeglefinus	0.11		*Melanogrammus aeglefinus*	0.08
	Ceratoscopelus maderensis	0.10		*Gadus morhua*	0.08

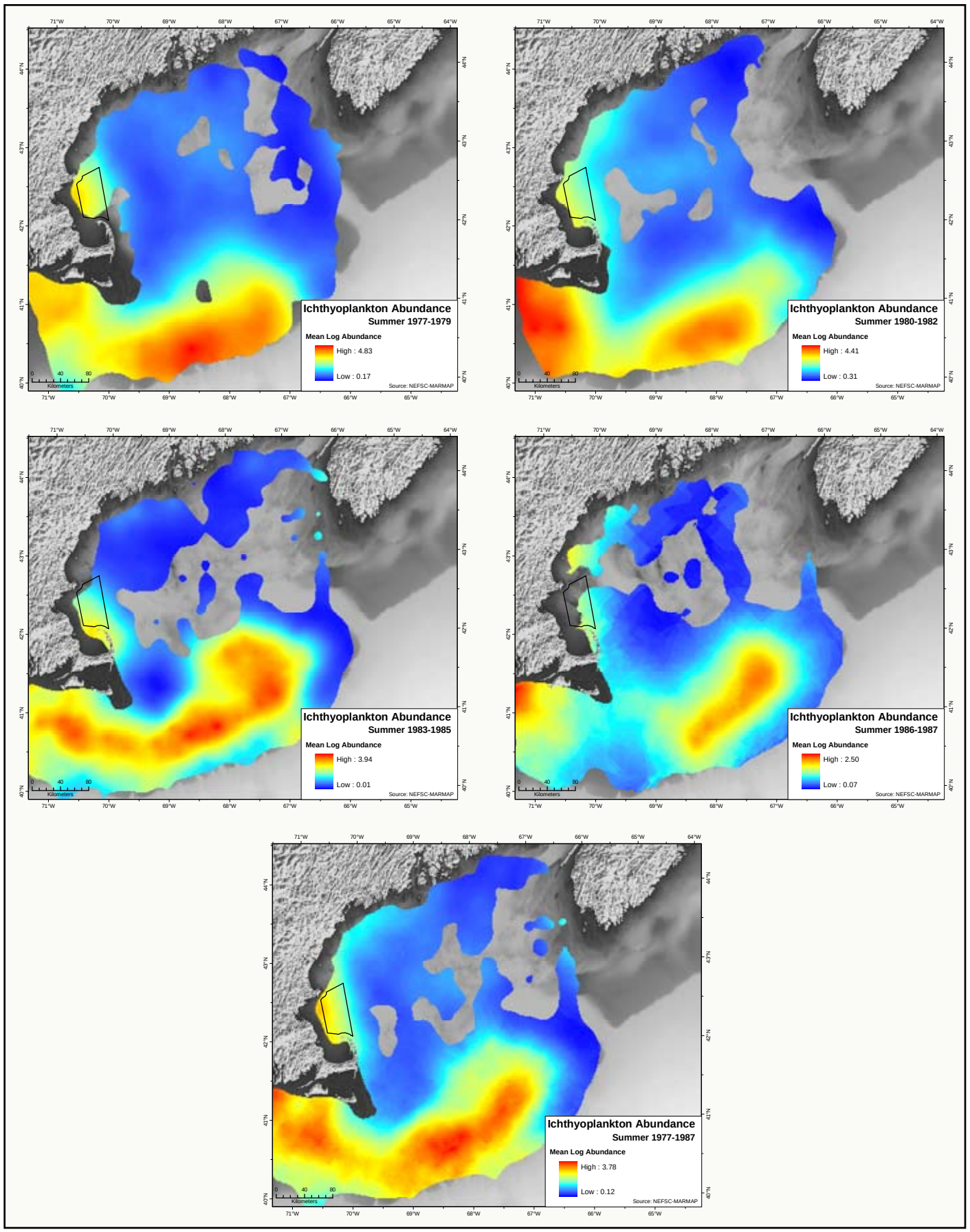

Figure 3.2.4. Predicted ichthyoplankton abundance during summer (1977-1987) within the Gulf of Maine. Data source: NEFSC MARMAP.

Fall

Species richness was high during the fall (88). Mean abundance was highly variable during this season compared to spring and summer. Areas of peak abundance were located in southern New England, Massachusetts Bay (including SBNMS), and off Cape Sable (Figure 3.2.5). In contrast to spring and summer results, the Georges Bank area contained moderate larval abundance compared to the rest of the study area. Throughout the time series, larval abundance was lowest for the study area during 1977-79 and increased through 1983-85 and slightly decreased during 1986-87.

Approximately 65% of the total fall abundance was comprised of larval silver hake (*M. bilinearis*), Atlantic herring (*Clupea harnegus*), hakes (*Urophycis* spp.), and windowpane flounder (*S. aquosus*). In general, these patterns were consistent within the localized areas of SBNMS, Georges Bank, southern New England and the Gulf of Maine proper. Atlantic herring were most dominant within SBNMS and the Gulf of Maine, while silver hake was most abundant at Georges Bank and southern New England (Table 3.2.4). High abundance of fourbeard rockling (*E. cimbrius*), witch flounder (*G. cynoglossus*), and cunner (*T. adspersus*) were observed within SBNMS during the fall. The lanternfish (*Ceratoscopelus maderensis*) and flounder from the genus *Bothus* were present in moderate abundance throughout the Gulf of Maine and southern New England, but were absent in Massachusetts Bay and SBNMS.

Table 3.2.4. Dominant species taken in ichthyoplankton samples within the Gulf of Maine, fall 1977-1987. Data source: NEFSC MARMAP.

Location	Taxa	Mean Log Abundance	Location	Taxa	Mean Log Abundance
SBNMS	*Clupea harengus*	1.63	Southern NE	*Merluccius bilinearis*	0.96
	Merluccius bilinearis	0.62		*Urophycis* spp.	0.86
	Enchelyopus cimbrius	0.60		*Citharichthys arctifrons*	0.50
	Urophycis spp.	0.31		*Paralichthys dentatus*	0.36
	Glyptocephalus cynoglossus	0.29		*Scophthalmus aquosus*	0.35
	Tautogolabrus adspersus	0.13		*Ceratoscopelus maderensis*	0.26
	Peprilus triacanthus	0.10		*Hippoglossina oblonga*	0.23
	Pollachius virens	0.09		*Clupea harengus*	0.17
	Scophthalmus aquosus	0.08		*Lepophidium profundorum*	0.17
	Limanda ferruginea	0.07		*Bothus* spp.	0.13
Georges Bank	*Merluccius bilinearis*	0.67	Gulf of Maine	*Clupea harengus*	0.86
	Scophthalmus aquosus	0.57		*Merluccius bilinearis*	0.37
	Urophycis spp.	0.34		*Urophycis* spp.	0.26
	Ceratoscopelus maderensis	0.12		*Ceratoscopelus maderensis*	0.17
	Clupea harengus	0.11		*Enchelyopus cimbrius*	0.12
	Bothus spp.	0.07		*Bothus* spp.	0.10
	Citharichthys arctifrons	0.07		*Glyptocephalus cynoglossus*	0.05
	Merluccius albidus	0.06		*Scophthalmus aquosus*	0.03
	Lepophidium profundorum	0.05		*Pollachius virens*	0.03
	Tautogolabrus adspersus	0.04		*Citharichthys arctifrons*	0.03

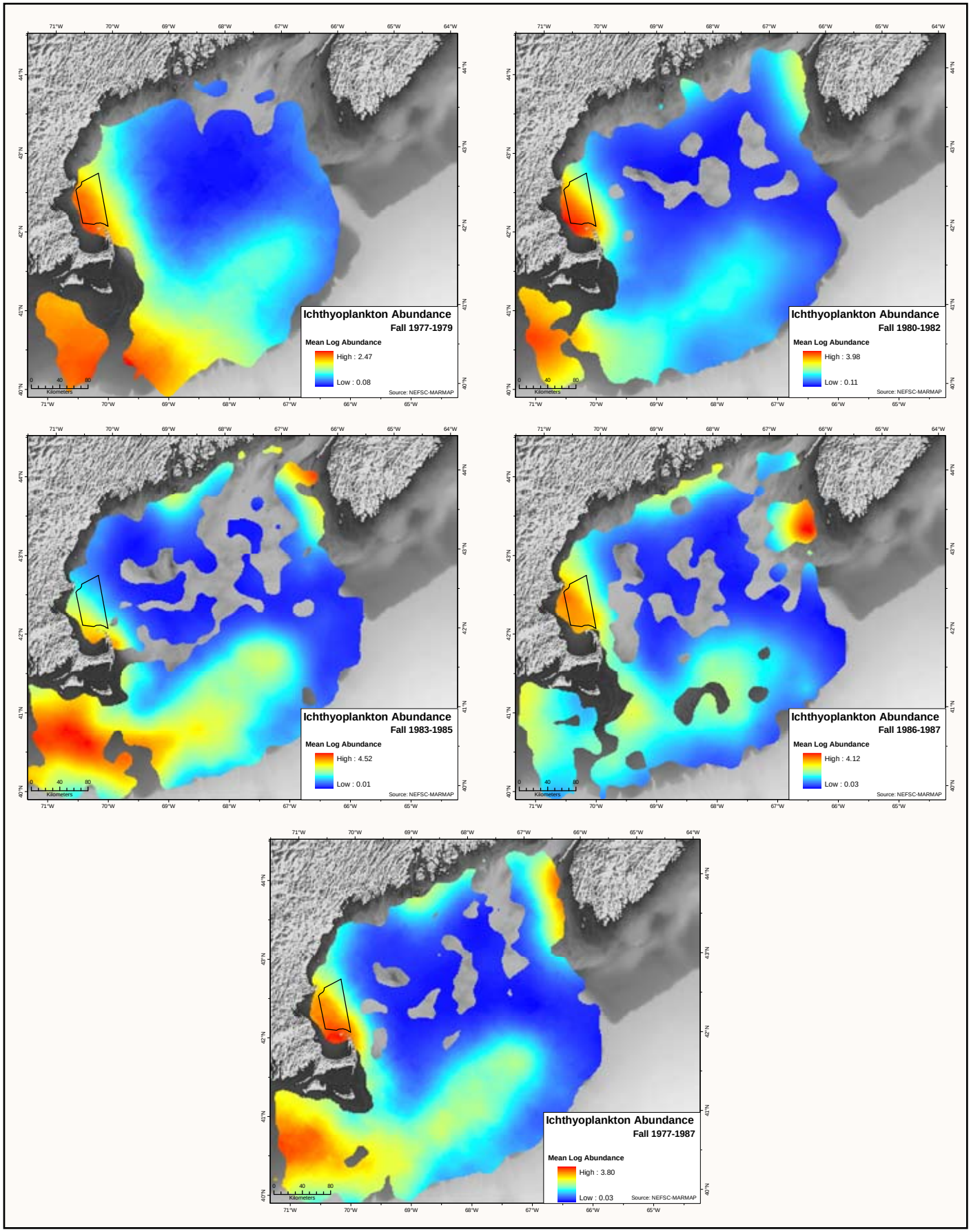

Figure 3.2.5. Predicted ichthyoplankton abundance during fall (1977-1987) within the Gulf of Maine. Data source: NEFSC MARMAP.

Winter

Ichthyoplankton sampling effort was lowest during winter (N=1,164). Species richness was significantly lower than all other seasons (46 species) and mean abundance was the most variable among all seasons (Figure 3.2.2). As such, model results were less spatially resolved due to fewer samples and associated standard error extraction. Regardless, the same general patterns of larval abundance and distribution were observed during winter as that of the remaining seasons: high abundance in southern New England, Georges Bank, and Massachusetts Bay and low abundance throughout the deeper portions of the Gulf of Maine (Figure 3.2.6).

Approximately 55% of the total larval abundance was comprised of sand lance (*Ammodytes* spp.) larvae. An additional 30% of the total abundance was comprised of pollock (*Pollachius virens*), Atlantic herring (*C. harengus*), and Atlantic cod (*G. morhua*) larvae. Sand lance were most abundant in southern New England, Georges Bank, and the Gulf of Maine proper, while pollock were most abundant in SBNMS during winter (Table 3.2.5). Samples were minimal within SBNMS (N=10) during this time series and only six species were present, three of which comprised 99% of the total abundance: pollock, sand lance, and Atlantic herring.

Table 3.2.5. Dominant species taken in ichthyoplankton samples within the Gulf of Maine, winter 1977-1987. Data source: NEFSC MARMAP.

Location	Taxa	Mean Log Abundance	Location	Taxa	Mean Log Abundance
SBNMS	*Pollachius virens*	1.34	Southern NE	*Ammodytes* spp.	1.55
	Ammodytes spp.	0.66		*Gadus morhua*	0.41
	Clupea harengus	0.46		*Paralichthys dentatus*	0.36
	Gadus morhua	0.08		*Clupea harengus*	0.27
	Aspidophoroides monopterygius	0.08		*Merluccius bilinearis*	0.26
	Lumpenus lumpretaeformis	0.08		*Pollachius virens*	0.23
				Urophycis spp.	0.07
				Merluccius albidus	0.06
				Brevoortia tyrannus	0.05
				Scophthalmus aquosus	0.05
Georges Bank	*Ammodytes* spp.	1.23	Gulf of Maine	*Ammodytes* spp.	0.69
	Gadus morhua	0.31		*Clupea harengus*	0.47
	Pollachius virens	0.22		*Pollachius virens*	0.40
	Clupea harengus	0.17		*Gadus morhua*	0.09
	Melanogrammus aeglefinus	0.07		*Lumpenus lumpretaeformis*	0.04
	Notolepis rissoi	0.06		*Notolepis rissoi*	0.04
	Merluccius albidus	0.04		*Myoxocephalus octodecemspinosus*	0.03
	Paralepis coregonoides	0.03		*Benthosema glaciale*	0.02
	Merluccius bilinearis	0.02		*Merluccius bilinearis*	0.02
	Myrophis punctatus	0.01		*Paralepis coregonoides*	0.02

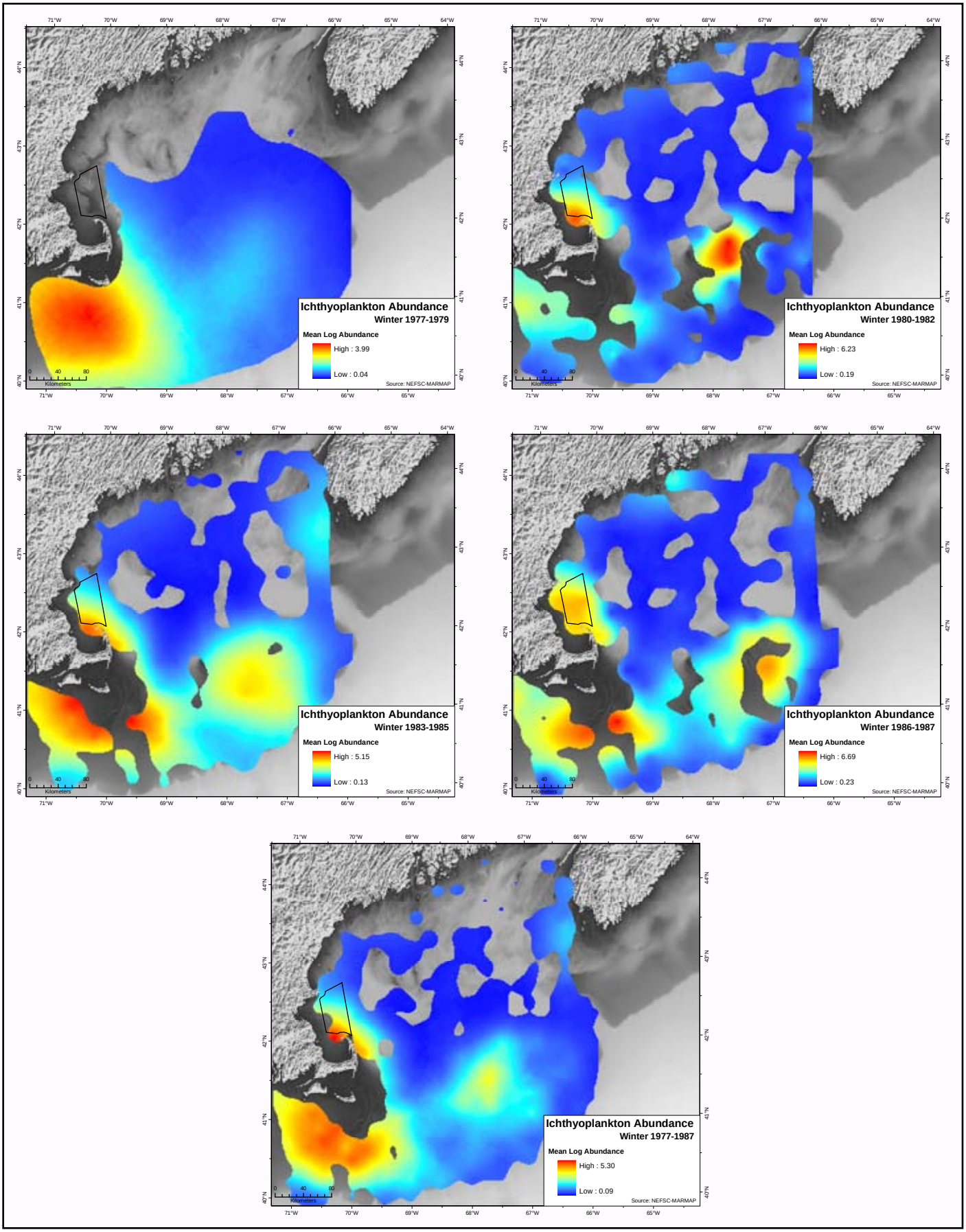

Figure 3.2.6. Predicted ichthyoplankton abundance during winter (1977-1987) within the Gulf of Maine. Data source: NEFSC MARMAP.

Conclusions

The NEFSC has previously described the abundance and distribution patterns of the 26 most abundant species from Cape Hatteras, North Carolina to Cape Sable, Nova Scotia (Morse *et al.,* 1987). The patterns observed in this analysis provide a spatially resolved depiction of ichthyoplankton abundance and distribution communities for the Gulf of Maine, and in particular, the Stellwagen Bank NMS. The dominant pattern of ichthyoplankton abundance and distribution agree with Bigelow (1926) where the majority of species are found within the 200 m bathymetric contour. Patterns of abundance described here show that while there are many species of larvae on the continental shelf during each season, the community is generally dominated by relatively few taxa. Typically five or six species will comprise over 90% of the total larval abundance within an area (Morse *et al.,* 1987).

The study area is situated at the confluence of two biogeographic areas, the Gulf of Maine and the Mid-Atlantic region. The area consisting of southern New England and Georges Bank acts as a transition zone between the two. This transition zone was consistently highlighted as an area of peak larval abundance where species from both biogeographic areas spawn (Morse *et al.,* 1987). Additionally, most ichthyoplankton feed on smaller zoo/phytoplankton and areas of peak abundance are highly correlated with areas of high zooplankton and phytoplankton abundance (generally located within the 200 m bathymetric contour) described in Chapter 1. Peak spawning for several important species has been shown to be synchronous with increasing abundance levels of their seasonally-dominant copepod prey (Sherman *et al.,* 1984).

The mid-Atlantic area is a primary spawning ground for many taxa which migrate from southern and northern waters during spring and fall. The southern New England region contains most of these spawning species and exhibits the highest concentration of fish larvae within the study area (Morse *et al.,* 1987). Many of the southern species are at their northern physiological limits in this region. Georges Bank contains few southern migrants and the larval community is dominated by species of the family Gadidae (hakes, haddock, Atlantic cod) as well as yellowtail flounder. The Gulf of Maine contains the fewest larvae in both relative abundance and species richness. Few larvae are captured within the central basin of the Gulf and those samples are dominated by Acadian redfish, (*Sebastes* spp.). Atlantic herring are abundant along the coastal regions (Morse *et al.,* 1987).

High larval abundance within the Sanctuary during the winter and spring months appears to be primarily driven by sand lance where their long hatching period (Nov-May) and persistent larval stage maintains a dominant presence in this area (Reay, 1970). During summer several gadoid fishes (hakes, Atlantic cod), flatfish (witch and yellowtail flounder), cunner, and fourbeard rockling are dominant within the Sanctuary. During winter, species abundance shifts slightly with the Atlantic herring being the most dominant species. Larval abundance was somewhat limited during winter, but that may be an artifact of limited samples collected for this time period. Regardless, SBNMS and Massachusetts Bay is an area of elevated larval abundance due to the high larval biomass of sand lance.

Although the MARMAP dataset represents a relatively narrow time period (1977-1988), it is one of the only comprehensive mesoscale ichthyoplankton datasets for the Northeast Atlantic. These data provide good insight into historical patterns of larval abundance patterns within SBNMS and identifies a data gap that should be examined to fully understand the dynamics of larval dispersal and retention within the Sanctuary.

3.3 SELECT SPECIES SPATIAL AND TEMPORAL DISTRIBUTION

This section examines the spatial and temporal distribution of 16 species that were selected due to some combination of their ecological role, life history characteristics, population status, or habitat requirements. Thirty years (1975-2005) of fisheries-independent monitoring data were provided by NMFS NEFSC which were subsequently categorized into two seasons (spring and fall) and grouped into 5-year bins (1975-1979, 1980-1984, 1985-1989, 1990-1994, 1995-1999, 2000-2005). Where information was available, separate maps were produced for adults and juveniles.

Redfish (*Sebastes* spp.)
Redfish populations in the Gulf of Maine declined by 99% between 1968-1984 and have been identified as a species with a risk of extinction (Musick *et al*., 2001). Redfish are a long-lived resident species within the Gulf of Maine region and exhibit low reproductive capability. As a result, populations can be sensitive to overfishing (Mayo, 2000). Redfish are important shrimp-fish predators and juveniles show a strong affinity for boulder reefs and dense burrowing anemone forests (Auster and Lindholm, 2005; Auster *et al*., 2003a).

In the current nomenclature, the common name redfish refers both to the Acadian redfish (*Sebastes fasciatus*) and the deepwater redfish (*Sebastes mentella*). The two species are difficult to discriminate at all life stages and as a matter of fisheries practice are usually combined. Redfish are Federally managed under the New England Fishery Management Councils Northeast Multispecies Management Plan. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of redfish inhabiting U.S. waters, primarily in the Gulf of Maine (Pikanowski *et al.,* 1999).

Life history
The redfish is a slow-growing, long-lived, ovoviviparous species with an extremely low natural mortality rate. In U.S. waters, redfish are common in the Gulf of Maine, in the deeper waters north and west of Georges Bank, and to a lesser extent Browns Bank and the continental slope.

Redfish larvae are released soon after the spring plankton bloom and through the summer production of zooplankton in the Gulf of Maine. Newly spawned larvae occur in the upper 10 m of the water column. At 10-25 mm they occur within the thermocline (10-30 m). Larvae from various areas in North Atlantic have fairly constant, slow relative growth rate of 1-1.5 % per day. Larvae are planktonic for 4 months or more. Post-larvae descend below the thermocline when they are about 25 mm. Young-of-the-year are pelagic until they reach 40-50 mm at 4-5 months old, at which time they move to the bottom by early fall of their first year. The duration of the pelagic stage would allow transport of larvae and young-of-the-year fish for hundreds of miles. However, the cyclonic gyre in the Gulf of Maine keeps the larvae within the Gulf. They feed on copepods, euphausiids, and fish and invertebrate eggs. Prey size is proportional to fish size.

Redfish of 22 cm or greater are considered adults. As a general rule, the size of landed redfish is positively correlated with depth. The reason for this may involve differential growth rates of stocks, confused species identification (deepwater redfish are a larger species), size specific migration, gender specific migration (females are larger), or a combination of these factors. More redfish are captured by bottom trawl during the day than at night, so the fishery for redfish has been primarily a daytime pursuit. Redfish make diurnal vertical migrations linked to their primary euphausiid prey. Juvenile and adult redfish eat euphausiids, mysids, and bathypelagic fish. They feed most actively at night when they rise off the bottom following the vertical migration of their primary euphausiid prey.

Habitat Characteristics
Acadian redfish are found in shoal waters in the Gulf of Maine, they are most common at depths of 128-366 m and have been collected down to 592 m. Redfish are classified in the “deep-water sedentary” group with white hake, witch flounder, pollock, and American plaice. Gulf of Maine redfish prefer a temperature range of 3-7°C. Within the preferred depth and temperature zones, redfish are most abundant among boulder reefs (Auster and Lindholm, 2005) and adults are occasionally found on silt, mud, or hard bottom; they are rarely taken over sand.

Juveniles have been collected from 50-275 m deep in spring and 25-400 m deep in the fall, with most occurring between 50-200 m. Adults were collected from 50-350 m deep in spring and 25-350 m deep in the fall, with most collected between 125-200 m. Late juveniles and adults occur on boulder reefs and other gravel habitats as well as in mud habitats with dense forests of burrowing anemones (Auster *et al*. 2003).

Time Series Analysis

Adult redfish were widely distributed throughout the Gulf of Maine during spring (Figure 3.3.1). Frequency of occurrence was highest during 1975-79 (26.9% of total trawls) and varied between 16.3%-19.4% between 1980-2005. Abundance initially declined significantly in the spring and then increased during the later part of the time series. The fall samples reflect a steady increase in abundance over time. This pattern is reflective of the recovery of redfish populations from severe overfishing earlier in the century. Abundance and distribution of juveniles followed the same spatial and depth patterns as adults. Juveniles were captured less frequently than adults in all year-bins, with the exception of 1995-1999 (Figure 3.3.2). Juvenile abundance was not significantly different throughout the study area between 1975-1994, however total trawl abundance nearly doubled during 1995-2005.

Adult redfish frequency of occurrence was higher during fall than spring (Figure 3.3.3). Abundance and distribution patterns were similar to that observed for adults during spring; little variability during 1975-1994, and increasing abundance through 2004. Similar to adults, juvenile frequency of occurrence was higher in the fall than spring (Figure 3.3.4). Juveniles exhibited a positive increase in frequency of occurrence throughout the time series.

Adult and juvenile redfish exhibited high frequency of occurrence in trawls within the Sanctuary (Table 3.3.1), however abundance was quite variable throughout the time series. Redfish abundance was variable during the spring, with lowest values attained during 1980-1989. Peak abundance was observed between 2000-2005. Mean adult redfish size was not considerably different during spring and maximum size ranged from 29-44 cm. Adults were captured at depths ranging between 37-144 m. Mean lengths for juveniles ranged from 14.5-18.8 cm. Juveniles did not exhibit a shallower or deeper depth range than adults (46-149 m).

On average, redfish frequency of occurrence and abundance was highest during fall. Redfish abundance within the Sanctuary increased throughout the time series and exhibited peak abundance during 2000-2004. Adults were slightly larger than those captured in the spring (25.3-29.5 cm), but were captured in approximately the same depth range (48-149 m). Juveniles exhibited similar mean lengths to those captured in spring (15.3-19.2 cm) and were found at depths between 37-144 m.

Table 3.3.1. Frequency of occurrence and abundance for all redfish captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	46.43	29.43	27.5	44	37-133	18.8	8	46-104
	80-84	22	36.36	2.32	26.3	29	47-88	16.2	8	58-101
	85-89	16	25.00	1.06	27.5	31	88-106	15.8	5	53-138
	90-94	21	42.86	15.19	26.2	34	66-120	15.8	4	60-117
	95-99	17	70.59	8.65	26.9	34	75-89	14.9	4	48-95
	00-05	17	64.71	48.76	28.2	39	80-144	14.5	4	55-149
Fall	75-79	61	52.46	5.97	28.2	45	48-105	19.2	13	37-133
	80-84	22	31.82	6.27	29.5	45	66-101	15.9	10	67-121
	85-89	20	55.00	16.40	28.1	37	53-138	14.6	8	81-106
	90-94	19	57.89	21.79	26.0	33	77-116	16.0	5	66-120
	95-99	18	72.22	77.22	25.3	30	66-95	15.6	5	74-123
	00-04	16	68.75	109.50	26.6	32	93-149	15.3	5	72-144

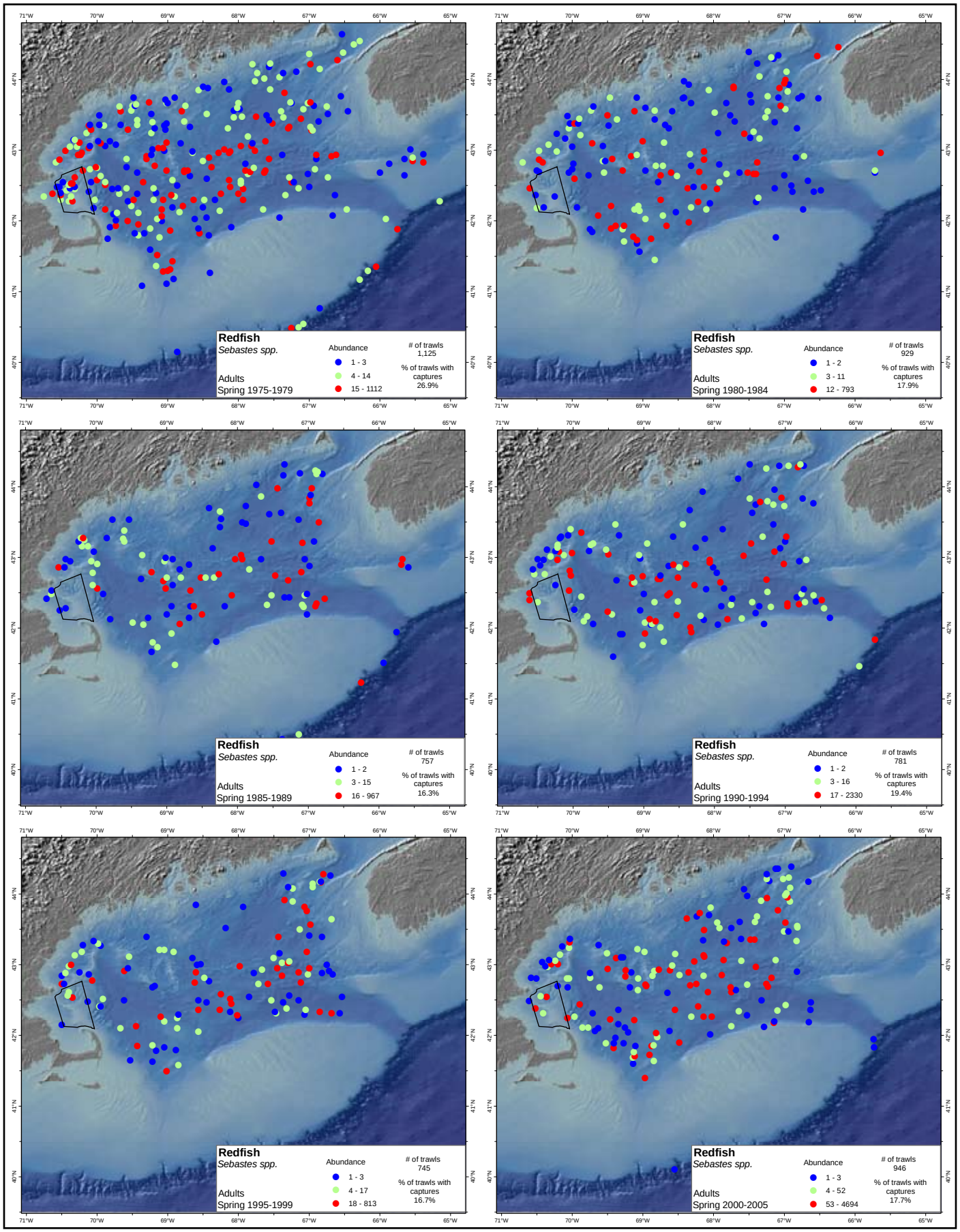

Figure 3.3.1. Abundance and distribution of adult redfish (*Sebastes* spp.) within the Gulf of Maine, Spring 1975-2005.

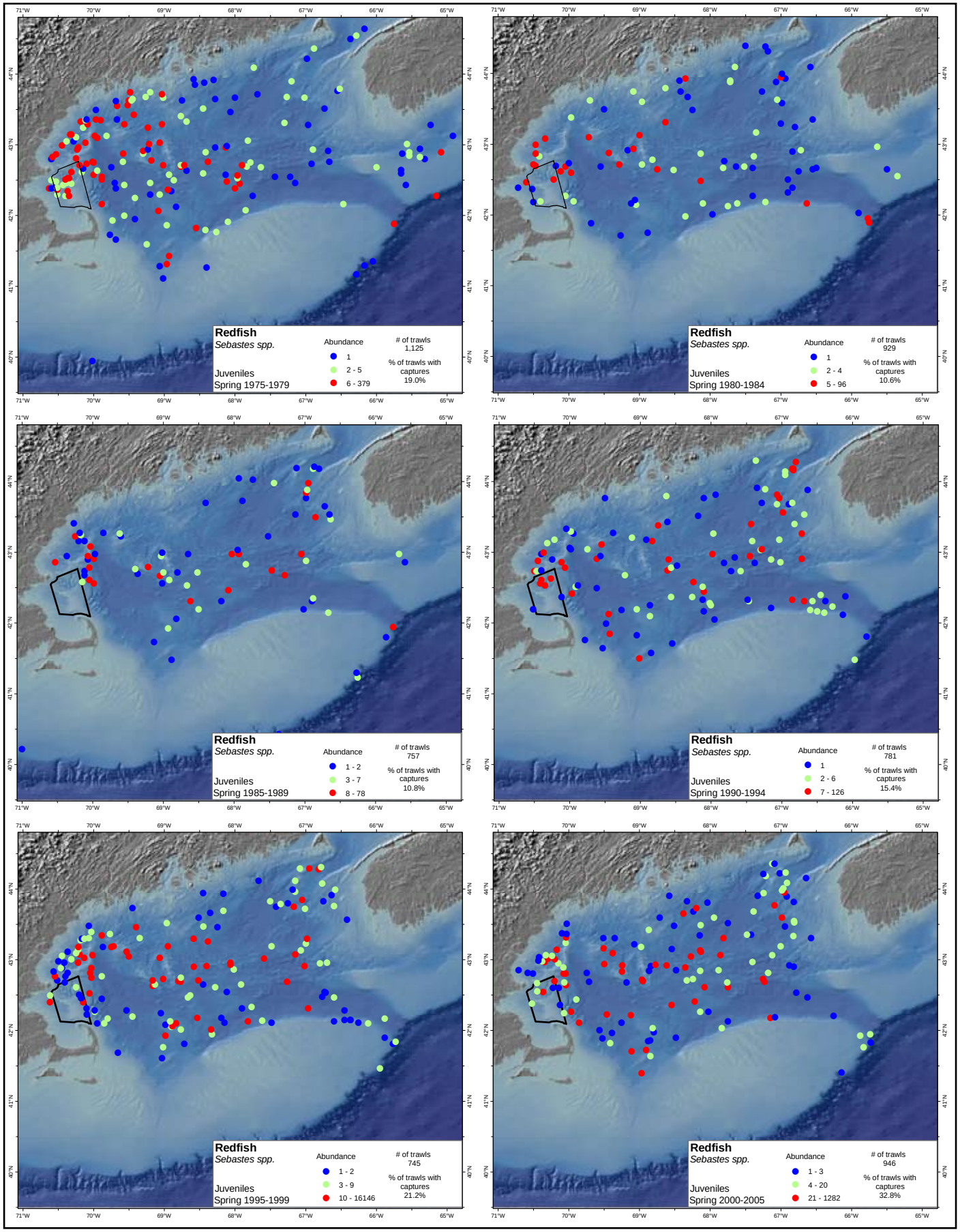

Figure 3.3.2. Abundance and distribution of juvenile redfish (*Sebastes* spp.) within the Gulf of Maine, Spring 1975-2005.

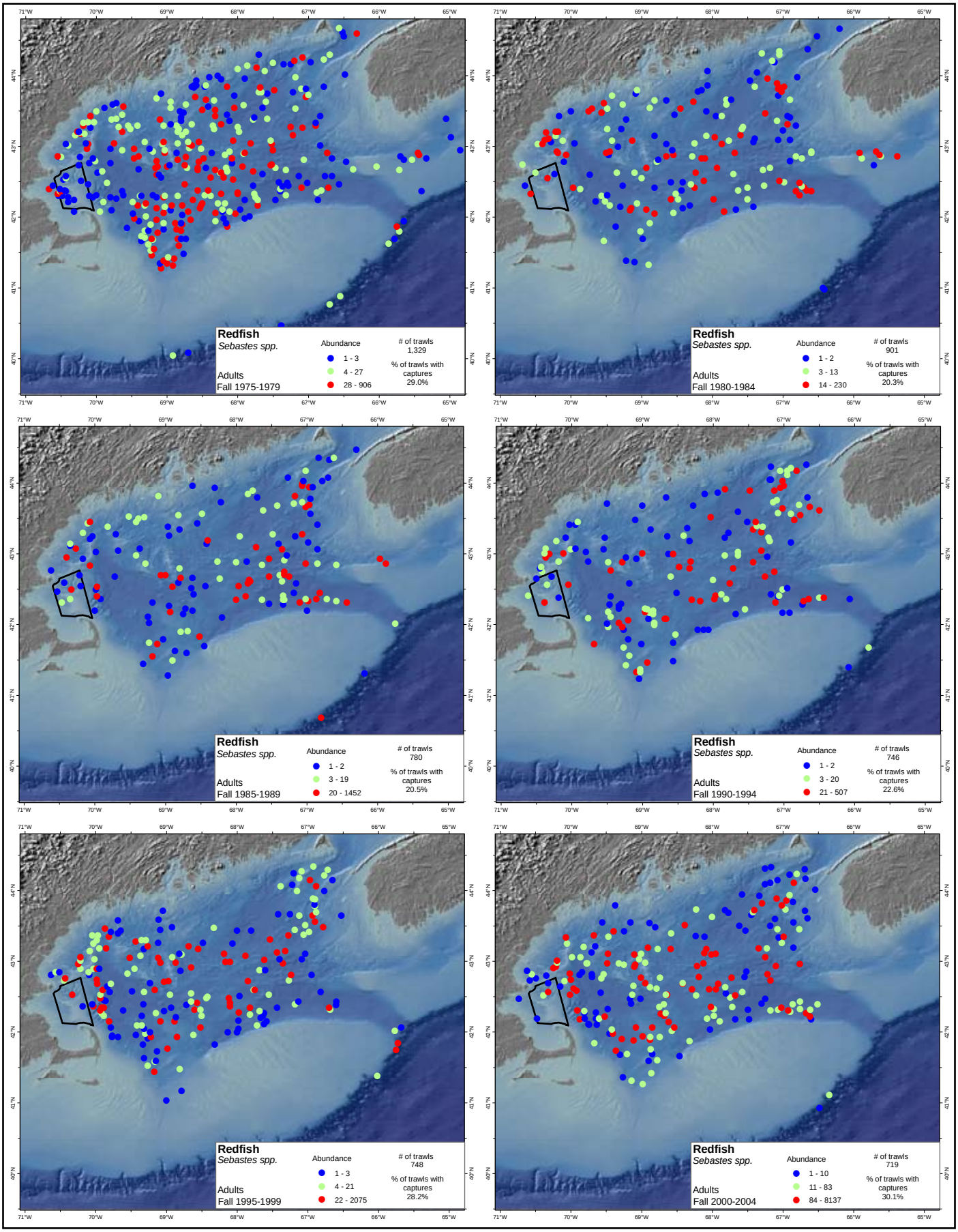

Figure 3.3.3. Abundance and distribution of adult redfish (*Sebastes* spp.) within the Gulf of Maine, Fall 1975-2004.

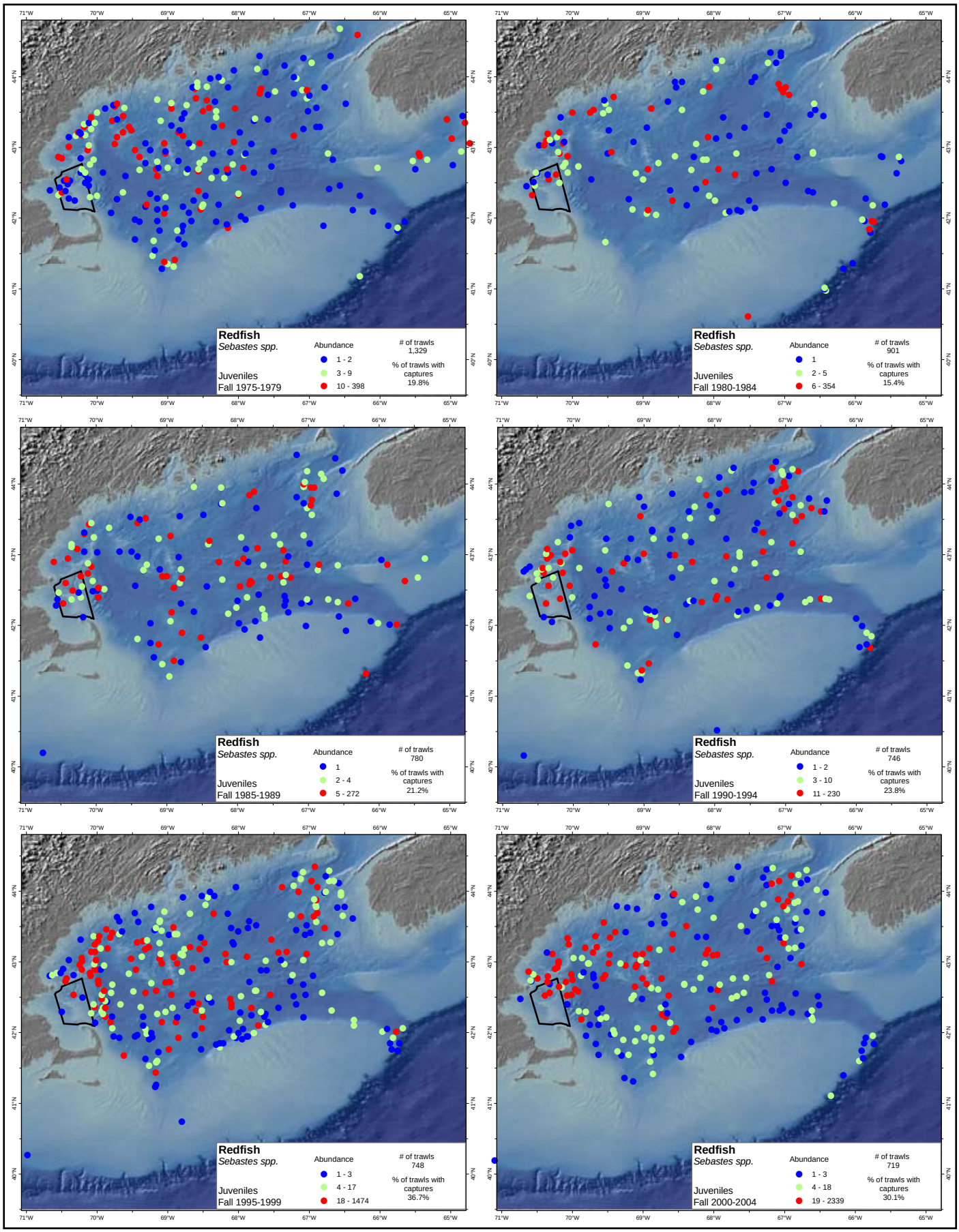

Figure 3.3.4. Abundance and distribution of juvenile redfish (*Sebastes* spp.) within the Gulf of Maine, Fall 1975-2004.

Barndoor skate (*Dipturus laevis)*
During 1999, barndoor skate were petitioned to be listed under the Endangered Species Act (ESA) due to extremely low population sizes (Casey and Meyers, 1998). Bigelow and Schroeder (1953) reported that barndoor skate were one of the most common species in the Gulf of Maine during the earlier portion of the 20th century, but its numbers have since severely declined. Due to slow growth, late maturity, and few offspring, barndoor skate are susceptible to overfishing. Seven species of skate, including the barndoor, are managed as a complex under the 2003 Skate Fishery Management Plan. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of barndoor skate inhabiting U.S. waters, primarily in the Gulf of Maine (Packer *et al.,* 2003a).

Life History
Barndoor skate are presumed to be a relatively long-lived, slow growing species, but no estimates of age and growth parameters are currently available. A similar species from the northeast Atlantic, *Raja batis*, has been estimated to attain an age of 50 years. Fertilized eggs are encapsulated in a leathery yellowish or greenish egg capsule and are rectangular in shape, 124-132 mm long, and 68-72 mm wide with a short horn at each corner. Juveniles do not hatch until late spring or early summer (under the assumption that eggs are laid in winter). The young are thought to be 180-190 mm total length (TL) at hatching, but small specimens are seldom captured. Skate greater than 101 cm TL are considered sexually mature. Adults can grow to 1.5 m in length and attain weights of 20 kg.

Barndoor skate primarily prey on benthic invertebrates and fishes, such as polychaetes, gastropods, bivalve mollusks, squids, crustaceans, and hydroids. Smaller individuals subsist mainly on benthic invertebrates, such as polychaetes, copepods, amphipods, isopods, the shrimp *Crangon septemspinosa*, and euphausiids, while larger skate eat larger and more active prey such as razor clams (*Ensis directus*), large gastropods, squids, crabs (*Cancer* spp. and spider crabs), lobsters and fishes. Fish prey includes spiny dogfish, alewife, Atlantic herring, menhaden, hakes, sculpins, cunner, tautog, sand lance, butterfish, and various flounder. Nothing is known of the predators of barndoor skate, but it is probably eaten by sharks. A similar species in the eastern North Pacific is preyed upon by sperm whales.

Habitat Characteristics
Barndoor skate occurs from the banks of Newfoundland, the southern Gulf of St. Lawrence, and along the northeastern coast and offshore banks of Nova Scotia down to North Carolina. Barndoor skate are found throughout the Gulf of Maine including off Nova Scotia, in St. Mary Bay, in the Bay of Fundy and Passamaquoddy Bay, from Eastport, Casco Bay, and the remainder of the coast of Maine, and from various localities in Massachusetts Bay. It also occurs on Georges Bank and Nantucket Shoals. However, based on surveys from Nova Scotia to Cape Hatteras during 1967-1970, barndoor skate was most abundant in the eastern Gulf of Maine and on the eastern section of Georges Bank, but none were found in the western Gulf of Maine.

Barndoor skate are found on mud bottoms as well as on sand and gravel, and occurs from the shoreline to about 750 m, but is most abundant at depths < 150 m. McEachran and Musick (1975), during trawl surveys conducted from Nova Scotia to Cape Hatteras, found it to be widespread from 38-351 m. Barndoor skate are widespread (but not numerous) to a depth of 183 m both in the open trough of the Gulf of Maine and in the bowl west of Jeffreys Ledge. They are perhaps more plentiful at 46-64 m on Georges Bank and Nantucket Shoals and has been reported as deep as 430 m off Nantucket. Juveniles are generally widespread from approximately 21-400 m, with most from about 61-140 m and adults are found from approximately 31-400 m, and often at depths greater than approximately 70 m in spring and 40 m in fall.

Time-Series Analysis
No adult barndoor skate were captured in NMFS surveys within the study area during spring between 1975-1989 (Figure 3.3.5). Adults were scarce during 1990-1994 and increased steadily through 2005. Juveniles were present throughout the 30 year sampling period, and, like adults, catches were scarce between 1975-1989 and frequency of occurrence increased significantly between 1990-2005 (Figure 3.3.6). Adults and juveniles were captured most frequently during the spring in the eastern Gulf of Maine, most notably near the shelf edge from the Northeast Channel to southern New England.

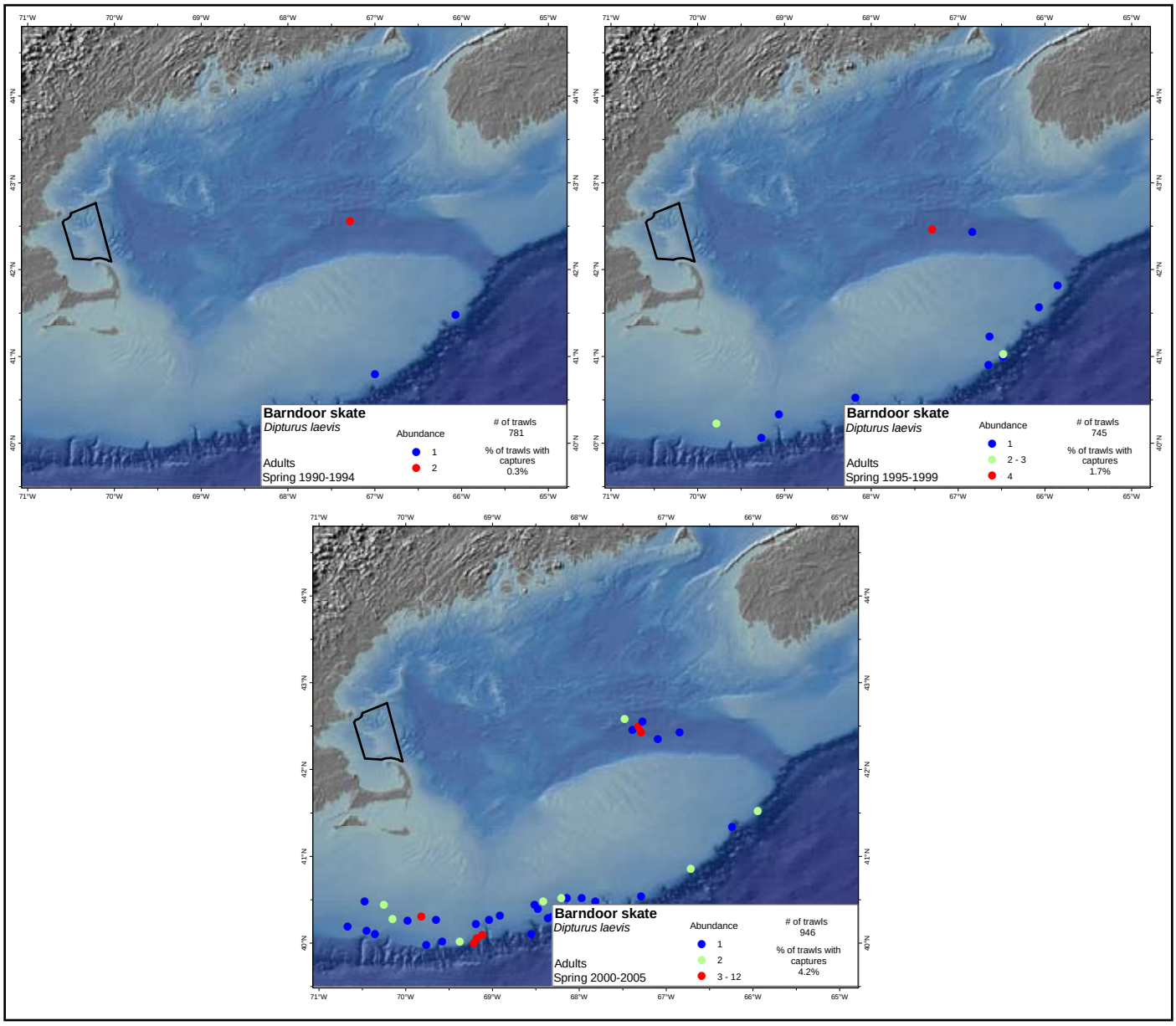

Figure 3.3.5. Abundance and distribution of adult barndoor skate (*Dipturus laevis*) within the Gulf of Maine, Spring 1975-2005. No adults were captured between 1975-1989.

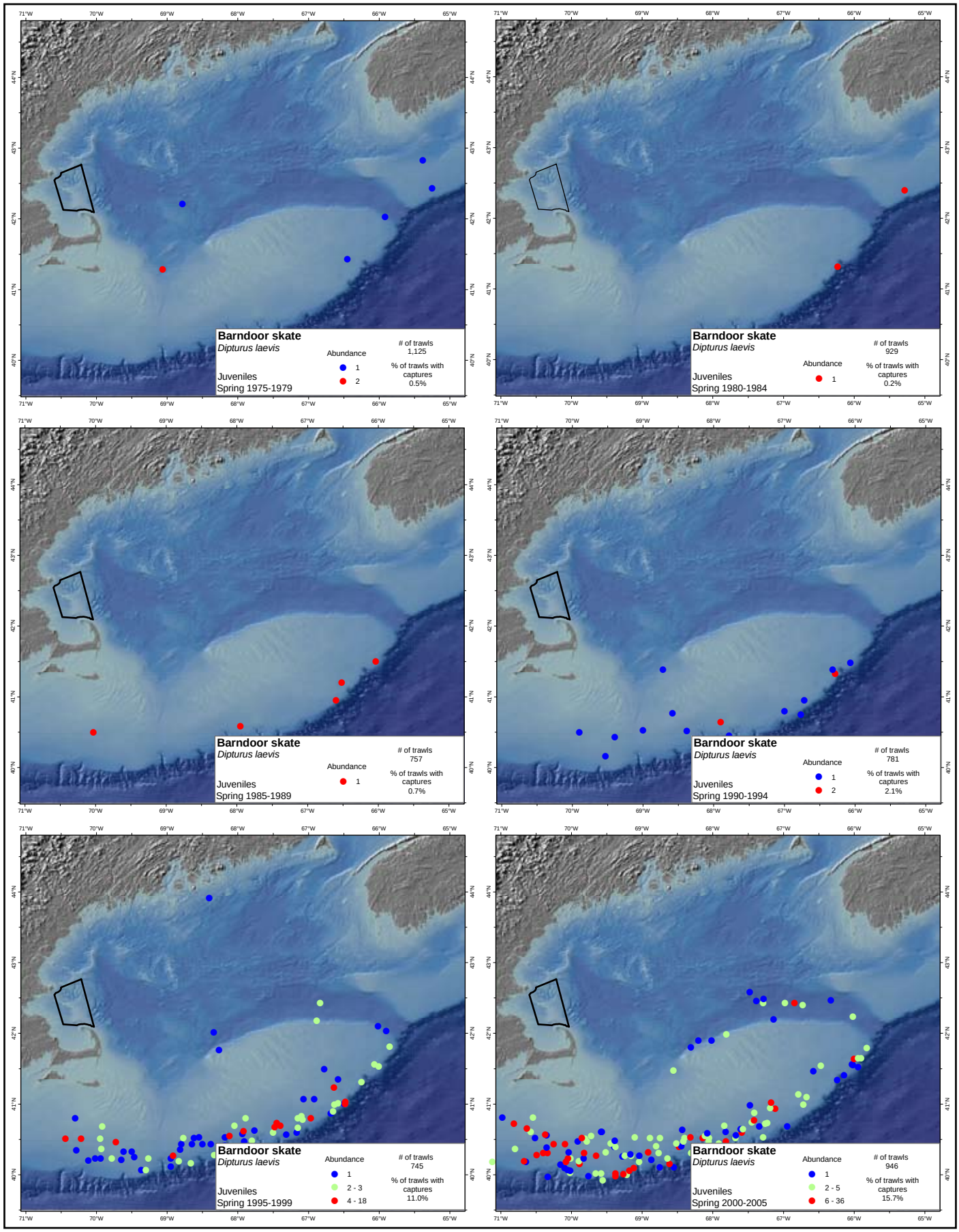

Figure 3.3.6. Abundance and distribution of juvenile barndoor skate (*Dipturus laevis*) within the Gulf of Maine, Spring 1975-2005.

During fall, adult and juvenile abundance and distribution followed similar patterns as observed during spring. Adult frequency of occurrence was considerably less than that observed during spring with catches only occurring during the years between 1999-2004 (Figure 3.3.7). Juvenile frequency of occurrence was low during 1975-1984 and gradually increased through 2004 (Figure 3.3.8). During the fall, the distribution of catches was similar to those observed during spring. Throughout the time series data, no barndoor skate were captured within the Sanctuary. In fact, few barndoor skate were captured in the northern and western Gulf of Maine. This pattern was described in prior trawl surveys by McEachran and Musick (1975).

Table 3.3.2. Frequency of occurrence and abundance for all barndoor skate captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	46.43	29.43	27.5	44	37-133	18.8	8	46-104
	80-84	22	36.36	2.32	26.3	29	47-88	16.2	8	58-101
	85-89	16	25.00	1.06	27.5	31	88-106	15.8	5	53-138
	90-94	21	42.86	15.19	26.2	34	66-120	15.8	4	60-117
	95-99	17	70.59	8.65	26.9	34	75-89	14.9	4	48-95
	00-05	17	64.71	48.76	28.2	39	80-144	14.5	4	55-149
Fall	75-79	61	52.46	5.97	28.2	45	48-105	19.2	13	37-133
	80-84	22	31.82	6.27	29.5	45	66-101	15.9	10	67-121
	85-89	20	55.00	16.40	28.1	37	53-138	14.6	8	81-106
	90-94	19	57.89	21.79	26.0	33	77-116	16.0	5	66-120
	95-99	18	72.22	77.22	25.3	30	66-95	15.6	5	74-123
	00-04	16	68.75	109.50	26.6	32	93-149	15.3	5	72-144

Atlantic cod (*Gadus morhua)*

Atlantic cod, at former levels of abundance, were keystone predators in the Gulf of Maine ecosystem, influencing the trophic relationships of many other functional groups of organisms (Jackson *et al*. 2001). Atlantic cod are important benthivores within the Gulf of Maine and Stellwagen Bank NMS. Historically, cod have been highly abundant in this region and supported a significant fishery in the U.S. and other countries. Cod abundance exhibits seasonal variability in Stellwagen Bank NMS, and the Gulf of Maine, and this species has a significant ecological role in the region.

The Atlantic cod is a demersal gadoid distributed in the northwest Atlantic Ocean from Greenland to Cape Hatteras, North Carolina. Densities are highest off Newfoundland, in the Gulf of St. Lawrence and on the Scotian Shelf, while in U.S. waters, densities are highest on Georges Bank and the western Gulf of Maine. The Georges Bank cod stock is the most southerly cod stock in the world. Atlantic cod are managed as two stocks in American waters: (1) Gulf of Maine and (2) Georges Bank and southward. Little interchange occurs between the two areas. Cod occur from nearshore areas to depths rarely exceeding 400 m.

Atlantic cod are Federally managed under the New England Fishery Management Councils Northeast Multispecies Management Plan. The information that follows is a summary of the Essential Fish Habitat source document

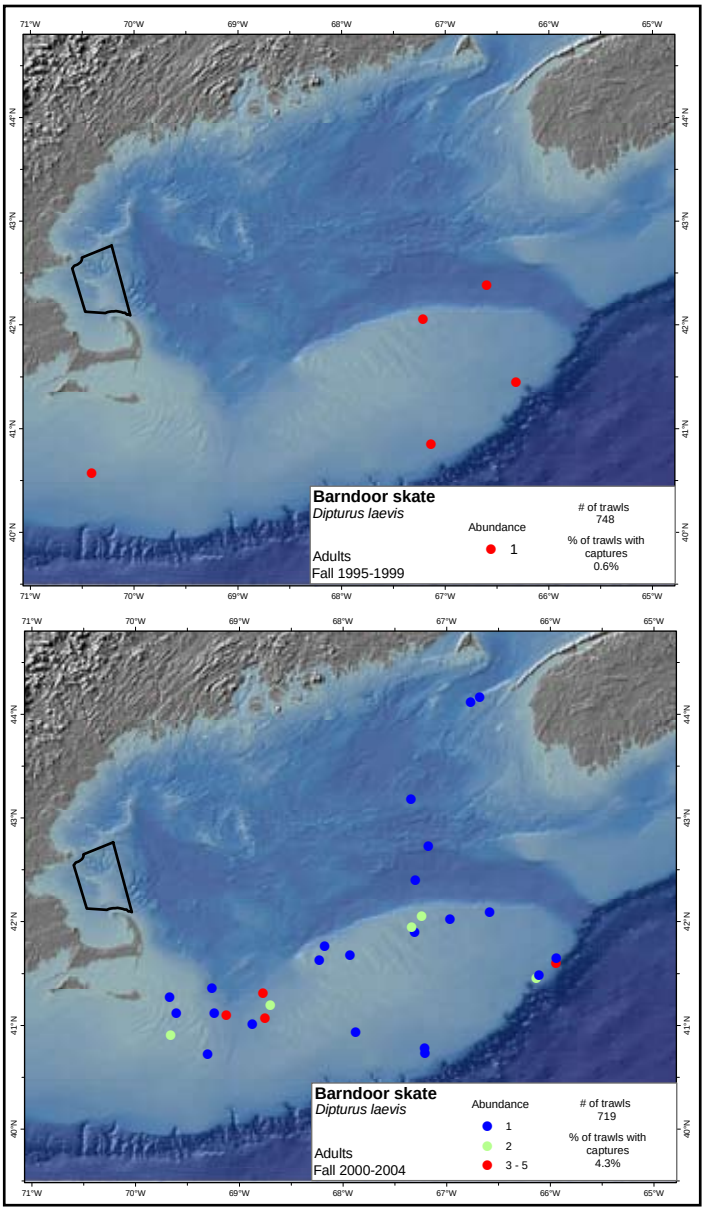

Figure 3.3.7. Abundance and distribution of adult barndoor skate (*Dipturus laevis*) within the Gulf of Maine, Fall 1975-2004. No adults were captured between 1975-1994.

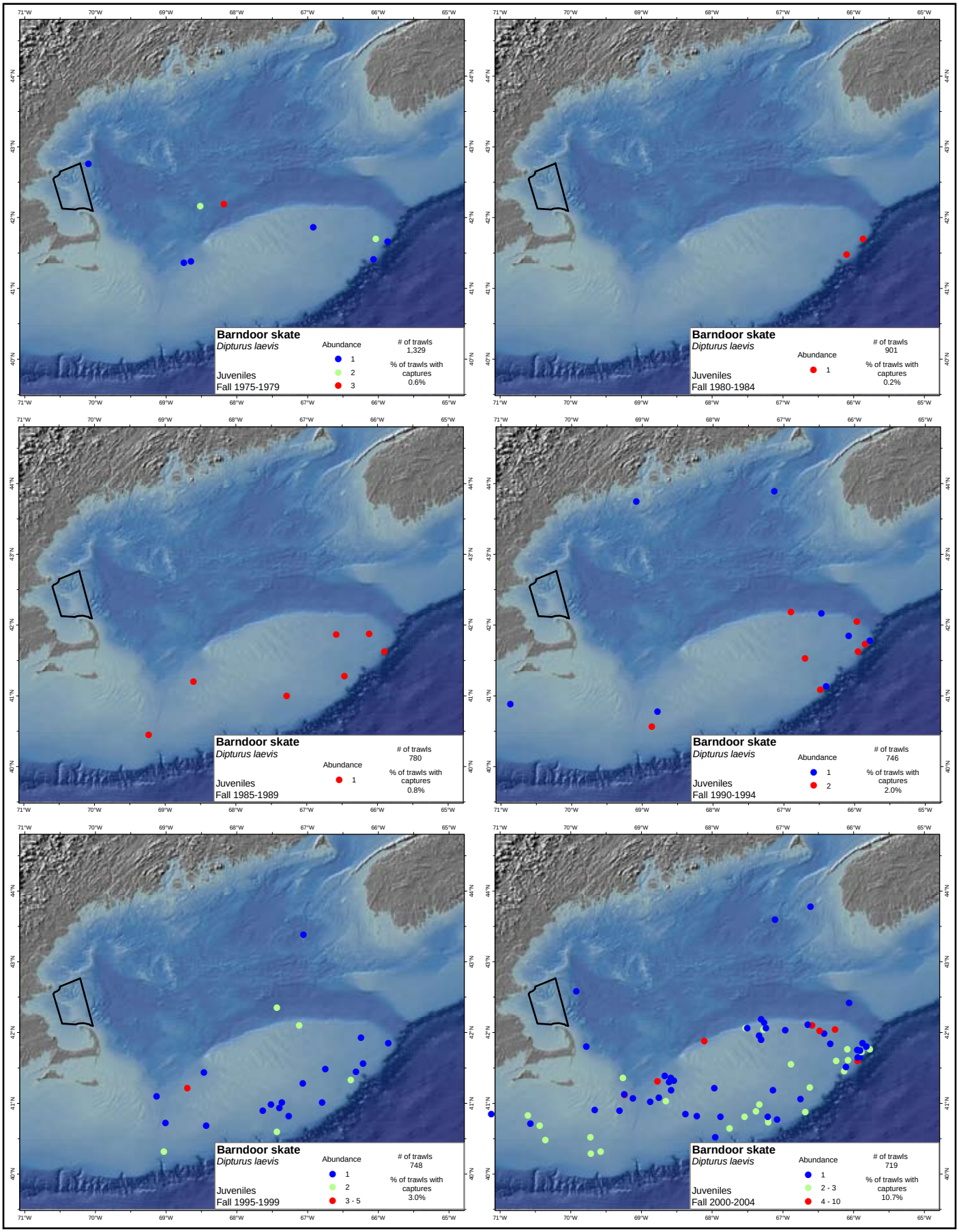

Figure 3.3.8. Abundance and distribution of juvenile barndoor skate (*Dipturus laevis*) within the Gulf of Maine, Fall 1975-2004.

for this species which provides life history information and habitat requirements of Atlantic cod inhabiting U.S. waters, primarily in the Gulf of Maine (Lough, 2004).

Life History

Atlantic cod eggs are pelagic, buoyant, spherical, and transparent. Hatching occurs after 8 to 60 days in varying temperatures and averages 2-3 weeks in typical spring conditions. Within the Gulf of Maine larvae hatch at sizes between 3.2 and 5.7 mm, occurring from near-surface to depths of 75 m, and move deeper with growth.

Transformation to the juvenile stage occurs at sizes greater than 20 mm and reach a mean length of 26 cm by the end of their first year. Adults are heavy-bodied and have a large head, blunt snout and a distinct barbel under the lower jaw tip. Color varies, but usually includes many small spots and a pale lateral line. Size averages 2.3-3.6 kg and the largest recorded was 95.9 kg. They tend to move in schools, usually on the bottom, although they may also occur in the water column.

Both size and age at maturity have declined in recent decades, likely in response to fishery harvest of older and larger fish, or to a general decline in stock biomass due to intense exploitation. Median lengths at maturity declined from 51 to 39 cm in males and 54 to 42 cm in females. This trend continued between 1972 and 1995 between Georges Bank and Labrador. Gulf of Maine cod attain sexual maturity at a later age than Georges Bank cod which is related to differences in growth rates between the two stocks.

On Georges Bank, an analysis of the MARMAP ichthyoplankton data set indicates that 60% of spawning occurs between February 23 and April 6, based on the abundance of Stage III eggs, back-calculated to spawning date. Ninety percent occurs between mid-November and mid-May, with a median date of mid-March. Spawning begins along the southern flank of Georges Bank and progresses toward the north and west and ends later in the year on the eastern side of the Bank. Historically, cod have spawned on both eastern and western Georges Bank. Within Massachusetts Bay, reported peak spawning activity occurs during January and February.

Reported food items vary by life history stage: early juveniles consumed pelagic invertebrates, medium-sized cod consumed benthic invertebrates and fish, and larger cod consumed larger amounts of fish. Adult and juvenile cod are opportunistic feeders, preferring sand lance, *Cancer* crab, and herring.

Planktivorous fish can be important predators of larval cod, especially Atlantic herring and Atlantic mackerel as they migrate northward in the spring and overlap with patches of larvae on the southern flank of Georges Bank. Juvenile cod are preyed upon by many piscivorous fish, such as dogfish, silver hake, larger cod, and sculpin. Because of their large size, adults have few predators other than large sharks.

Habitat Characteristics

Recently-settled juveniles are widely dispersed over the Bank and are present on a range of sediment types from sand to gravelly sand to gravel pavement. Juvenile cod are found predominantly in shoal waters, coastal or offshore banks, during summer and move to deeper water in winter. Cobble substrate is preferred over finer grained sediments and epibenthic invertebrates may be used for shelter from predators and high currents. Survival may be enhanced in structurally complex habitats. Adults are most abundant in Massachusetts Bay, northeast Georges Bank, and Nantucket Shoals and are predominantly found on rock, pebble, and gravel substrates. Adults are usually on bottom during day and may move up into the water column at night.

Time-Series Analysis

Adult cod were frequently captured in spring trawl samples throughout the Gulf of Maine with areas of high abundance occurring on Georges Bank, Browns Bank, and Massachusetts Bay (Figure 3.3.9). Frequency of occurrence was greater than 50% between 1975-1984 and gradually declined through 1999. Lowest adult frequency of occurrence was observed during 2000-2005 (34%). Juveniles were less frequent than adults during spring where frequency of occurrence ranged from 14-25% (Figure 3.3.10). Juveniles were most abundant on Georges Bank, Browns Bank, southern New England, and Massachusetts Bay.

Frequency of occurrence was considerably lower for adult cod (Figure 3.3.11) and juveniles (3.3.12) during fall compared to spring. Adults were captured most frequently during 1975-1979 (49%) and decreased steadily

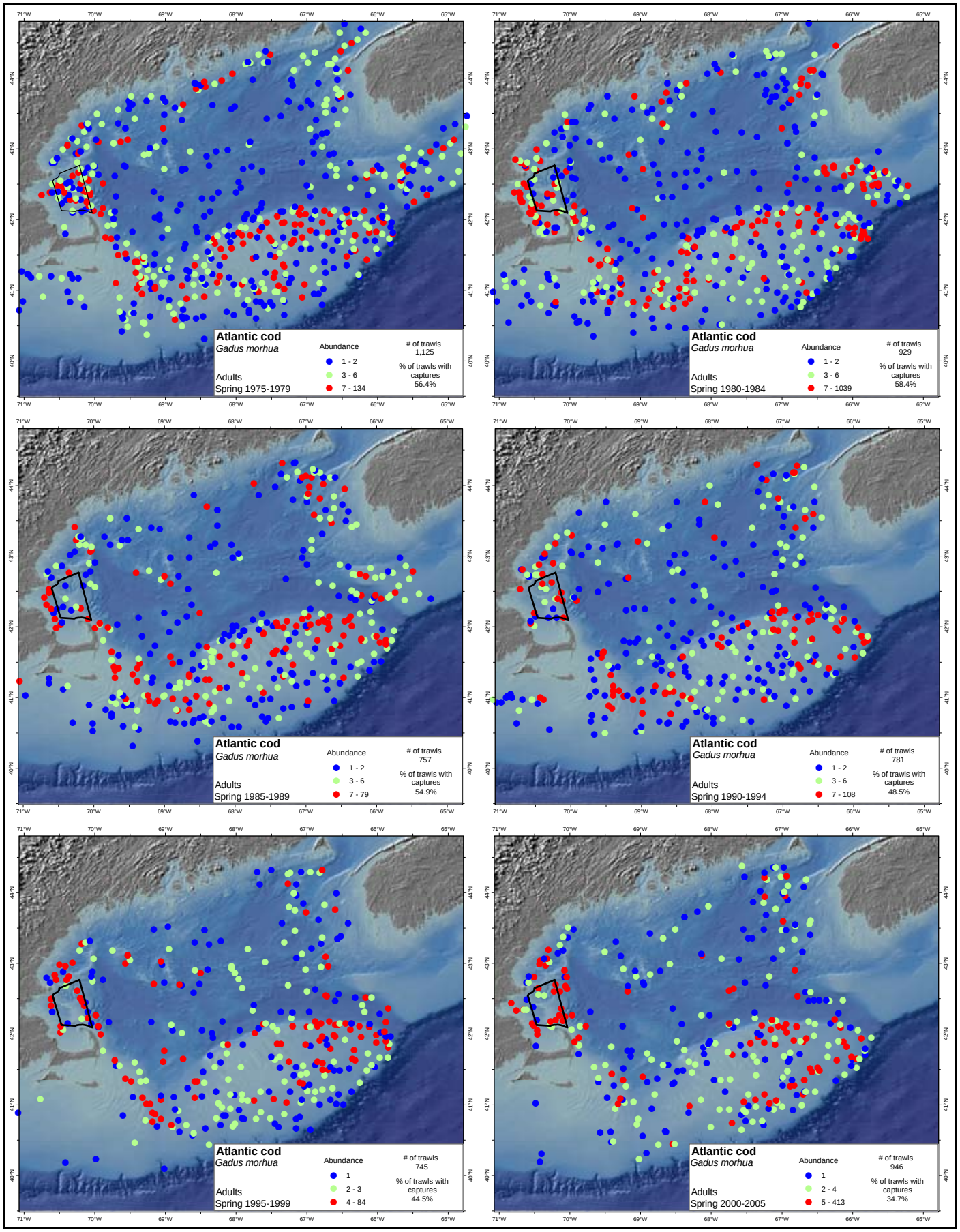

Figure 3.3.9. Abundance and distribution of adult Atlantic cod (*Gadus morhua*) within the Gulf of Maine, Spring 1975-2005.

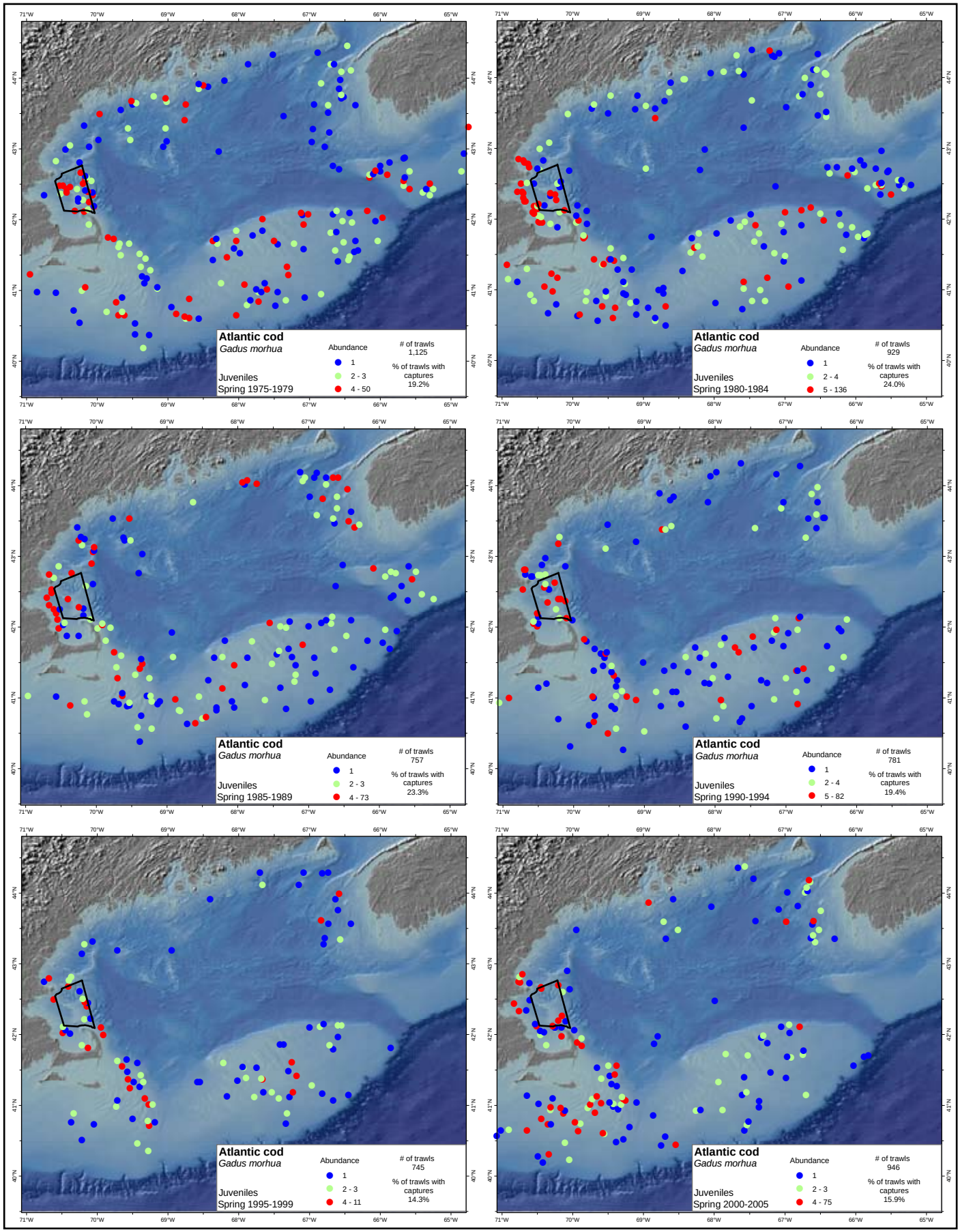

Figure 3.3.10. Abundance and distribution of juvenile Atlantic cod (*Gadus morhua*) within the Gulf of Maine, Spring 1975-2005.

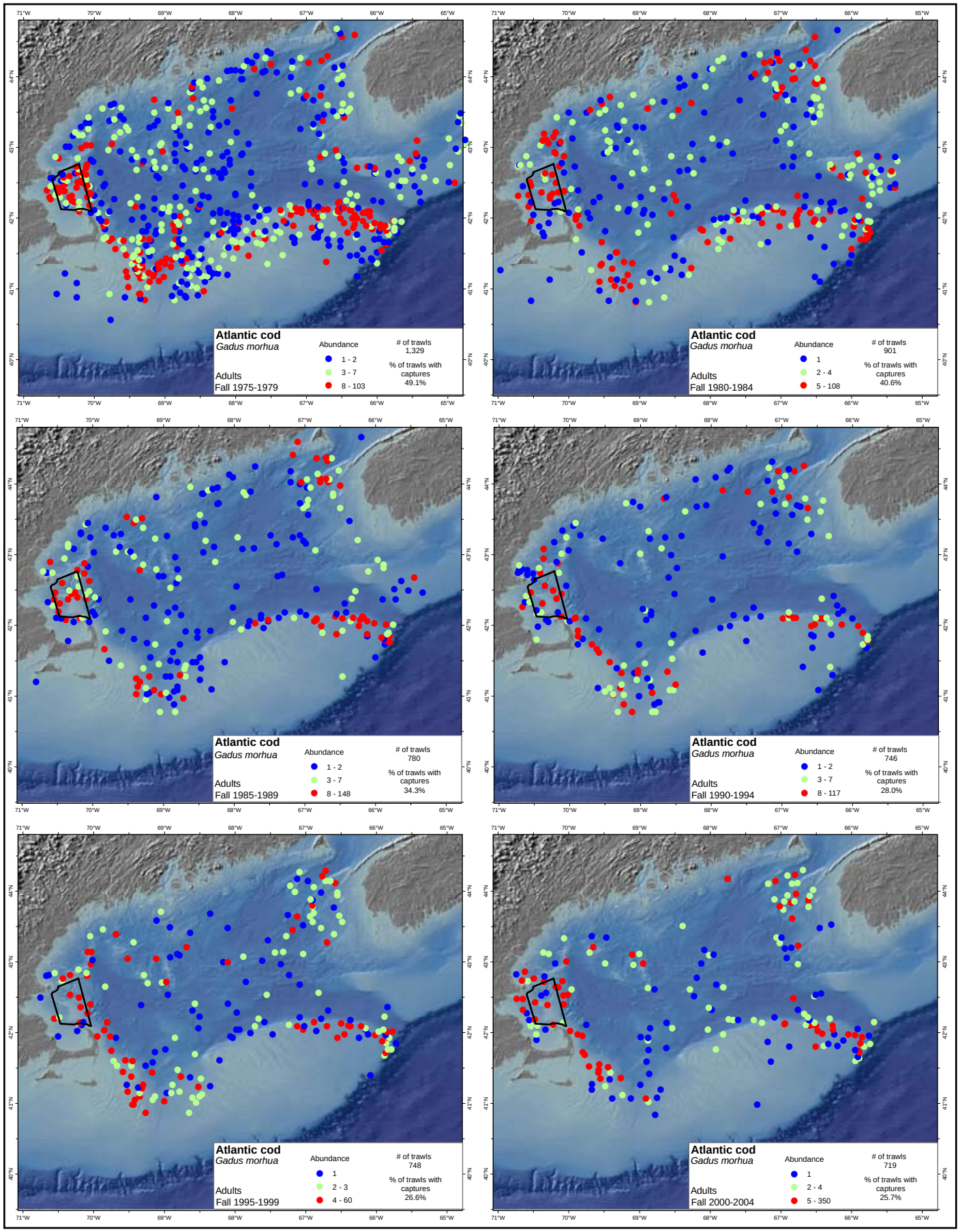

Figure 3.3.11. Abundance and distribution of adult Atlantic cod (*Gadus morhua*) within the Gulf of Maine, Fall 1975-2004.

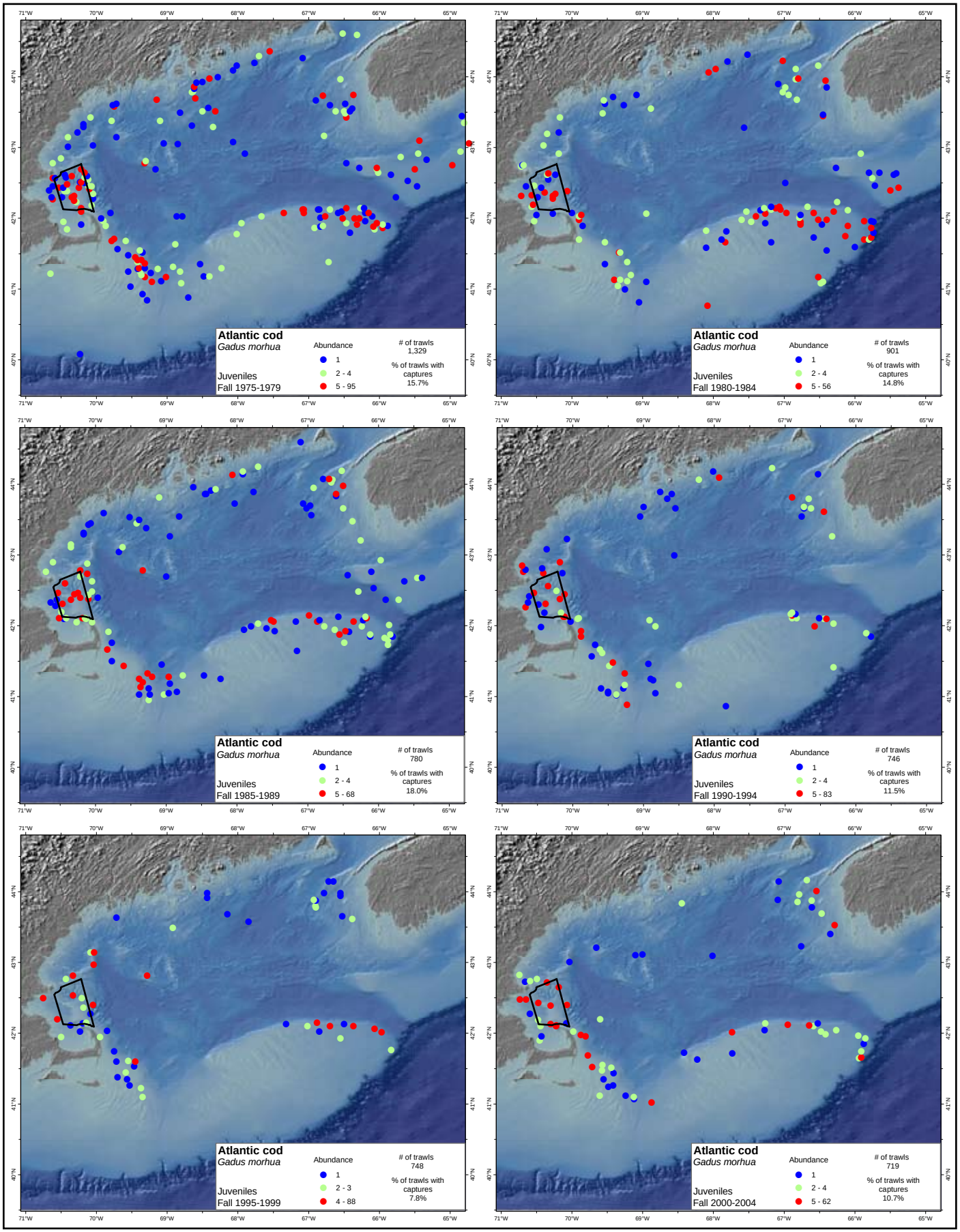

Figure 3.3.12. Abundance and distribution of juvenile Atlantic cod (*Gadus morhua*) within the Gulf of Maine, Fall 1975-2004.

throughout the time-series to 25% during 2000-2004. Juveniles exhibited a similar pattern with frequency of occurrence ranging from 18% in 1985-1989 to 10% during 2000-2004. As abundance declined through the time-series, distribution retracted in spatial extent.

Adult and juvenile cod were highly abundant and frequently captured in trawls within the Sanctuary during spring and fall (Table 3.3.3). Mean lengths for adults captured in spring ranged between 47-64 cm throughout the time period and maximum length for adults ranged from 74-141 cm. Mean length of adults was greatest during 2000-2005. Adults and juveniles were captured at depths ranging between 30-144 m and cod abundance was greatest between 70-100 m. Similar length frequency and abundance estimates were observed during fall.

Table 3.3.3. Frequency of occurrence and abundance for all Atlantic cod captured in NMFS trawl surveys within Stellwagen Bank NMS. Length and depth ranges are segregated for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	91.07	11.55	57.70	130	33-133	27.43	5	33-113
	80-84	22	90.91	16.73	57.92	121	33-121	25.69	13	33-93
	85-89	16	87.50	11.50	53.54	136	30-126	25.57	11	32-106
	90-94	21	71.43	11.33	47.71	74	30-120	28.37	18	30-120
	95-99	17	94.12	17.41	55.35	141	41-123	29.70	20	41-123
	00-05	17	94.12	21.94	64.75	115	27-144	26.69	18	36-97
Fall	75-79	61	86.89	18.69	53.83	131	30-118	28.22	2	30-104
	80-84	22	90.91	20.05	55.83	127	28-101	28.70	6	29-101
	85-89	20	75.00	27.25	54.73	128	53-138	26.84	7	53-93
	90-94	19	84.21	14.05	49.71	89	44-111	26.08	7	44-111
	95-99	18	72.22	13.61	52.67	99	48-95	27.55	5	48-95
	00-04	16	87.50	23.44	61.46	126	45-149	23.43	5	45-93

Atlantic herring (*Clupea harengus)*

Atlantic herring are important planktivores in the Gulf of Maine and are a primary prey for many higher trophic level species. Herring populations in the Gulf are recovering after severe population decline during the 1960s. Atlantic herring are Federally managed under the New England Fishery Management Councils Northeast Multispecies Management Plan. Herring are assessed and managed in U.S. waters as a single stock complex with two major spawning components, one in the Gulf of Maine and another on Georges Bank and Nantucket Shoals. Herring that spawn in the Bay of Fundy and off southwest Nova Scotia are assessed and managed by Canada. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of Atlantic herring inhabiting U.S. waters, primarily in the Gulf of Maine (Stevenson and Scott, 2005).

Life History

The Atlantic herring is a pelagic, schooling, plankton-feeding species that inhabits both sides of the North Atlantic Ocean. In the western North Atlantic this species ranges from Labrador to Cape Hatteras and supports major commercial fisheries. Adult herring undergo complex north-south migrations for feeding, spawning, and overwintering. Herring produce demersal eggs and spawn during the summer and fall in the Gulf of Maine and Georges Bank region. Larvae overwinter offshore and in coastal waters and metamorphose into juveniles in the spring. Juveniles and adults are heavily preyed upon by a variety of marine fish, marine mammals, and seabirds.

Atlantic herring deposit demersal eggs in 5-90 m of water in areas with strong tidal currents on a variety of substrates ranging from boulders, rocks, and gravel, to sand, shell fragments, and macrophytes. The larval stage of fall-spawned herring in the Gulf of Maine lasts 4-8 months, depending on the timing of spawning. The larval stage is shortest for early spawned (August) larvae, and longest for late-spawned (December) herring. Currents

affect the pelagic larvae, however, they may or may not disperse randomly from the spawning grounds. Some larvae are retained for several months after hatching on or near the spawning site, while others are dispersed soon after hatching and drift with residual currents. Larvae metamorphose into juveniles at 40-55 mm standard length (SL) in the spring (April-May). Growth is rapid, with juveniles in coastal Maine waters reaching lengths of 90-125 mm by the end of their first year. Schooling behavior begins during metamorphosis and is well established by the time the larvae have made the transition to the juvenile life stage. In the Gulf of Maine, one year-old juveniles move out of nearshore waters in the summer and fall to overwinter in deep bays or near the bottom in offshore areas. Two-year old juveniles return inshore the following spring when they are fully recruited to the coastal fishery. Juvenile herring do not make seasonal north-south migrations. One and two-year-old juveniles form large schools in coastal waters throughout the Gulf of Maine in the spring and summer. They are abundant or highly abundant in most estuaries and embayments north of Cape Cod and are particularly numerous in summer between Penobscot Bay and Passamaquoddy Bay. Juvenile herring perform diurnal vertical migrations that are linked to changing light intensity, most likely in response to prey movement. Juvenile and adult herring feed on a variety of planktonic organisms.

Like juveniles, adult herring are pelagic and form large schools, feeding on planktonic organisms. Adults in the Gulf of Maine region occupy inshore and offshore waters to depths of 200 m and make extensive seasonal migrations between summer and fall spawning grounds on Georges Bank and in the Gulf of Maine and overwintering areas in southern New England and the Mid-Atlantic region. Adults occur in estuaries and embayments from Passamaquoddy Bay (Bay of Fundy) to Long Island Sound. They are abundant or highly abundant from April to November in estuaries and embayments north of Muscongus Bay, in mid-coast Maine. Adults generally are common or rare south of Long Island Sound. Thermal oceanic fronts between colder and less saline continental shelf water and warmer, more saline continental slope water provide an abundance of plankton and other food sources and greatly influence the migratory behavior and spatial distribution patterns of this species.

Most Atlantic herring in the Gulf of Maine region mature at 3 years of age and a total length of about 25 cm. In this report herring ≥ 25 cm were considered to be adults. In the northwest Atlantic, herring spawn from Labrador to Nantucket Shoals. Spawning occurs in the spring, summer, and fall in more northern latitudes, but summer and fall spawning predominates in the Gulf of Maine and Georges Bank region.

Atlantic herring prey upon a variety of planktivorous organisms. They are visual particulate feeders with diverse feeding behaviors, often switching between filtering and biting in response to light intensity and the size of available food. Juveniles feed on up to 15 different groups of zooplankton. The most common are copepods, decapod larvae, barnacle larvae, cladocerans, and molluscan larvae. Adults have a diet dominated by euphausiids, chaetognaths, and copepods.

Herring is an important species in the food web of the northwest Atlantic. Demersal fish species that have been observed feeding on herring eggs include cod, haddock, cunner, and red hake. Invertebrates that consume herring eggs include moon snails, hermit crabs, and starfish. Herring eggs and larvae are also consumed by sand lance. Atlantic herring is an important prey species for a large number of piscivorous fish, elasmobranchs (sharks and skate), marine mammals, and seabirds in the northwest Atlantic. The principal finfish and elasmobranch species that feed on Atlantic herring are Atlantic cod, silver hake, thorny skate, bluefish, goosefish, weakfish, summer flounder, white hake, spiny dogfish, and, in certain locations and times of year, Atlantic bluefin tuna. The spiny dogfish is a much more important predator on Atlantic herring than is indicated by diet composition data. Estimates indicate that spiny dogfish consumed an average of 67,660 metric tons (mt) of Atlantic herring a year during 1977-1998, with a range of 15,526 to 148,197 mt. Thus, in some years, spiny dogfish may consume a greater quantity of herring biomass than is taken in the commercial fishery.

Habitat Characteristics

Juveniles are entirely pelagic and prefer temperatures between 8-12°C. Physiological stress has been observed at temperatures below 4°C and above 16°C. In the spring, juveniles were found between 2-12°C, with most between 3-7°C. During autumn, they were found between 5-17°C, with the majority between 6-10°C. They occurred on the outer continental shelf to a maximum depth of 300 m in the spring and fall. In the spring, the majority were found in depths < 100 m. Juveniles were caught in a salinity range of 30-35 ppt in the spring and 32-35 ppt in the autumn, with the majority found at 32-33 ppt during spring and 33-34 ppt in the autumn. Salinity is probably

not as important a factor as temperature in affecting their distribution and movements. There is a tendency for herring to prefer higher salinities and to avoid brackish conditions with increasing age.

Like juvenile herring, adults utilize pelagic habitats, only using the bottom for spawning. Observations of seasonal distribution on Georges Bank suggested a preferred temperature range of 5-9°C. Adults regularly enter bays and estuaries, but are rarely found in low salinities. Factors that may affect herring distribution include currents and frontal zones. Well-mixed waters and transition zones between well-mixed and stratified waters are preferred habitats for adult herring. Fronts created by currents and eddies act as distribution boundaries for herring through their direct effects on the fish themselves, and also indirectly by aggregating planktonic food organisms and increasing the production of zooplankton.

In the spring, adults are found between 2-13°C, with most between 4-7°C. During autumn, adult herring are found between 4-16°C, with the majority between 6-10°C. They occur on the outer continental shelf to a maximum depth of 300 m in both spring and fall. In the fall, most were found > 80 m, while in the spring, the majority were found at shallower depths. They were caught in a salinity range of 27-35 ppt in the spring and 32-35 ppt in the autumn, with the majority found at 33 ppt during spring and 33-34 ppt in the autumn.

Time-Series Analysis

Within the study area, adult herring were captured at depths between 30-150 m with peak abundance between 60-90 m during the spring and 70-110 m during the fall. Peak abundance for adults generally centered around Massachusetts Bay, southern New England, and Georges Bank in both spring and fall. Adult frequency of occurrence was low during spring 1975-1989 (Figure 3.3.13) and increased by more than 100% during 1990-2005. During spring, juveniles were also abundant in Massachusetts Bay, southern New England, and Georges Bank, but were more abundant and exhibited higher frequency of occurrence than adults (Figure 3.3.14). Juveniles were captured at depths ranging from 10-370 m, but were most abundant between 30-90 m. Similar to adults, juvenile frequency of occurrence was low during the first half of the time-series (1975-1989) and increased considerably between 1990-2005.

Similar patterns of abundance, distribution, and frequency of occurrence were observed during fall for both adults (Figure 3.3.15) and juvenile herring (Figure 3.3.16). Adult and juvenile frequency of occurrence was low during 1975-1989 and increased significantly between 1990-2004. In general, patterns of peak abundance appeared to follow the bathymetric contour of Stellwagen Bank and Georges Bank whereas this trend was not apparent during the spring. This pattern may reflect a response to fronts that frequently form during the summer and fall periods of stratification which may aggregate prey items for both adult and juvenile herring.

Table 3.3.4. Frequency of occurrence and abundance for all Atlantic herring captured in NMFS trawl surveys within Stellwagen Bank NMS. Length and depth ranges are segregated for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	44.64	6.29	28.24	37	33-90	18.62	10	38-85
	80-84	22	50.00	20.64	27.79	31	37-121	22.43	20	58-92
	85-89	16	62.50	10.63	27.44	30	32-88	20.71	4	33-88
	90-94	21	76.19	82.81	27.44	32	30-116	18.66	12	30-116
	95-99	17	70.59	10.88	27.11	31	41-123	19.86	14	41-123
	00-05	17	47.06	22.06	27.54	32	27-144	21.69	14	27-144
Fall	75-79	61	22.95	5.54	29.51	39	46-105	20.00	12	71-82
	80-84	22	36.36	6.77	28.75	35	54-88	23.00	21	60-84
	85-89	20	80.00	199.55	28.43	35	53-93	21.90	14	53-89
	90-94	19	89.47	160.32	27.93	33	44-117	22.77	20	44-117
	95-99	18	88.89	55.94	27.63	33	59-95	21.26	12	53-95
	00-04	16	100.00	62.19	26.79	30	45-149	21.24	13	45-149

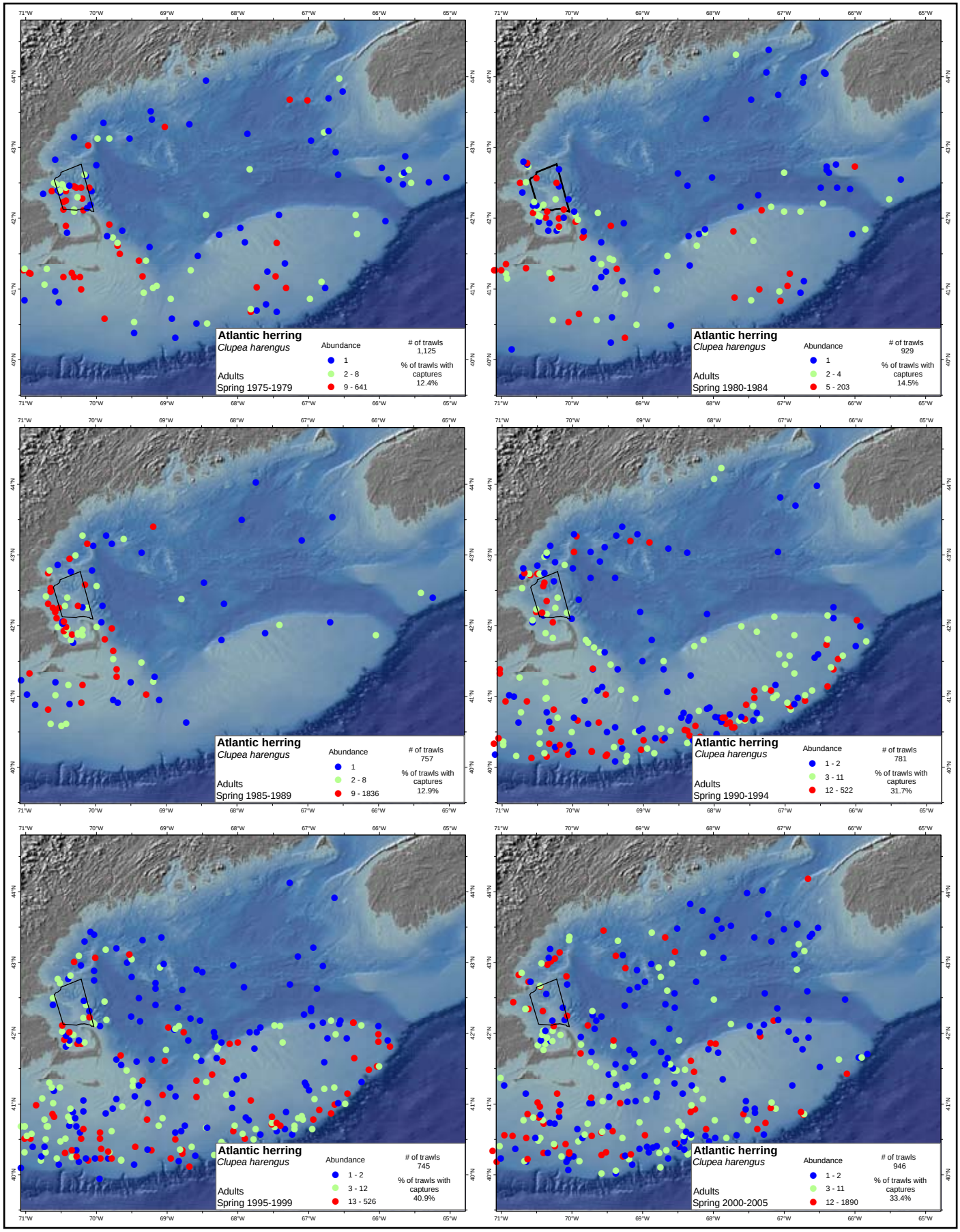

Figure 3.3.13. Abundance and distribution of adult Atlantic herring (*Clupea harengus*) within the Gulf of Maine, Spring 1975-2005.

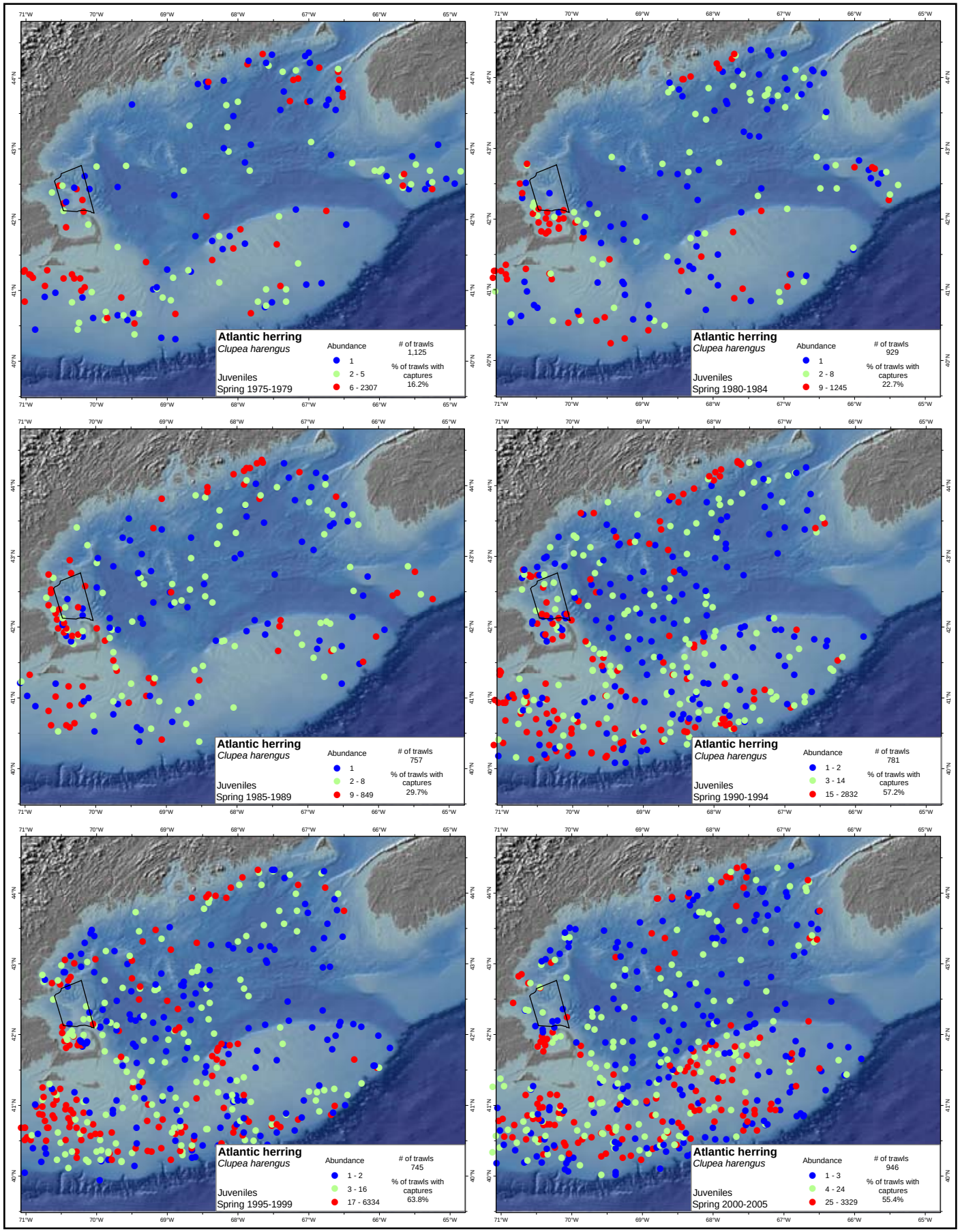

Figure 3.3.14. Abundance and distribution of juvenile Atlantic herring (*Clupea harengus*) within the Gulf of Maine, Spring 1975-2005.

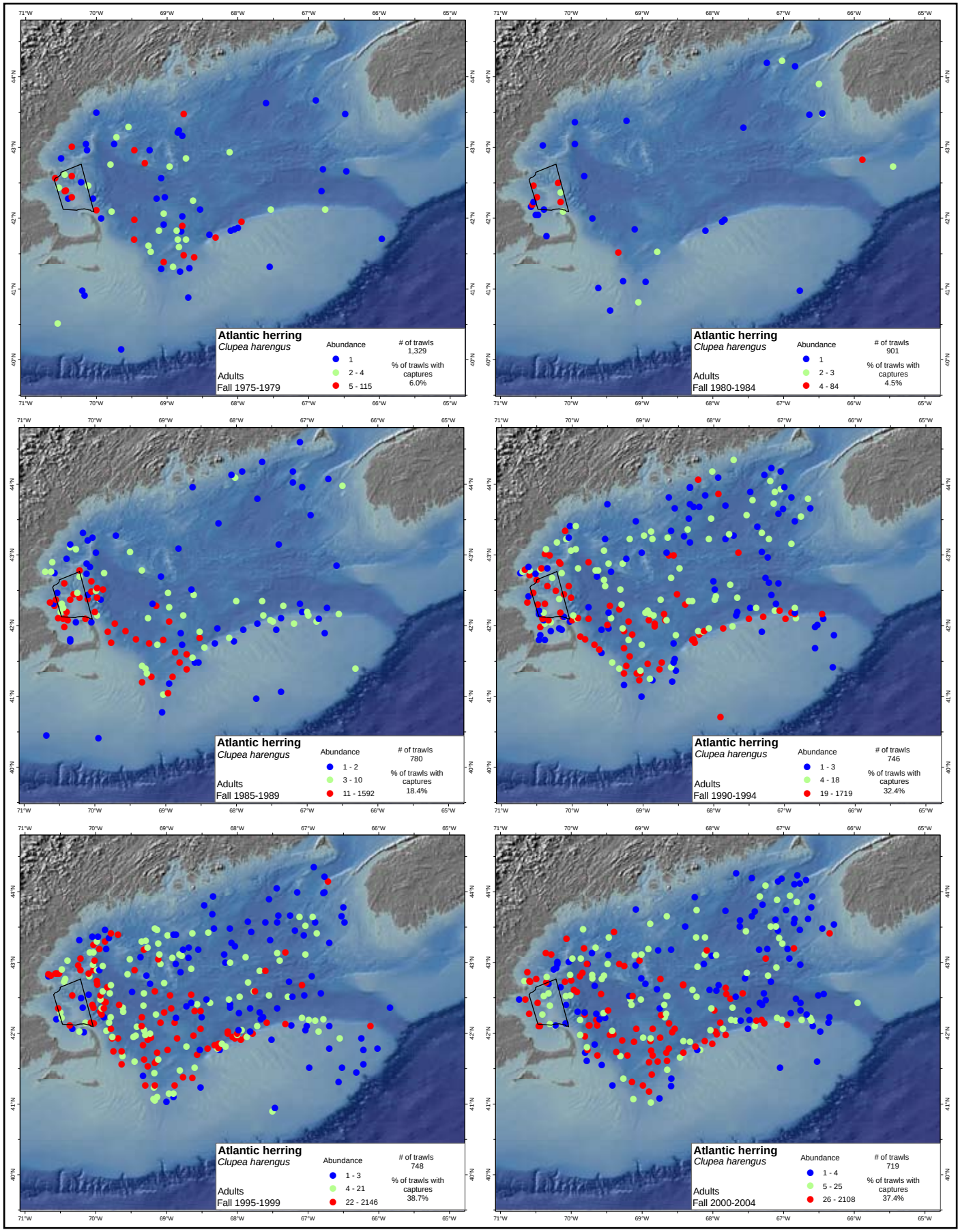

Figure 3.3.15. Abundance and distribution of adult Atlantic herring (*Clupea harengus*) within the Gulf of Maine, Fall 1975-2004.

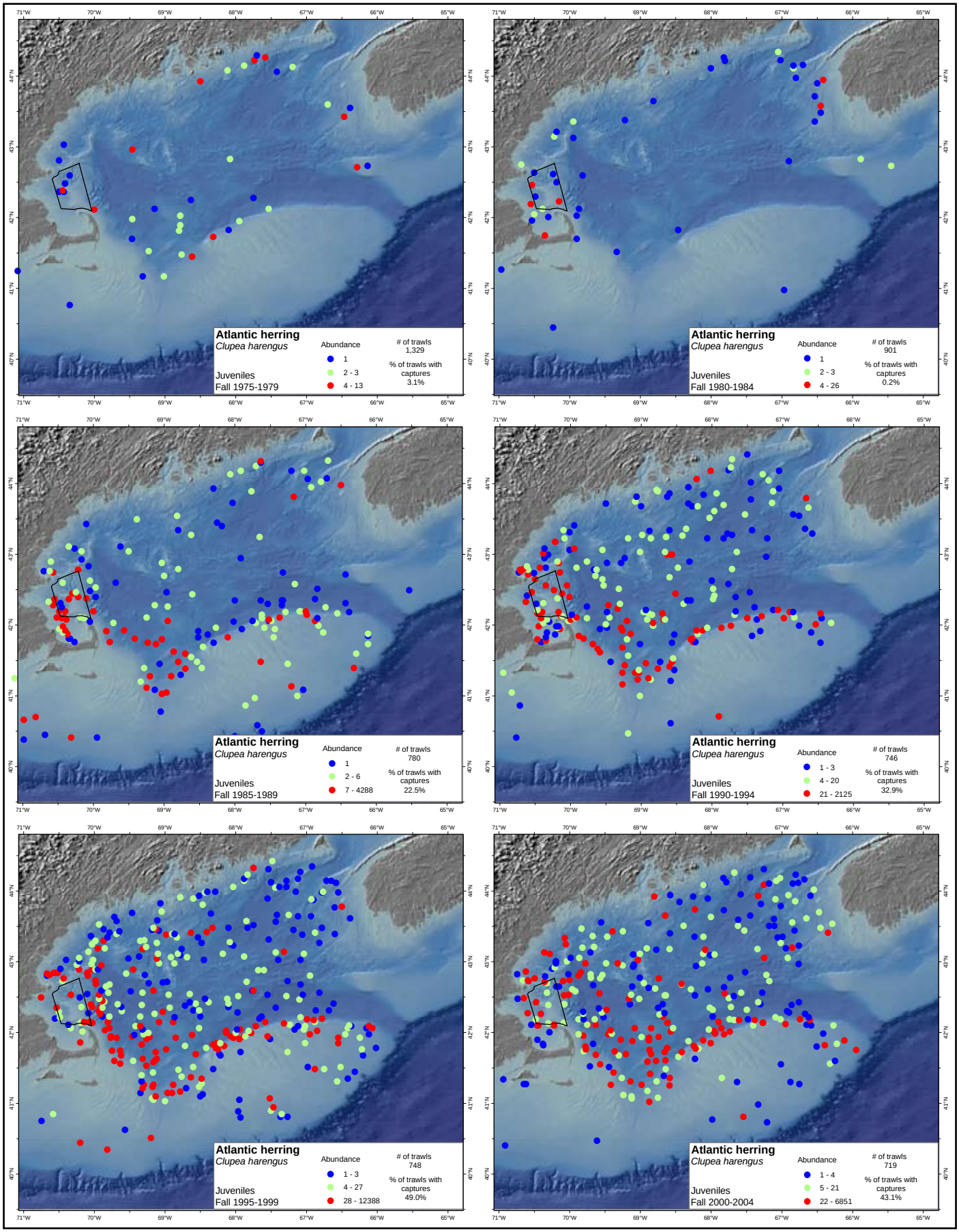

Figure 3.3.16. Abundance and distribution of juvenile Atlantic herring (*Clupea harengus*) within the Gulf of Maine, Fall 1975-2004.

Adult and juvenile herring abundance was variable at sampling stations within the Sanctuary (Table 3.3.4). Frequency of occurrence followed the broader study area pattern during 1975-1984 and was significantly greater between 1985-2005. Overall, juvenile and adult abundance was higher during fall than spring. During both spring and fall, peak abundance for juveniles occurred at shallower depths (60-80 m-spring, 60-90 m-fall) than adults (60-120 m-spring, 70-100 m-fall). Little difference was observed between mean adult size across seasons and a slight decrease throughout the time-series. Maximum size of adults decreased during each season through the time-series. Juveniles exhibited greater mean size variability and were generally larger in fall samples.

Atlantic mackerel (*Scomber scombrus)*
Along with Atlantic herring, mackerel are important planktivores and an important prey item for many predators in the Gulf of Maine. Historically, mackerel have been highly abundant in the region, however the stock is currently recovering from severe population decline in the 1970s. Atlantic mackerel are managed under the Mid-Atlantic Fishery Management Plan for Atlantic mackerel, squid and butterfish. While there are two separate spawning contingents in the northwest Atlantic, all mackerel in this area have been assessed as a unit stock since 1975 and are considered one stock for management purposes. A brief synopsis of the life history of Atlantic mackerel is provided in Amendment #5 to the Fishery Management Plan for Atlantic Mackerel, Squid and Butterfish Fisheries (MAFMC, 1994). The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of Atlantic mackerel inhabiting U.S. waters, primarily in the Gulf of Maine (Studholme *et al.,* 1999).

Life History
Atlantic mackerel is a fast swimming, pelagic schooling species distributed in the northwest Atlantic from the Gulf of St. Lawrence to Cape Lookout, North Carolina. There are two spawning contingents, a southern group that spawns primarily in the Mid-Atlantic Bight and Gulf of Maine from mid-April to June and a northern contingent that spawns in the southern Gulf of St. Lawrence from the end of May to mid-August. The southern contingent begins the spring spawning migration by moving inshore between Delaware Bay and Cape Hatteras, usually between mid-March and mid-April depending to some extent on water temperature. The northern contingent begins to move inshore off southern New England usually in late May, mixing temporarily with part of the southern contingent before migrating eastward along the coast of Nova Scotia. Most of the spawning occurs in the shoreward half of continental shelf waters, although there is some spawning on the shelf edge and beyond. Southern New England and the Middle Atlantic states are the most important spawning grounds for mackerel. The southern side of the Gulf of St. Lawrence is considered extremely productive for the northern contingent, while the Gulf of Maine and coast of outer Nova Scotia are the least productive. Some open bays such as Cape Cod Bay and Massachusetts Bay, are sites of importance with spawning fish abundant or common from May to July and August.

The NEFSC MARMAP ichthyoplankton surveys found eggs from offshore waters off Chesapeake Bay to Georges Bank and the Gulf of Maine. The ichthyoplankton surveys also found larvae (< 13 mm) from waters off Chesapeake Bay to the Gulf of Maine, although more were concentrated offshore of Delaware Bay to Massachusetts Bay from inshore waters to the seaward limits of the survey. Larvae were collected from May through August with the highest average mean density (> 10,000/10 m^2) occurring in June and ranging from inshore to offshore from southern New England to the Hudson Canyon with considerable numbers collected north of Cape Cod. Postlarvae gradually transform from planktonic to swimming and schooling behavior at about 30-50 mm. Fish reach a length of about 50 mm in approximately two months at which time they closely resemble adults and reach 20 cm in December after about one year of growth. By the end of their second year, Atlantic mackerel attain a size of about 26 cm and about 33 cm after five years. Adults are considered to be >25 cm standard length (SL).

Atlantic mackerel are opportunistic feeders that can ingest prey either by individual selection of organisms or by passive filter feeding. Larvae feed primarily on zooplankton. First-feeding larvae (3.5 mm) collected from Long Island Sound were found to be phytophagous while slightly larger individuals (> 4.4 mm) fed on copepod nauplii. Consumption rates of larvae average between 25 and 75% body weight per day and they probably feed continuously. Larvae feed selectively, primarily on the basis of prey visibility. Juveniles eat mostly small crustaceans such as copepods, amphipods, mysid shrimp and decapod larvae. They also feed on small pelagic mollusks (*Spiratella* and *Clione*) when available. Adults feed on the same food as juveniles, but diets also include a wider assortment of organisms and larger prey items. For example, euphausiid, pandalid and crangonid shrimp are

common prey. Chaetognaths, larvaceans, pelagic polychaetes and larvae of many marine species have been identified in mackerel stomachs. Large prey such as squids (*Loligo*) and fishes (silver and other hakes, sand lance, herring, and sculpins) are not uncommon, especially for large mackerel.

Predation has a major influence on the dynamics of northwest Atlantic mackerel. Predation mortality is probably the largest component of mackerel natural mortality, and based on model predictions, may be higher than previously thought. Atlantic mackerel serve as prey for a wide variety of predators including other mackerel, dogfish, tunas, bonito, and striped bass. Small mackerel are prey for Atlantic cod and squid, which feed on fish < 10 to 13 cm in length. Pilot whales, common dolphins, harbor seals, porpoises and seabirds are also significant predators. Other predators include swordfish, bigeye thresher, thresher, shortfin mako, tiger shark, blue shark, spiny dogfish, dusky shark, king mackerel, thorny skate, silver hake, red hake, bluefish, pollock, white hake, goosefish and weakfish.

During the winter, Atlantic mackerel overwinter in deep water of the continental shelf from Sable Island Bank, off Nova Scotia to the Chesapeake Bay region and move inshore and northeast in spring. This pattern is reversed in the fall. In April and early May, the fish form the two spawning aggregations. As fish from the southern contingent move northeast along the coast, they are joined by the schools from the northern contingent which are also moving inshore. The overwintering area and timing of migration varies annually, probably influenced by meteorological events or regional conditions with low spring temperatures significantly delaying the timing, extent and duration. By late April and May, the southern contingent is distributed off New Jersey and Long Island moving into the western side of the Gulf of Maine by June and July, and returning to the shelf edge probably between Long Island and Chesapeake Bay by October.

Habitat Characteristics

Mackerel eggs are pelagic in water over 34 ppt, floating in surface waters above the thermocline or in the upper 10-15 m. Based on the NEFSC MARMAP offshore ichthyoplankton surveys, eggs were collected at near surface temperatures ranging from 5-23°C with the largest proportion between ~ 7°C and 16°C. Larvae were found at water column temperatures ranging from 6-22°C with the largest proportion between about 8°C and 13°C. Larvae were collected at depths ranging from 10-130 m. With the exception of July when 50% were collected at a depth of 70 m, larvae were primarily distributed at depths <50 m. Larvae conduct vertical diurnal migration from the surface at night to the thermocline during the day.

Juveniles are pelagic and depth range varies seasonally. They occur offshore in fall, range from 0-320 m and are most abundant at ~ 20-40 m. In winter, juveniles are found at deeper depths, 50-70 m. During spring, juveniles are dispersed throughout the water column, but are concentrated between 30-90 m. Juveniles are found higher in the water column during summer to 20-50 m. Juveniles were captured with water temperatures ranging from 4-22°C, but most abundant at 10°C.

Similar to juveniles, adult mackerel are pelagic and depth range changes seasonally, perhaps influenced by prey availability. During fall, mackerel are found at depths from 10-340 m, where the majority are found at 60-80 m. Mackerel range from 10-270 m during winter with most occurring at depths between 20-30 m. Mackerel are widely dispersed throughout the water column during spring and are most common between 60-170 m. During summer, schools of mackerel are most common at depths between 50-70 m. Distribution may also be correlated with downwelling events and onshore advection of warm surface water. Offshore distribution varies with seasonal temperature changes. Fall- >80% of abundance at 9-12°; Winter- 70% at 5-6°; Spring- >25% at 13°; Summer- >30% at 10-11°, >35% at 14°. Within Massachusetts Bay mackerel are most abundant in the spring at 14° and at 10-15° during the fall.

Time-Series Analysis

Adult mackerel distribution during spring was primarily centered on Georges Bank and southern New England (Figure 3.3.17). Abundance and frequency of occurrence was low during the first 10 years of the time-series (1975-1984) and increased through 2005. Frequency of occurrence was significantly greater during spring 1995-2005 where captures were dispersed over the western portion of Georges Bank and southern New England. Few adult mackerel were captured in Massachusetts Bay or areas north of Georges Bank during spring.

Juvenile mackerel displayed similar abundance and distribution patterns exhibited by adults during spring (Figure 3.3.18). Abundance and frequency of occurrence was low between 1975-1984 and increased through 2005. Similar to adults, juvenile abundance and frequency of occurrence were significantly greater during 1995-2005. Juveniles were rare in spring samples in Massachusetts Bay and within central and northern Gulf of Maine waters.

During fall, adult mackerel were more widely dispersed throughout the study area with abundance and frequency of occurrence patterns were similar to that observed during spring. During the first 10 years of the time series abundance and frequency was low, but increased through 2004. Highest abundance and frequency of adults were primarily located around Georges Bank, Massachusetts Bay, and off the western shore of Cape Sable (Figure 3.3.19). Juvenile mackerel exhibited the same abundance, frequency, and distribution patterns as adults during fall (Figure 3.3.20).

The time-series trawl data indicate that mackerel are rare within the Sanctuary during spring. Only two trawl samples yielded mackerel (Table 3.3.5). Approximately one-third of the trawl samples during fall months yielded adult and juvenile mackerel. Abundance was typically low, but peak abundance was observed during 1985-1989. Mean length of adults ranged from approximately 28-33 cm and maximum size of adults ranged between 31-43 cm. Adults were captured at depths between 30-95 m, but tended to be most frequent at depths between 60-70 m. Juvenile mackerel abundance was also typically low throughout the time-series, but peaked during 1985-1989. Juvenile mean length was consistent throughout ranging from 20-22 cm. Juveniles were captured at depths between 28-101 m, but abundance was highest at 60-70 m.

Table 3.3.5. Frequency of occurrence and abundance for all Atlantic mackerel captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	NC	-	-	-	-	-	-	-
	80-84	22	NC	-	-	-	-	-	-	-
	85-89	16	NC	-	-	-	-	-	-	-
	90-94	21	NC	-	-	-	-	-	-	-
	95-99	17	5.88	0.12	33.00	33.00	83	18	18	83
	00-05	17	5.88	0.06	27.00	27.00	144	N/A	N/A	N/A
Fall	75-79	61	19.67	0.62	33.17	38	36-88	20.73	16	48-85
	80-84	22	36.36	1.45	33.25	38	29-75	22.33	21	28-73
	85-89	20	30.00	48.20	32.80	43	46-74	20.29	17	63-93
	90-94	19	15.79	0.21	29.00	31	81	20.50	20	81-101
	95-99	18	33.33	4.78	28.33	31	53-95	22.73	20	66-86
	00-04	16	12.50	0.63	32.83	35	65-83	N/A	N/A	N/A

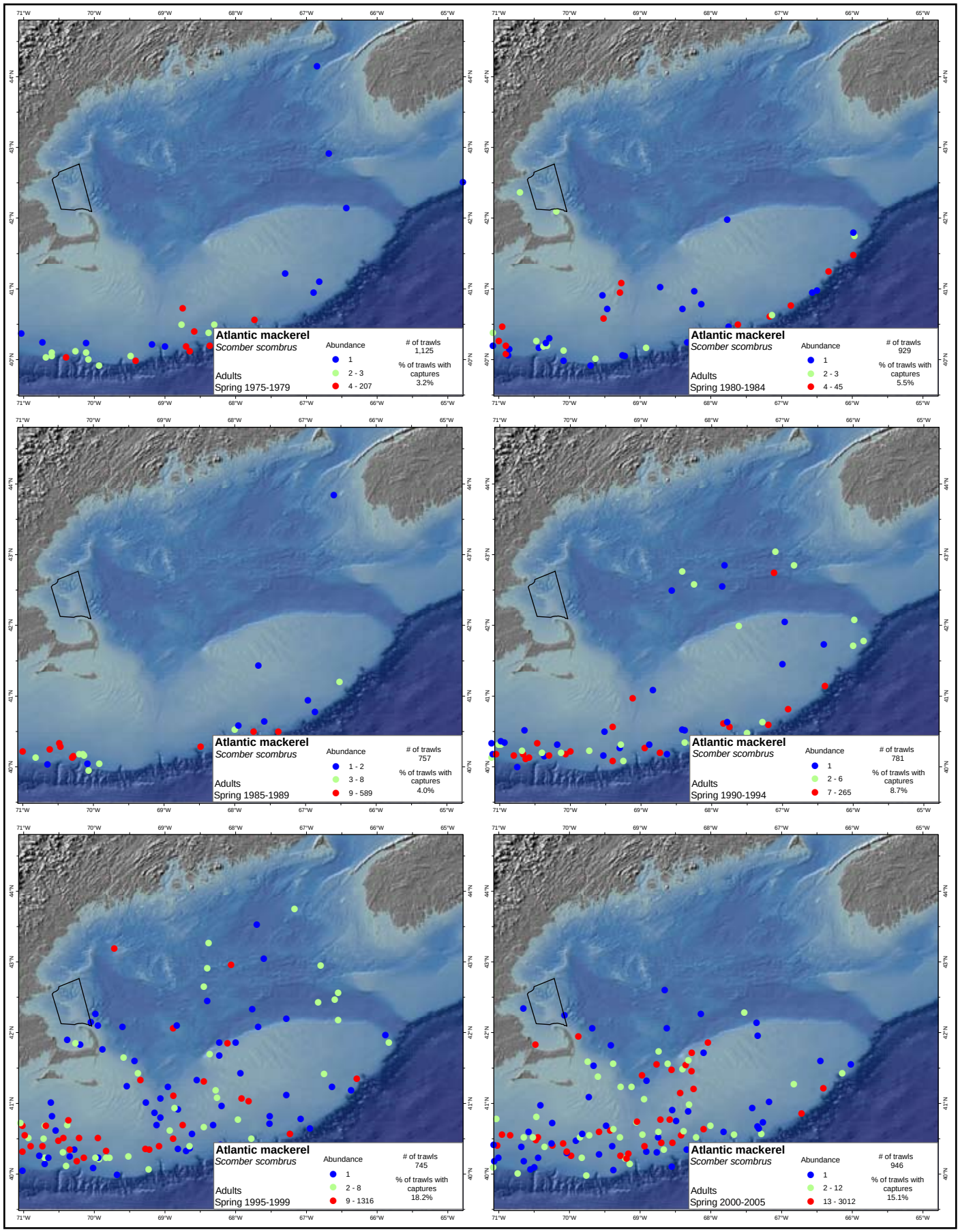

Figure 3.3.17. Abundance and distribution of adult Atlantic mackerel (*Scomber scombrus*) within the Gulf of Maine, Spring 1975-2005.

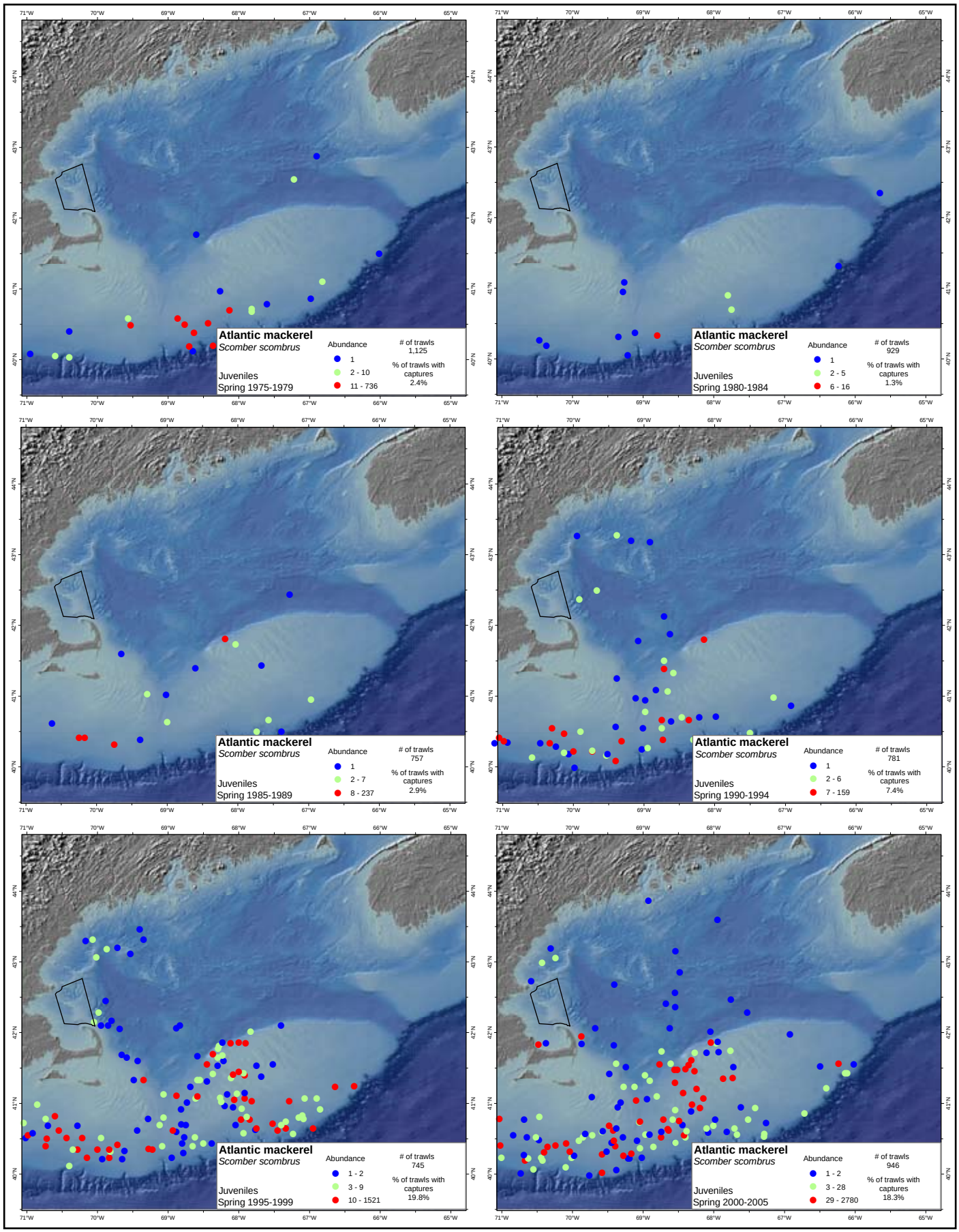

Figure 3.3.18. Abundance and distribution of juvenile Atlantic mackerel (*Scomber scombrus*) within the Gulf of Maine, Spring 1975-2005.

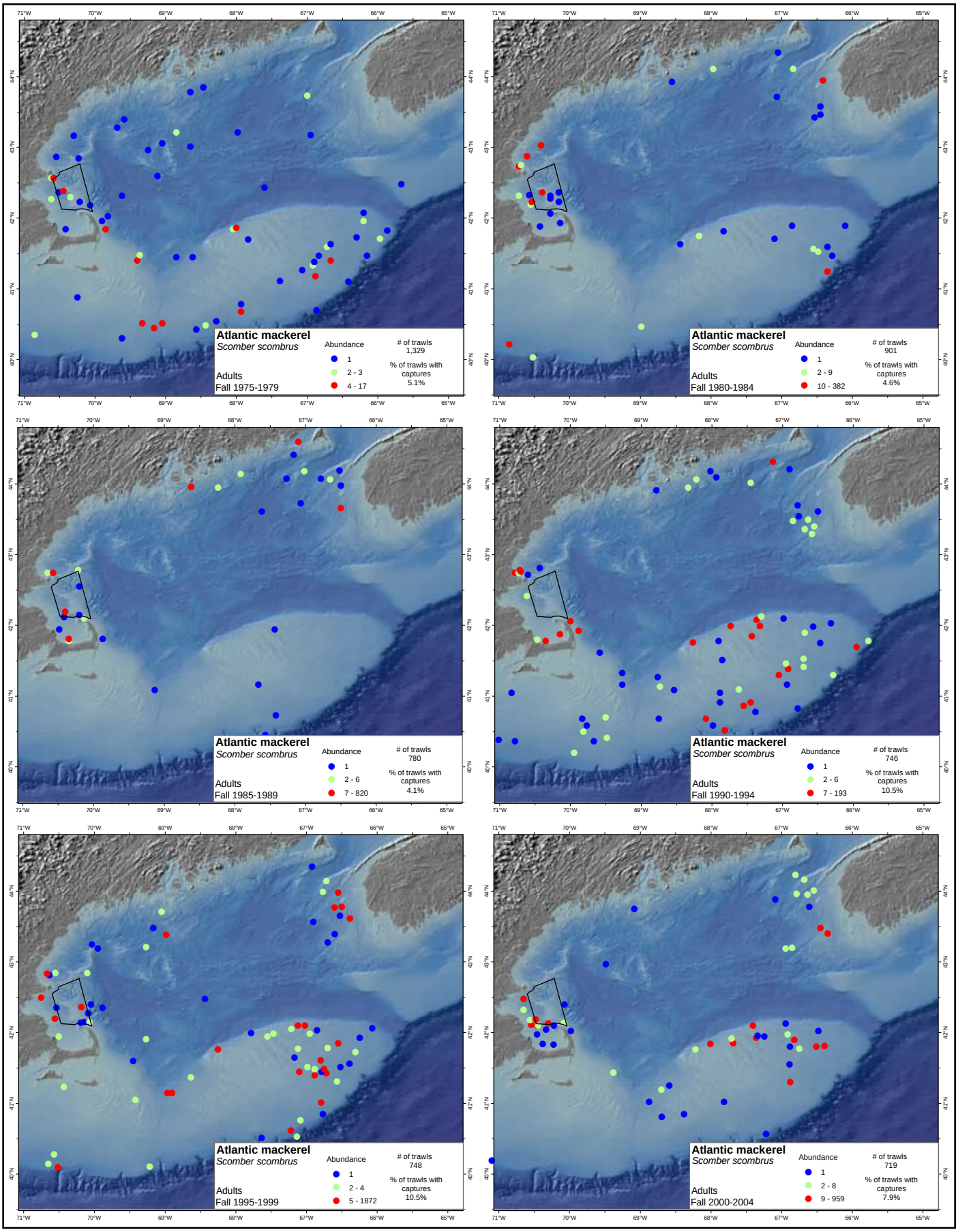

Figure 3.3.19. Abundance and distribution of adult Atlantic mackerel (*Scomber scombrus*) within the Gulf of Maine, Fall 1975-2004.

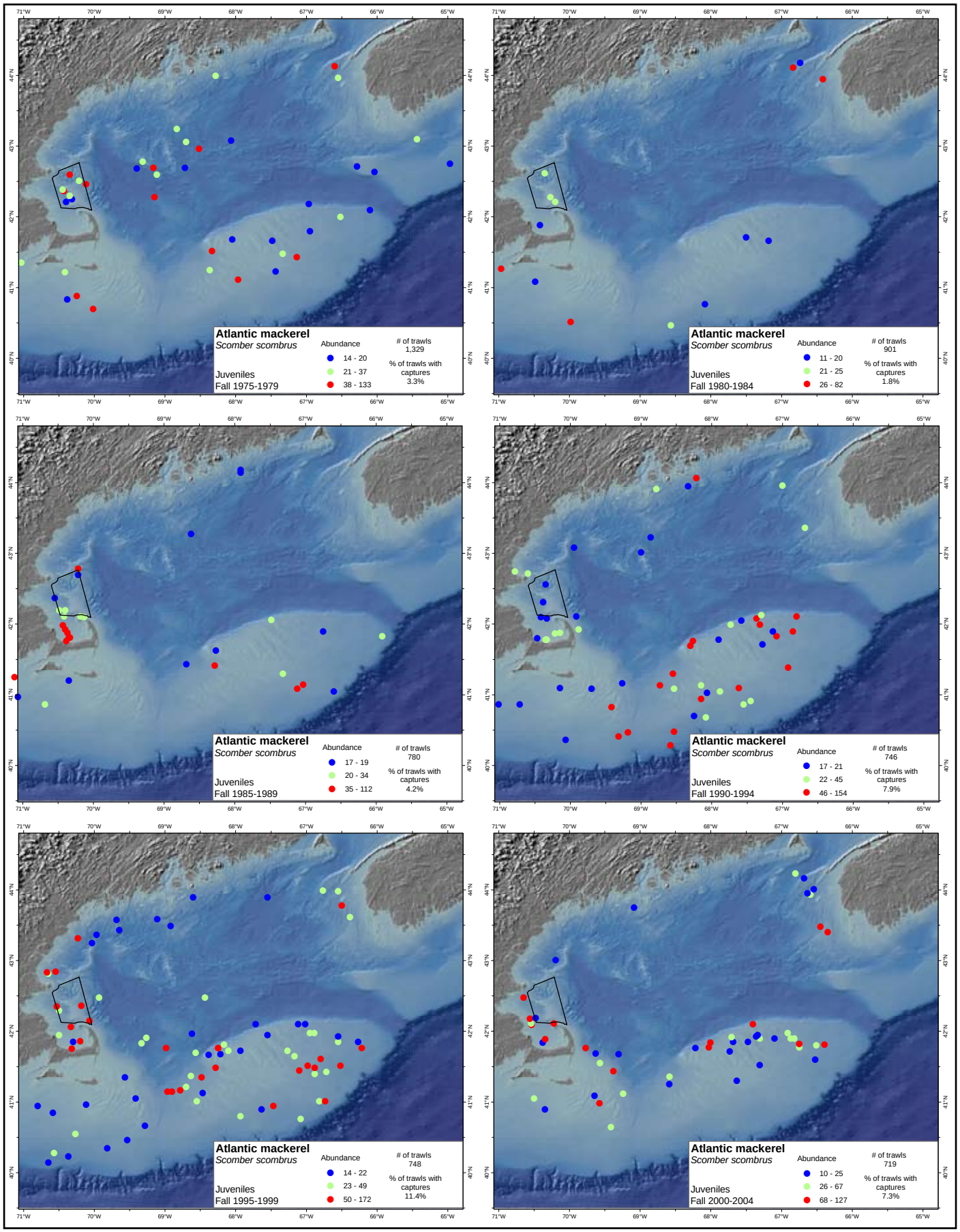

Figure 3.3.20. Abundance and distribution of juvenile Atlantic mackerel (*Scomber scombrus*) within the Gulf of Maine, Fall 1975-2004.

Haddock (*Melanogrammus aeglefinus)*
Haddock are echinoderm feeders with strong associations with the benthos. As such, haddock populations are tightly linked with overall benthic production. The haddock is a demersal gadid found on both sides of the North Atlantic. In the northwest Atlantic, haddock are distributed from Cape May, New Jersey to the Strait of Belle Isle, Newfoundland. Six haddock stocks have been identified in the northwest Atlantic from Newfoundland to Georges Bank. There are two haddock stocks in U.S. waters, Georges Bank and Gulf of Maine. U.S. haddock fisheries are managed by the New England Fishery Management Council under the Northeast Multispecies Fishery Management Plan. The Georges Bank haddock stock is also a transboundary resource, which is co-managed with Canada. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of haddock inhabiting U.S. waters, primarily in the Gulf of Maine (Brodziak, 2005).

Life History
Haddock spawn over various substrates including rocks, gravel, smooth sand, and mud. Eggs are broadcast and fertilized near the bottom. Fertilized eggs are buoyant and remain in the water column where subsequent development occurs. At water temperatures typical of Georges Bank, haddock eggs hatch in about 15 days. Newly-hatched haddock larvae range from 2-5 mm in length. Larval survival and growth is influenced by hatching date and oceanographic conditions. On Georges Bank, stratified conditions appear to enhance larval survival and growth. Larvae may be advected long distances by ocean currents. In some years, wind-driven currents transport haddock larvae from Georges Bank to the Mid-Atlantic Bight. Larval growth appears to be positively correlated with temperatures of about 7-9°C, but may be suppressed at 4°C. Larvae metamorphose into juveniles in roughly 30-42 days at lengths of 2-3 cm. Small juveniles initially live and feed in the epipelagic zone. Juveniles remain in the upper part of the water column for 3-5 months. After reaching lengths of 3-10 cm, juveniles visit the ocean bottom in search of food. Once suitable bottom habitat is located, juveniles settle into a demersal existence. Adult haddock are demersal benthivores ranging in size from roughly 30 cm to up to 1 meter. Haddock do not make extensive seasonal migrations. In winter, they prefer deeper waters and tend to move shoreward in summer. When summer water temperatures reach 10-11°C, haddock move to colder, deeper waters.

Pelagic larvae and small juvenile haddock feed on phytoplankton, copepods, and invertebrate eggs in the upper part of the water column. Juvenile haddock eat small crustaceans, primarily copepods and euphausiids, as well as polychaetes and small fishes. Juveniles make a transition from pelagic to demersal habitat at ages from 3 to 5 months. During this transition, juvenile diet changes to primarily benthic prey. Planktonic prey such as copepods and pteropods decrease in importance after juveniles become demersal, while ophiuroids and polychaetes increase in importance. When juveniles reach 8 cm in length, they primarily feed on echinoderms, small decapods, and other benthic prey. Benthic juveniles above 30 cm and adults primarily feed on crustaceans, polychaetes, mollusks, echinoderms, and some fish.

Habitat Characteristics
In the northwest Atlantic, haddock are distributed from Cape Charles, Virginia to Labrador, Canada. Georges Bank, the Scotian Shelf, and the southern Grand Bank have the highest densities of haddock. MARMAP ichthyoplankton surveys caught haddock eggs from New Jersey to southwest Nova Scotia. The highest densities were found on Georges Bank and Browns Bank, which are important haddock spawning areas. The highest concentrations occurred in April, followed by March and May. This pattern is consistent with the timing of peak spawning from March to May. MARMAP ichthyoplankton surveys captured haddock larvae from the Delmarva Peninsula to southwest Nova Scotia. Larvae were collected from January through July. The highest mean densities occurred in May (8.3 larvae/10 m^2) and April (8.1 larvae/10 m^2). High densities of larvae were found off southwest Nova Scotia and Georges Bank, spreading southward. Mean densities were low in January and February. Larval densities were highest in April through June and declined substantially by July. Haddock egg and larval stages are pelagic. They are usually found at depths of 10-50 m below the surface and in water temperatures of 4-10°C and salinities of 34-36 ppt. Juvenile and adult haddock are demersal. Juveniles and adults are usually found at depths between 40-150 m. Their preferred depth range is from 50-100 m but can sometimes be found as shallow as 10 m or deeper than 200 m. Juveniles are commonly found at water temperatures of 4.5-10°C. Adults can be found at a wider range of 0-13°C but prefer temperatures of 2-9°C. Juvenile and adult haddock are commonly associated with salinities of 31-35 ppt, although 32 ppt is optimal.

During spring and fall both juveniles and adults are found at depths of 21-400 m and temperatures of 2-16°C. Most juveniles and adults were captured at temperatures of 4-7°C with peaks at 5-6°C. The preferred juvenile depth range in spring was 71-140 m while the preferred salinity range was 33 ppt. The preferred adult depth range in spring was 51-120 m while the preferred salinity was 33 ppt. During autumn, the preferred juvenile temperature range was about 6-13°C with a peak at 8°C. Most juveniles were captured at depths of 41-120 m and at salinities of 32-34 ppt. The preferred adult temperature range during autumn was 6-10°C, and with a peak at 7°C. Most adults were found at depths greater than 81 m, with a preferred salinity of 33-34 ppt.

Preferred bottom types include gravel, pebbles, clay, and smooth hard sand, particularly smooth areas between rocky patches. Juvenile and adult haddock do not frequent ledges, rocks, kelp, or soft oozy mud. The distribution of substrate sediments on Georges Bank and in the Gulf of Maine area show regional differences. Substantial areas of suitable substrate for haddock (i.e. sand, gravelly sand, and gravel) are found on Georges Bank. In contrast, fewer areas of suitable substrate exist in the Gulf of Maine. Consequently, haddock are more abundant on Georges Bank than in the Gulf of Maine. In particular, the principal haddock spawning area on the northeast peak of Georges Bank contains large areas of suitable substrate. Similarly, the two principal spawning areas in the Gulf of Maine, Stellwagen Bank and Jeffreys Ledge, also contain gravelly sand substrate.

Time-Series Analysis

Haddock were prevalent within the study area during both spring and fall and abundance was comparable between the seasons. Frequency of occurrence for both adults (Figure 3.3.21) and juveniles (Figure 3.3.22) oscillated through the time series with highest frequency occurring during 1975-79 and was lowest during 1990-94. Adults were more frequently captured than juveniles throughout the time-series. Areas of highest abundance were consistent through the time-series where catches were greatest at Georges Bank, Browns Bank, the mouth of the Bay of Fundy, and Massachusetts Bay. Catches of haddock were rare in southern New England. The same general pattern of abundance, frequency, and distribution was observed during fall. Adult frequency of occurrence (Figure 3.3.23) was higher than juveniles (Figure 3.3.24) and abundance was considerably greater during the first ten years of the time-series.

Haddock were abundant within the Sanctuary. During the time-series frequency of occurrence was commonly greater than 50% (Table 3.3.6). Haddock frequency and abundance during spring and fall 1990-94 was significantly lower than any other year bin. Mean adult haddock size ranged from 43-52 cm SL and were captured at depths during spring ranging between 40-140 m, but were most abundant between 60-100 m. During fall adults were captured at similar depths (30-130 m) and were most abundant at depths between 70-110 m. Mean juvenile haddock size ranged between 16-27 cm SL. During spring juveniles were captured at similar depth ranges as

Table 3.3.6. Frequency of occurrence and abundance for all haddock captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	64.29	28.27	46.16	79	37-113	22.36	13	37-101
	80-84	22	77.27	12.68	47.09	80	37-121	22.37	17	37-101
	85-89	16	50.00	4.00	46.71	61	54-126	26.00	19	68-76
	90-94	21	23.81	0.76	43.67	50	80-90	16.13	4	48-80
	95-99	17	47.06	17.82	48.00	64	74-102	21.05	15	74-92
	00-05	17	58.82	20.53	49.65	74	72-144	25.67	19	72-144
Fall	75-79	61	80.33	20.54	49.90	82	30-118	17.84	8	30-104
	80-84	22	77.27	18.18	46.98	79	58-89	21.98	8	29-89
	85-89	20	40.00	4.95	52.11	72	63-86	23.40	14	43-81
	90-94	19	21.05	3.00	43.81	64	78-80	27.00	12	70-111
	95-99	18	66.67	28.39	46.66	66	48-95	21.64	7	32-90
	00-04	16	75.00	59.38	48.82	73	45-127	23.35	8	45-83

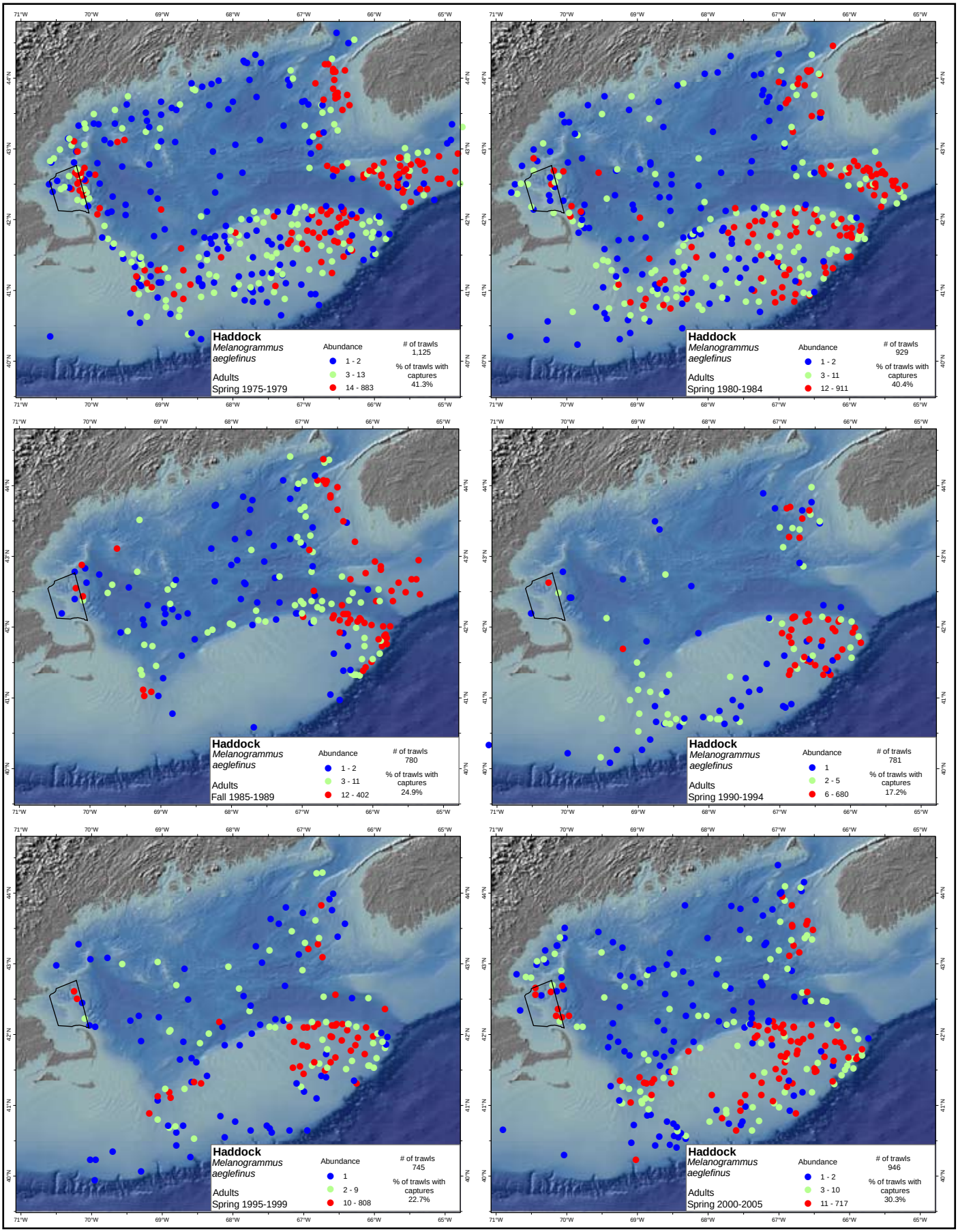

Figure 3.3.21. Abundance and distribution of adult haddock (*Melanogrammus aeglefinus*) within the Gulf of Maine, Spring 1975-2005.

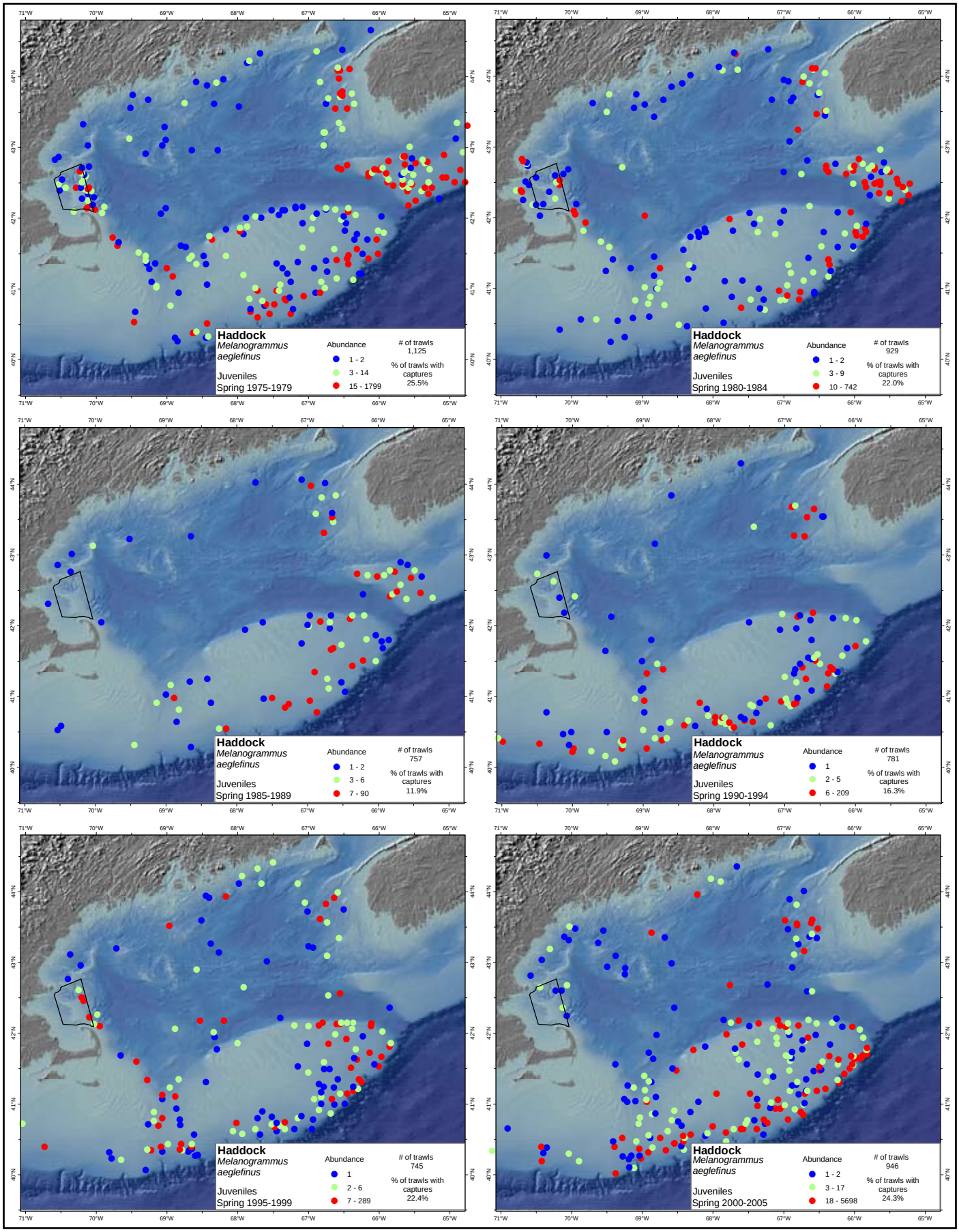

Figure 3.3.22. Abundance and distribution of juvenile haddock (*Melanogrammus aeglefinus*) within the Gulf of Maine, Spring 1975-2005.

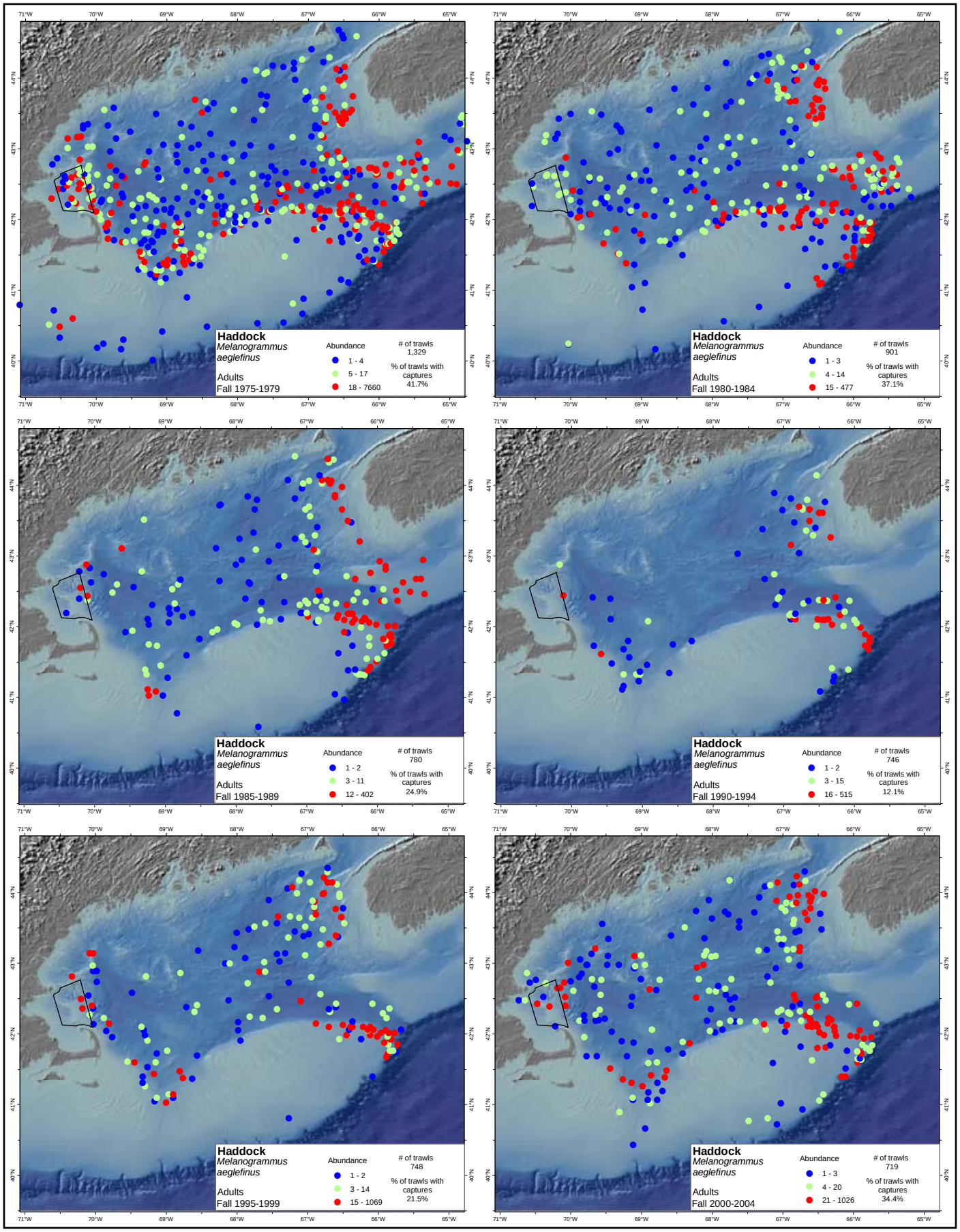

Figure 3.3.23. Abundance and distribution of adult haddock (*Melanogrammus aeglefinus*) within the Gulf of Maine, Fall 1975-2004.

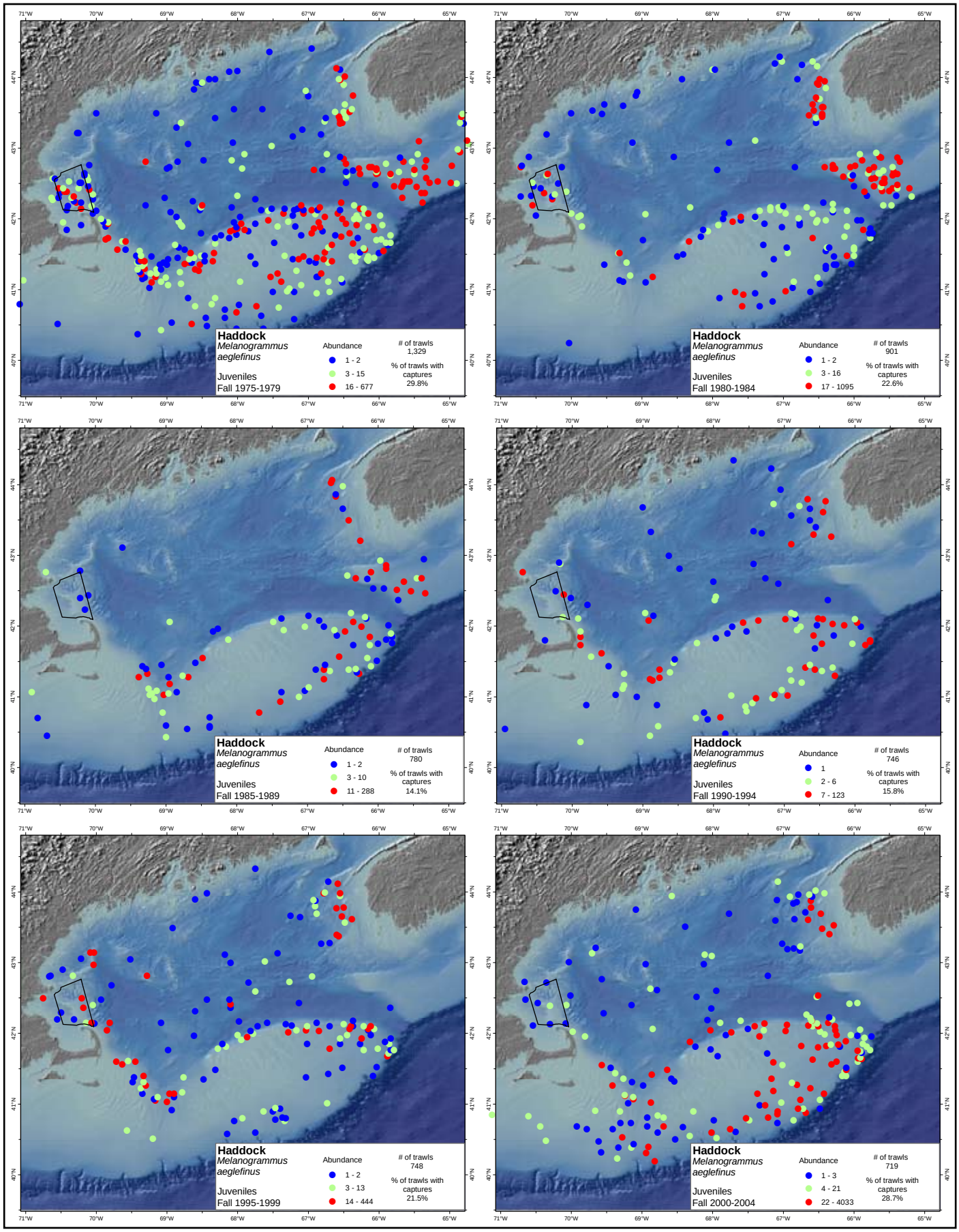

Figure 3.3.24. Abundance and distribution of juvenile haddock (*Melanogrammus aeglefinus*) within the Gulf of Maine, Fall 1975-2004.

adults, 40-140 m, and were most abundant between 80-100 m. During fall, juveniles were captured at depths ranging between 30-110 m, and the majority of juveniles were captured at depths shallower than adults (30-80 m).

Ocean pout (*Macrozoarces americanus)*

Ocean pout inhabit areas of moderate and high complexity within the Gulf. The ocean pout is a bottom dweller in waters north of Cape Hatteras, North Carolina, using both open and complex habitats, where it feeds on benthic organisms. It spawns in protected habitats, such as rock crevices and man-made artifacts, where it lays eggs in nests that it guards. Ocean pout do not make extensive migrations. It is currently considered as two stocks and managed by the New England Fishery Management Council under the Northeast Multispecies Fishery Management Plan. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of ocean pout inhabiting U.S. waters, primarily in the Gulf of Maine (Steimle *et al.,* 1999).

Life History

Adult ocean pout (>29 cm TL) are demersal and do not form schools or aggregations. Ocean pout are a long-lived species (>20 years) and can attain sizes up to 98 cm TL and 5.3 kg. Seasonal inshore/offshore migrations are minimal and are considered residents within the Gulf of Maine. Adults spawn during late summer and fall on the continental shelf within the Gulf of Maine and New England estuaries. Eggs are deposited in nests and guarded by adults. Eggs incubate for two to three months and larvae emerge in late fall through spring. Larvae are demersal and are approximately 30 mm at hatching. Juveniles are found throughout the inner-middle shelf within the Gulf of Maine, Massachusetts Bay and Georges Bank. The larval stage is relatively short. Juveniles exhibit linear growth during the first year where they attain lengths of 10-12 cm TL. Growth rates are slower in the Gulf of Maine region compared to populations in the Mid-Atlantic Bight.

Ocean pout feed on infaunal prey by sorting mouthfuls of sediments and do not use visual cues to stimulate feeding. Ocean pout are not very effective at capturing moving prey and rarely leave the bottom to feed. Auster (1985) and Auster *et al*. (1995), however, considered ocean pout an ambush predator that waits in sediment depressions for prey to approach or drift by in the current. Juveniles feed primarily on gammarid amphipods and polychaetes. Adult ocean pout feed on a variety of benthic invertebrates, including polychaetes, mollusks, crustaceans, and echinoderms. Juvenile ocean pout are consumed by squid (*Illex* spp.), spiny dogfish (*Squalus acanthias*), sea raven, cod, barndoor skate (*Raja laevis*), harbor seals, and cormorants. A variety of shark species prey upon adult pout.

Habitat Characteristics

Ocean pout is a bottom-dwelling species that occurs in cool waters (< 10^{o}C) across the continental shelf from Labrador to Cape Hatteras. They are non-migratory, but will move seasonally to remain at preferred water temperatures. Ocean pout eggs are deposited in sheltered nests where they are protected by one or both parents. There is limited information regarding larval habitat characteristics, but the larval stage is relatively short (some authors suggest there is no true larval stage). Hatchlings remain near the nest shelter. In the Gulf of Maine, juveniles occur in shallow coastal waters around rocks and attached algae, and in rivers with saline bottom waters. Juveniles (< 8 cm TL) use scallops shells for cover and Auster *et al*. (1995) reported that aggregated ocean quahog shell are also used for cover. Juvenile ocean pout were commonly found in the > 25 ppt saline parts of most major estuaries or coastal areas from Passamaquoddy Bay south to Cape Cod Bay throughout the year. On the continental shelf, juvenile ocean pout are commonly collected in bottom water temperatures between 3-14^{o}C at water depths < 100 m . Off Massachusetts, juvenile ocean pout prefer bottom temperatures < 11^{o}C, with about a 3^{o}C shift (from 6-9^{o}C) in the peak abundance mode from spring to autumn. Adult ocean pout occur from the intertidal across the continental shelf and on the upper continental slope to about 200 m on Georges Bank and in the Gulf of Maine. The bottom temperature and depth preference of the adults is similar to that of the juveniles. Adults are more abundant in cooler (3-14^{o}C) waters. They can tolerate temperatures up to 25^{o}C. Adults are commonly collected at depths < 100 m, in coastal waters of New England and in saline estuaries during most months. Some adults have been collected at depths > 300 m. Adult ocean pout occur on most sediment types, including shell patches. However, there appears to be seasonal variability in the use of certain habitats. Rocky shelter is especially important for spawning adults in the fall. Based on the species seasonal use of sheltered habitats and

the inefficiency of otter trawls in sampling these habitats, the range of habitats occupied may be broader than described here.

Time-Series Analysis

In general, adult ocean pout were more frequently captured in NMFS trawls than juveniles. Frequency of occurrence was higher in spring for both adults and juveniles. During spring, adults were common in trawl samples (Figure 3.3.25) with frequency of occurrence ranging from a high of 46% (1990-94) to a low of 23% (1975-79). Juvenile frequency of occurrence was significantly lower than adults, ranging from 6-10% (Figure 3.3.26). Patterns of highest abundance for both juveniles and adults occurred in Massachusetts Bay, Georges Bank, and southern New England. During fall, both adult (Figure 3.3.27) and juvenile (3.3.28) occurrence was well below that observed during spring. The lower frequency of occurrence may reflect that adults nest in areas of greater habitats complexity where trawls are less efficient. Highest abundance for adults and juveniles during fall was centered around Massachusetts Bay and Georges Bank.

Ocean pout were very common within the Sanctuary during the time-series (Table 3.3.7). Adults were significantly more common and abundant than juveniles. Frequency of occurrence was lower in the fall than spring although less evident than at the broader Gulf of Maine extent. On average, adult pout were slightly larger in the spring than fall. Adult pout mean length declined slightly from 56 cm in 1975-79 to 51 cm in 2000-05. Maximum size of pout also exhibited a declining trend through the spring time-series. During spring, adults were captured at depths between 27-144 m, with most occurring between 50-85 m. Mean length for juveniles ranged from 19-28 cm SL and captures occurred at depths between 46-133 m. Although juvenile occurrence was low, most juveniles were captured at depths between 60-80 m. Frequency of occurrence and abundance of adults and juveniles were lower during fall. Adults ranged in size from 42-49 cm SL and were most abundant at depths between 45-90 m. Mean length for juveniles ranged between 20-24 cm SL and were most abundant at 70-90 m.

Table 3.3.7. Frequency of occurrence and abundance for all ocean pout captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	58.93	2.46	56.12	95	40-133	19.52	12	53-133
	80-84	22	81.82	9.91	52.21	80	33-105	21.77	15	58-79
	85-89	16	87.50	20.50	51.37	100	30-126	21.33	11	46-97
	90-94	21	85.71	10.33	51.46	83	30-120	22.13	13	56-86
	95-99	17	82.35	15.47	48.26	71	41-123	22.86	17	76-102
	00-05	17	70.59	9.41	51.57	77	27-144	28.00	28	56
Fall	75-79	61	45.90	1.72	46.50	64	42-105	20.60	10	48-100
	80-84	22	86.36	5.41	49.07	92	29-101	24.17	14	60-89
	85-89	20	55.00	2.30	46.53	58	63-89	24.00	18	53-69
	90-94	19	73.68	5.11	42.16	71	44-116	23.47	14	44-111
	95-99	18	72.22	6.22	43.53	60	48-95	24.27	18	71-90
	00-04	16	31.25	2.25	46.36	58	52-118	N/A	N/A	N/A

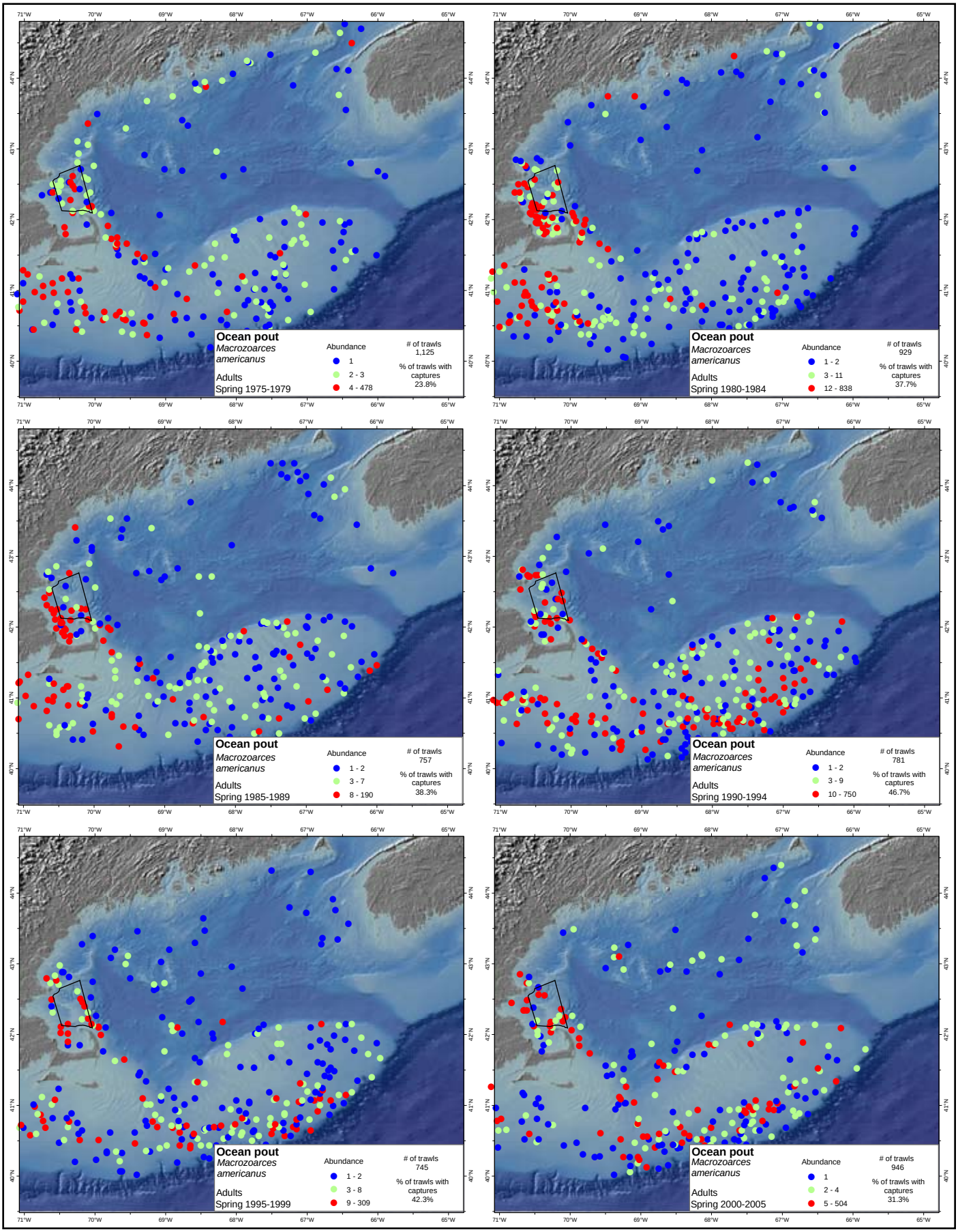

Figure 3.3.25. Abundance and distribution of adult ocean pout (*Macrozoarces americanus*) within the Gulf of Maine, Spring 1975-2005.

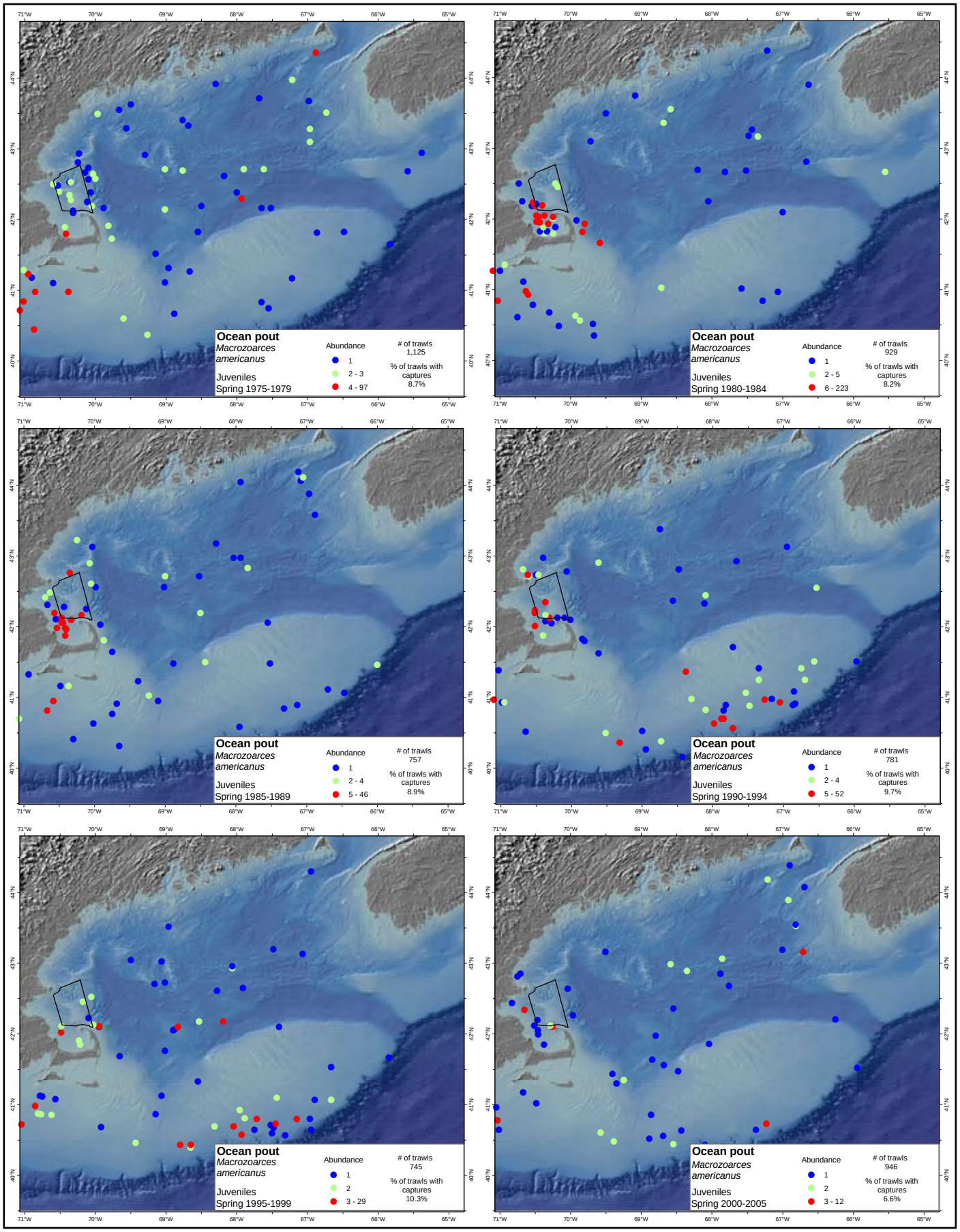

Figure 3.3.26. Abundance and distribution of juvenile ocean pout (*Macrozoarces americanus*) within the Gulf of Maine, Spring 1975-2005.

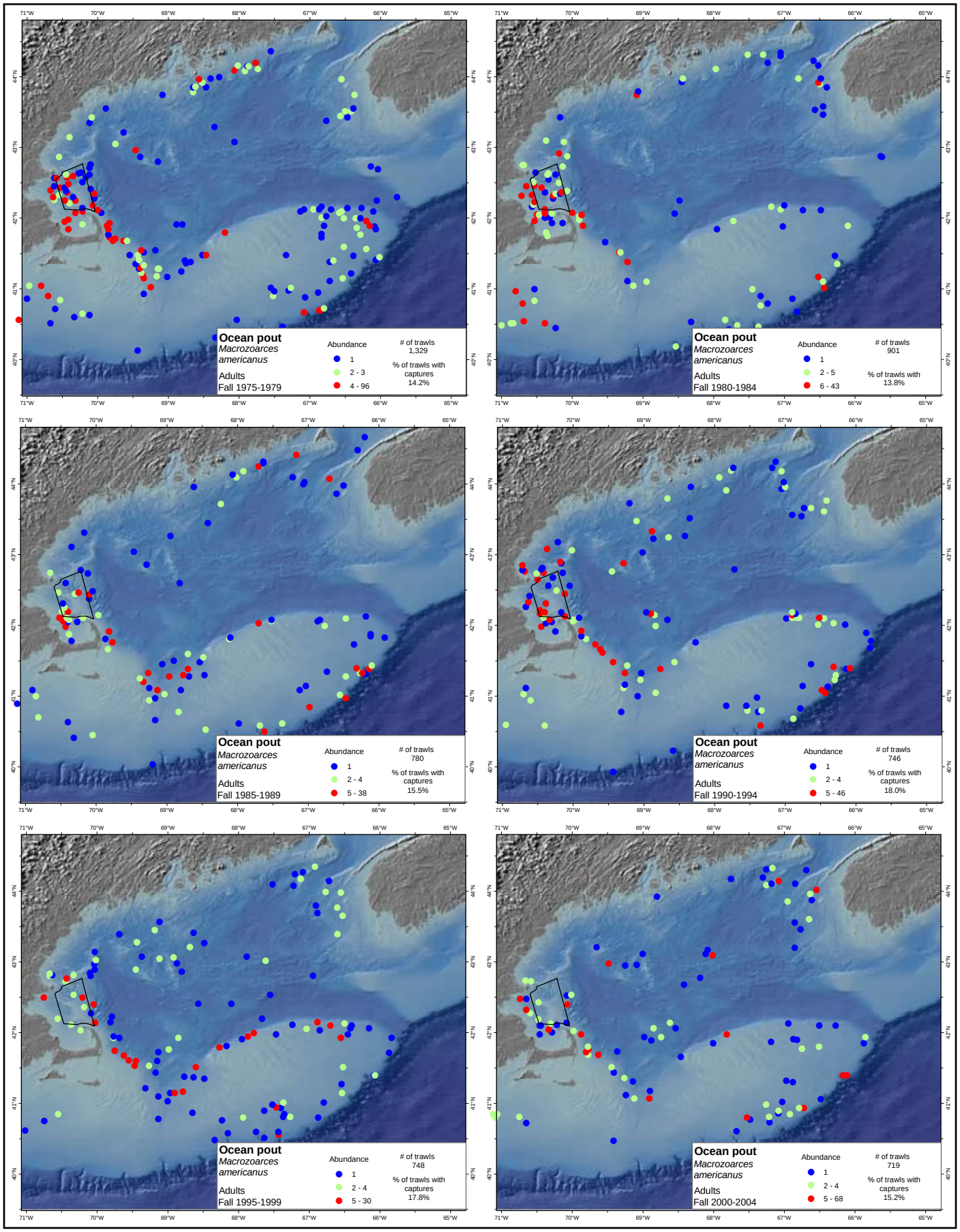

Figure 3.3.27. Abundance and distribution of adult ocean pout (*Macrozoarces americanus*) within the Gulf of Maine, Fall 1975-2004.

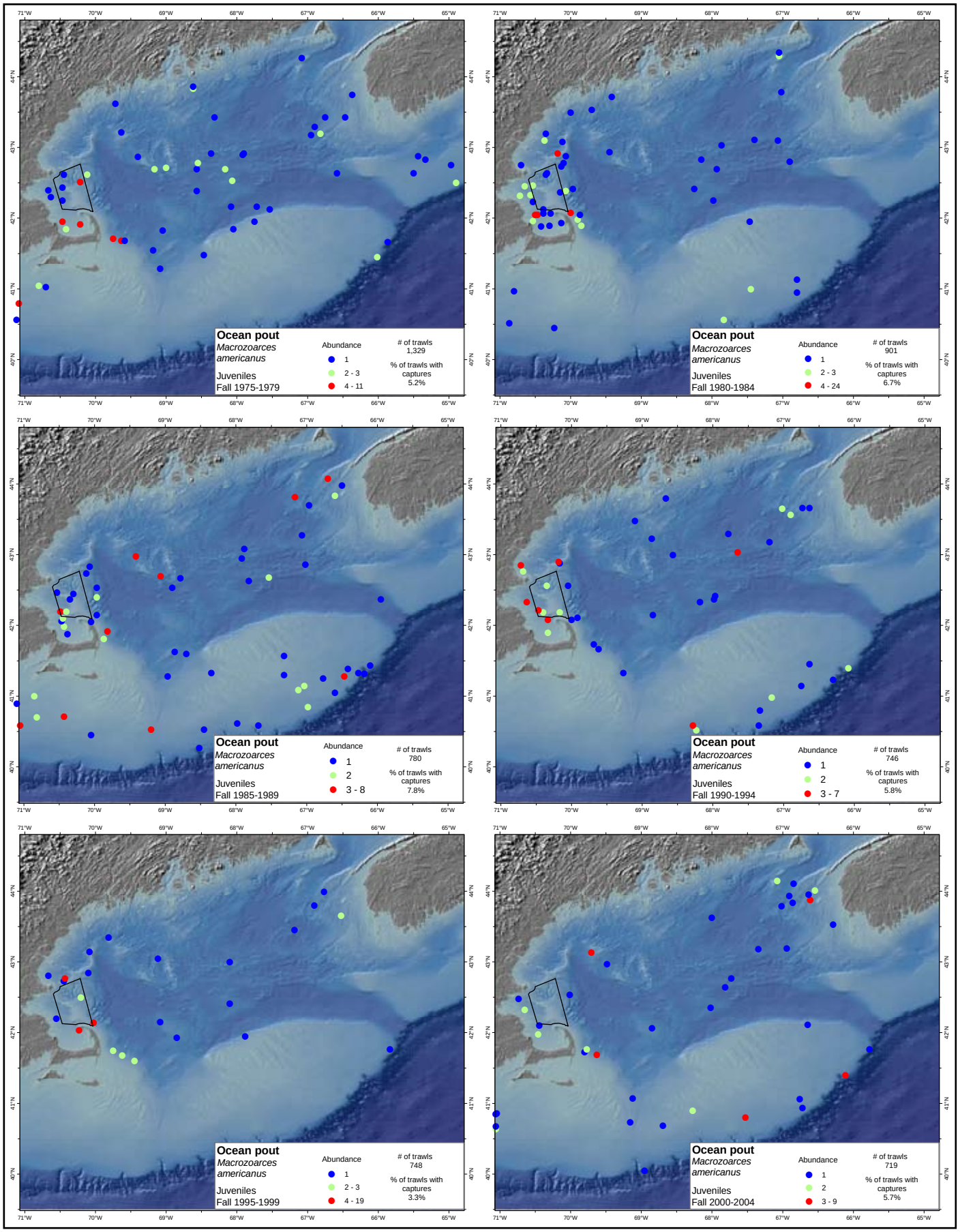

Figure 3.3.28. Abundance and distribution of juvenile ocean pout (*Macrozoarces americanus*) within the Gulf of Maine, Fall 1975-2004.

Pollock (*Pollachius virens)*

The pollock is a semi-pelagic gadoid species inhabiting both sides of the North Atlantic. They are an important shrimp-fish predator and provide a significant link between the water column and seafloor habitats. In the northwest Atlantic they are most common on the Scotian Shelf, Georges Bank, in the Great South Channel, and in the Gulf of Maine. There is considerable movement of the species between the Scotian Shelf, Georges Bank and the Gulf of Maine. Although some differences in meristic and morphometric characters have been shown, there are no significant genetic differences among areas. As a result, the Scotian Shelf, Georges Bank and the Gulf of Maine pollock are assessed as a single unit and managed under the New England Fishery Management Council's Northeast Multispecies Fishery Management Plan. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of ocean pout inhabiting U.S. waters, primarily in the Gulf of Maine (Cargnelli *et al.,* 1999).

Life History

Pollock eggs are buoyant, rising into the water column after fertilization. The pelagic larval stage lasts for three to four months, at which time the small juveniles or "harbor pollock" migrate inshore where they inhabit rocky subtidal and intertidal zones. They undergo a series of inshore-offshore movements linked to temperature until near the end of their second year. At this point the juveniles move offshore where they remain throughout the adult stage. Pollock are a schooling species and are found throughout the water column. With the exception of short migrations due to temperature changes and north-south movements for spawning, pollock are fairly stationary in the Gulf of Maine and along the Nova Scotian coast. Male pollock reach sexual maturity at a larger size and older age than females. Pollock age and size at maturity has declined in recent years, a trend which has also been reported in other marine fish species. The principal pollock spawning sites in the northwest Atlantic are in the western Gulf of Maine, Great South Channel, Georges Bank, and on the Scotian Shelf. In the Gulf of Maine, spawning is concentrated in Massachusetts Bay, Stellwagen Bank, and from Cape Ann to the Isle of Shoals. In the Gulf of Maine spawning occurs from November to February and peaks in December. Spawning occurs over hard, stony or rocky bottom. Spawning activity begins when the water column cools to near 8^{o}C, and peaks when temperatures are approximately 4.5-6^{o} C.

Small pollock larvae (4-18 mm) prey primarily on larval copepods while larger larvae (> 18 mm) feed on adult copepods. The primary prey of juvenile pollock are crustaceans. Euphausiids, in particular *Meganyctiphanes norvegica*, are the most important crustacean prey of juveniles. Fish and mollusks make up a smaller proportion of the juvenile diet. The diet of adults is comprised of euphausiids, fish and mollusks. *M. norvegica* is the single most important prey item and Atlantic herring is the most important fish species. The diet preferences of adults vary with size: crustaceans were the most important prey item among smaller adults (41-65 cm), fish were most important among medium size adults (66-95 cm), and mollusks (the squid *Loligo*) were the most important prey among the largest adults (> 95 cm).

Habitat Characteristics

Pollock in the northwest Atlantic are distributed from the Delmarva Peninsula north to the Gulf of St. Lawrence and the Grand Banks. The areas of highest abundance are the Scotian Shelf and the Gulf of Maine. Pollock eggs are spawned over broken substrate at salinities of 32-32.8 ppt. They are pelagic and free-floating, usually found in water 50-250 m in depth. Larvae are also pelagic, commonly found at temperatures of 3-9^{o}C and normally occur from the shore out to the 200 m depth contour, but have been reported in waters as deep as 1550 m. Juveniles have been reported over a wide variety of substrates, including sand, mud, or rocky bottom and vegetation. They are found at temperatures ranging from 0-16^{o}C and prefer salinities of around 31.5 ppt. Inshore subtidal and intertidal zones are utilized by age 0-1 juveniles and serve as important nursery areas. Age 2+ juveniles move offshore, inhabiting depths of 130-150 m. Adults show little preference for bottom type. They are found at high salinities, 31-34 ppt and temperatures of 0-14^{o}C although they tend to avoid temperatures > 11^{o}C and <3^{o}C. They inhabit a wide range of depths (35-365 m), but most occur shallower than the 137 m depth contour and depths of 100-125 m are preferred. Adults tend to inhabit deeper waters in spring and summer than in winter and they are typically found further offshore than juveniles.

Time-Series Analysis

Frequency of occurrence was higher for adults than juveniles during both seasons. Adult frequency (Figure 3.3.29) within the study area was variable and were higher in the earlier portion of the time-series (1975-1989)

compared to more recent years. Juvenile frequency was low overall, ranging between 7-11% throughout the study area (Figure 3.3.30). Areas of high adult pollock abundance were located on Georges Bank, Browns Bank and the central Gulf. High juvenile abundance was located in Massachusetts Bay, Georges Bank, and off the eastern coasts of Massachusetts and Maine at depths of 55-80 m. Similar patterns of frequency of occurrence were exhibited during fall for both adults (Figure 3.3.31) and juveniles (Figure 3.3.32). Adult frequency steadily declined during 1979-1994, followed by increasing frequency through 2005. Juvenile frequency of occurrence during fall was low and variable with no apparent patterns. Areas of high abundance for both life stages were similar to that described for the spring.

Within the sanctuary, pollock were more abundant during the fall than spring (Table 3.3.8). Frequency of occurrence was also higher during the fall. A significant decline in adult mean length and maximum length was observed throughout the spring time series, where mean lengths were, on average, 20 cm less in 2000-05 compared to highest means during 1975-79. Although adults were captured during 1995-99, no length data were available for this time period. Juvenile mean standard length ranged from 22-29 cm. Adults were captured at depths between 54-121 m during spring, but most were found at 50-85 m. Juveniles exhibited a slightly shallower depth range (40-135) with higher abundance found at 55-80 m. Mean length of adult pollock during the fall also exhibited a significant decline throughout the time series. Juvenile mean standard length was slightly higher than in the spring (29-33 cm). Depth at capture for both adults and juveniles in the fall was similar to that observed during the spring (adults: 42-149 m, highest abundance between 55-85; juveniles: 30-149 m, highest abundance between 45-90 m).

Table 3.3.8. Frequency of occurrence and abundance for all pollock captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	23.21	1.05	67.75	101	65-90	26.79	18	40-87
	80-84	22	40.91	1.00	64.50	99	76-121	24.75	17	42-92
	85-89	16	31.25	9.56	47.57	69	54-81	28.30	19	57-81
	90-94	21	33.33	4.52	46.00	46	80	22.95	16	66-120
	95-99	17	41.18	9.76	N/A	N/A	N/A	28.38	20	74-123
	00-05	17	29.41	1.94	47.58	58	81-84	29.00	17	72-135
Fall	75-79	61	47.54	5.46	78.26	110	42-118	33.10	18	30-92
	80-84	22	50.00	4.18	71.67	95	54-101	29.78	23	60-82
	85-89	20	60.00	14.55	53.06	99	72-93	30.28	20	53-89
	90-94	19	31.58	6.58	71.71	112	77-111	29.00	22	59-111
	95-99	18	44.44	35.56	47.83	59	48-95	29.67	21	48-90
	00-04	16	68.75	11.81	53.60	86	56-149	29.81	16	45-149

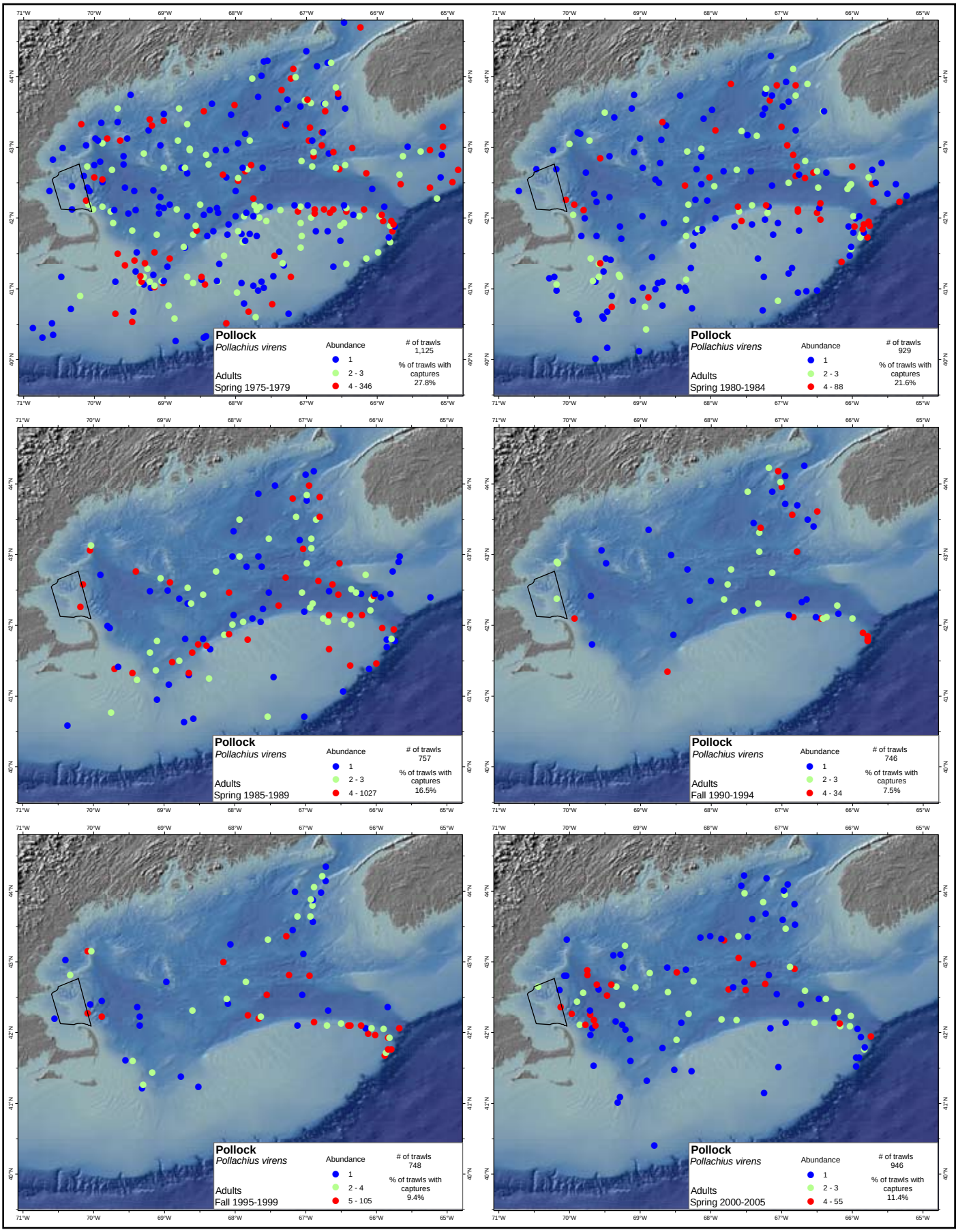

Figure 3.3.29. Abundance and distribution of adult pollock (*Pollachius virens*) within the Gulf of Maine, Spring 1975-2005.

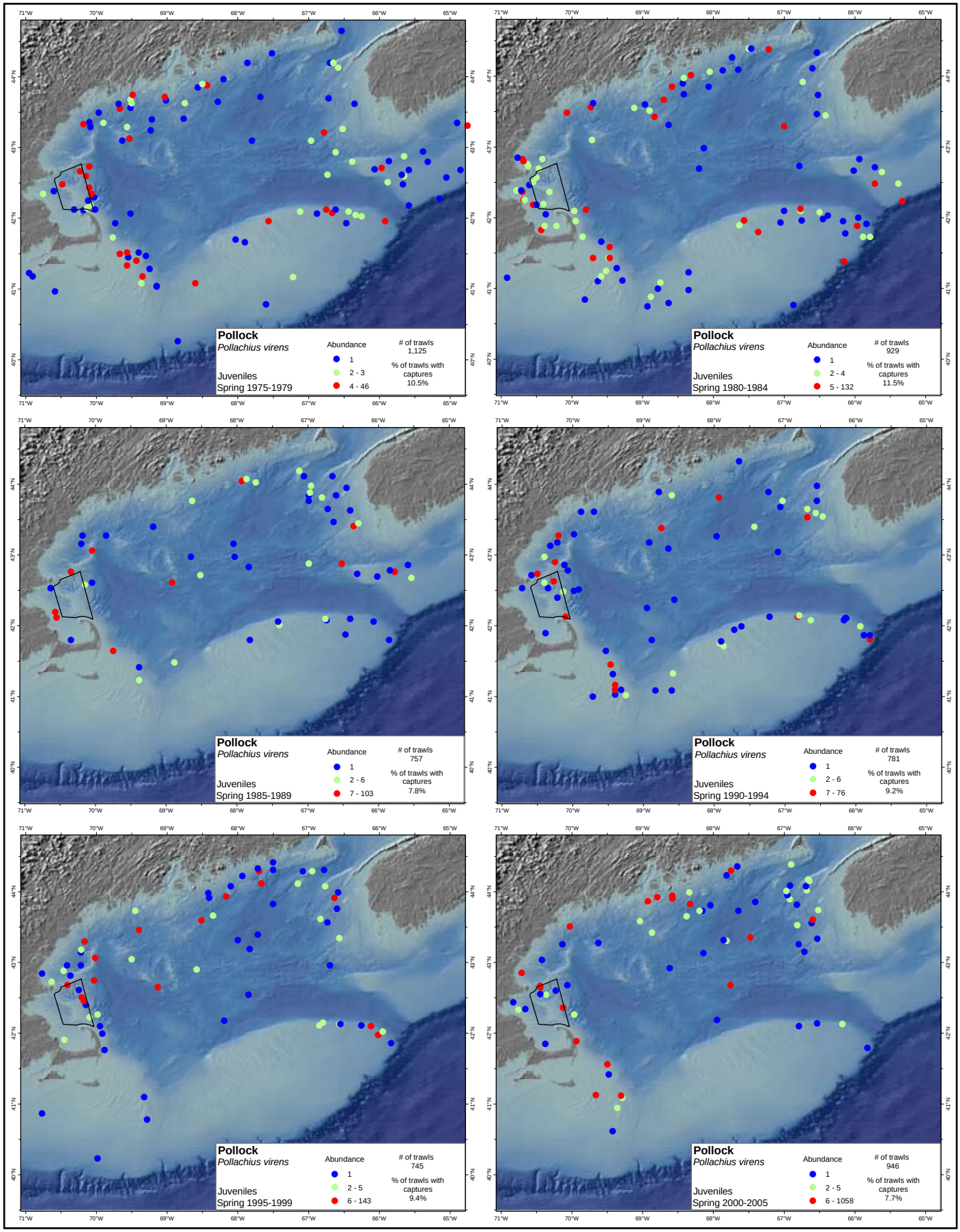

Figure 3.3.30. Abundance and distribution of juvenile pollock (*Pollachius virens*) within the Gulf of Maine, Spring 1975-2005.

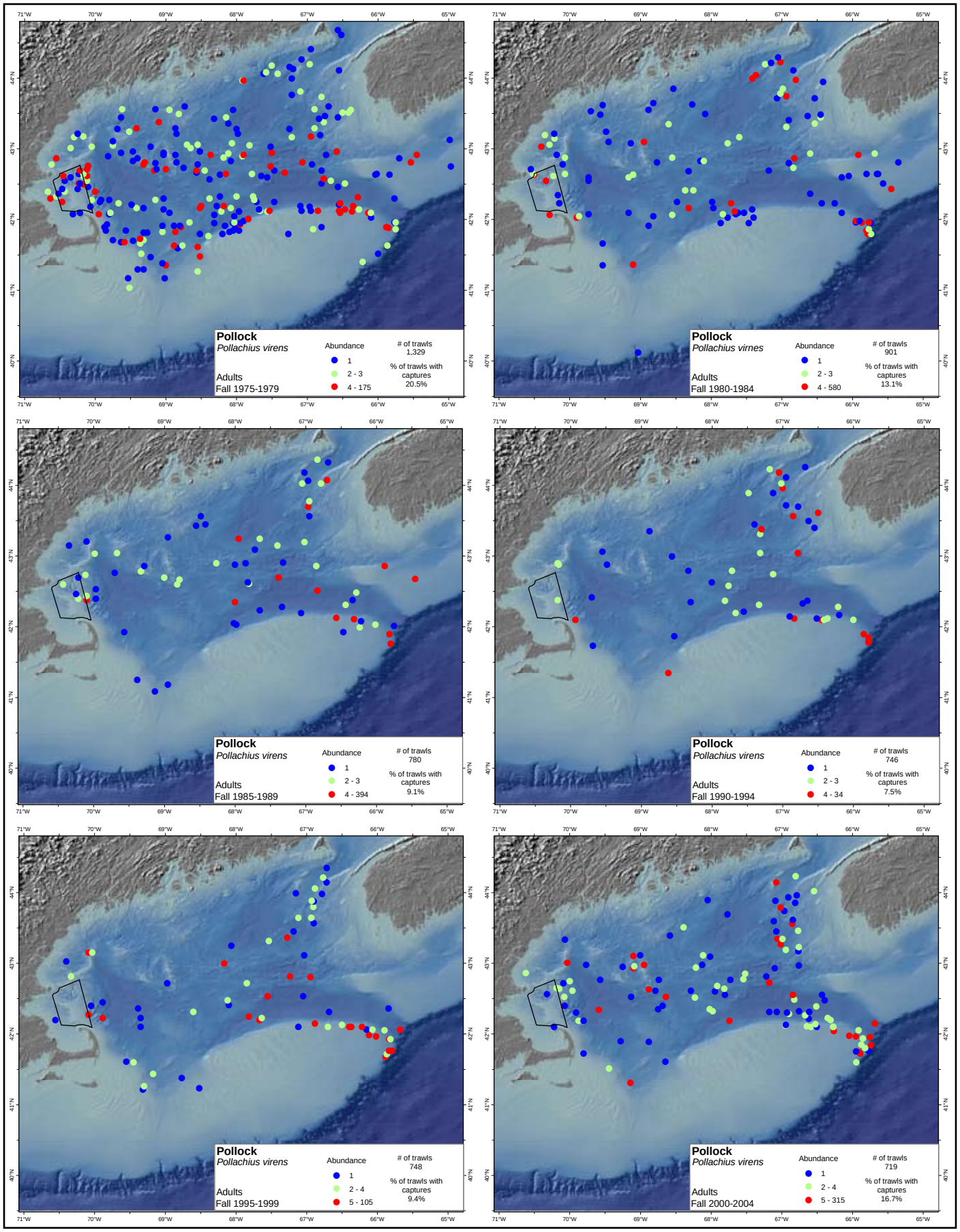

Figure 3.3.31. Abundance and distribution of adult pollock (*Pollachius virens*) within the Gulf of Maine, Fall 1975-2004.

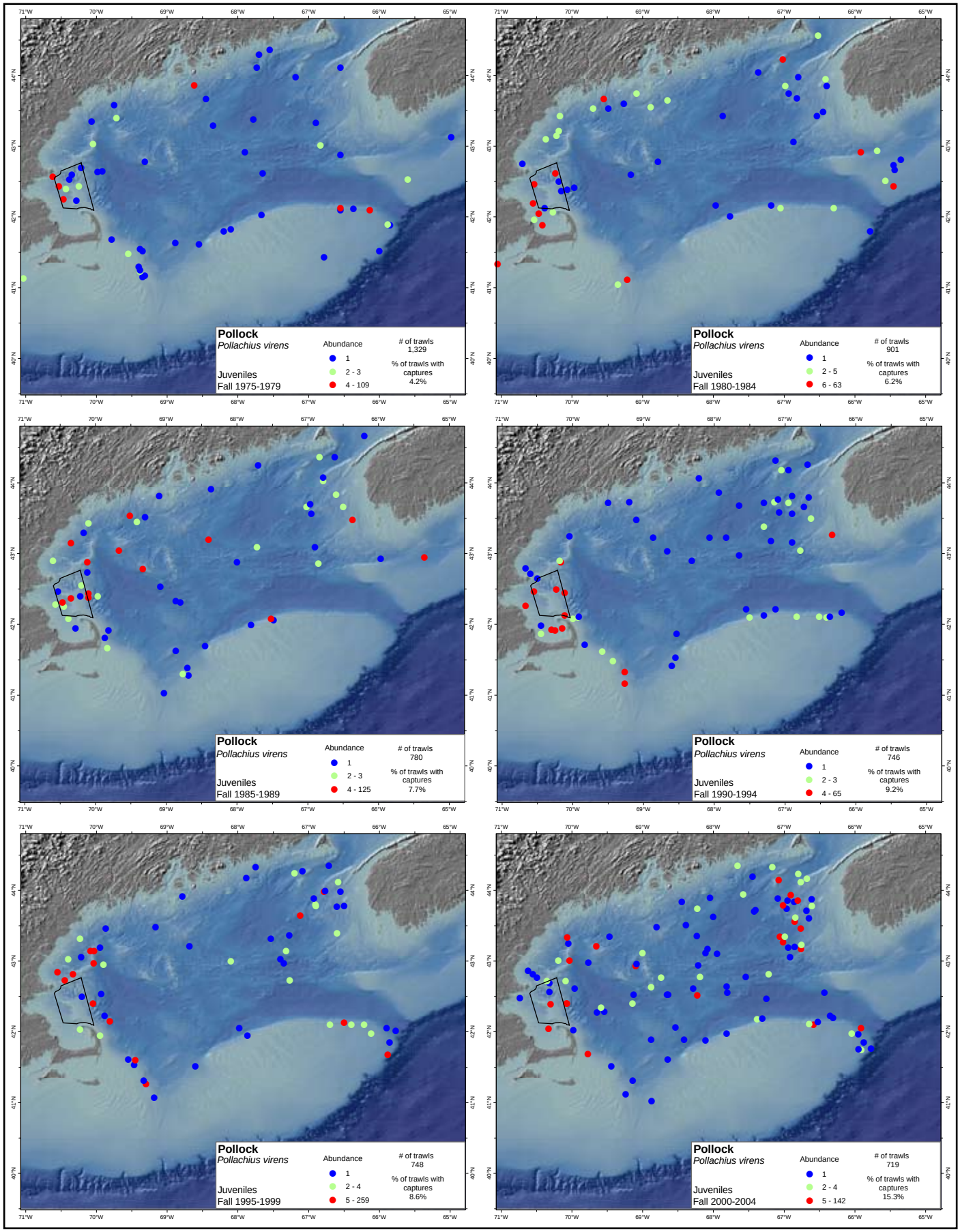

Figure 3.3.32. Abundance and distribution of juvenile pollock (*Pollachius virens*) within the Gulf of Maine, Fall 1975-2004.

Silver hake (*Merluccius bilinearis)*
Silver hake are a dominant species within the Gulf and Stellwagen Bank NMS. Adults are in important fish predator within the region, while smaller silver hakes are typically shrimp-fish predators. Silver hake of all sizes exhibit strong affinity to benthic habitats, in particular, juveniles are common among sand waves where they hide and ambush prey (Auster *et al*., 2003b). Silver hake are distributed on the continental shelf of the northwest Atlantic Ocean from the Gulf of St. Lawrence and the southern edge of the Grand Banks, Newfoundland, Canada to Cape Fear, North Carolina. Silver hake are demersal and often found in dense schools associated with specific hydrographic conditions and prey concentrations. In U.S. waters, two stocks of silver hake have been tentatively identified based on morphometric differences. They are managed separately by the New England Fishery Management Council. One stock ranges from the Gulf of Maine to northern Georges Bank, while the other stock ranges from southern Georges Bank to Cape Hatteras. Both can be found on Georges Bank during summer months. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of silver hake inhabiting U.S. waters, primarily in the Gulf of Maine (Lock and Packer, 2004).

Life History
Eggs are pelagic, drift with the prevailing currents, and hatch in about two days at 20°C. Newly hatched larvae are pelagic and are about 2.6-3.5 mm long. Larval duration in the New York Bight has been estimated at 34.5 days and are an important constituent of the summer ichthyoplankton. Within the Scotian Shelf larvae are pelagic for 3-5 months. When they reach 17-20 mm long, the larvae descend to the bottom as juveniles. Juvenile and adult silver hake migrate to deeper waters of the continental shelf as water temperatures decline in the fall and return to shallow waters in spring and summer to spawn. Major spawning areas include the coastal Gulf of Maine, southern and southeastern Georges Bank, and the southern New England area south of Martha's Vineyard. On the Scotian Shelf silver hake were distributed to depths of 150-250 m during spring, moving to depths of 100-150 m during the spawning season. In July, they migrated along the slope to 250 m. Long term studies have shown that such life-cycle stages as over-wintering and feeding occur in near bottom slope water. Older silver hake prefer the warmer waters of the shelf slope and deep-water shelf area. Silver hake are relatively fast growing, reaching sexual maturity at 2-3 years (20-35 cm), and live a maximum of 14 years, although in recent years fish older than 6 years are rare.

Silver hake spawn over a wide range of temperatures and depths. Hake found on the Scotian Shelf silver hake prefer warm, shallow waters (> 10ºC) at depths of 30-40 m for mass spawning. Spawning begins in January along the shelf and slope in the Middle Atlantic Bight. During May, spawning proceeds north and east to Georges Bank. By June, spawning spreads into the Gulf of Maine and continues to be centered on Georges Bank through summer. In October, spawning is centered in southern New England and by December is observed again along the shelf and slope in the Middle Atlantic Bight. Peak spawning occurs May to June in the southern stock and July to August in the northern stock. The primary spawning grounds most likely coincide with concentrations of ripe adults and newly spawned eggs. These grounds occur between Cape Cod, Massachusetts, and Montauk Point, New York, on the southern and southeastern slope of Georges Bank and the area north of Cape Cod to Cape Ann, Massachusetts.

Silver hake are an important predator species on the continental shelf of the Northwest Atlantic. Their dominant biomass and high prey consumption affect population dynamics and contribute heavily to the regulation of this ecosystem. These semi-pelagic predators are nocturnal feeders with a predictable diet consisting of fish, crustaceans, and squid. The diet of young silver hake consists of euphausiids, shrimp, amphipods, and decapods. All silver hake are ravenous piscivores that feed on smaller hake and other schooling fishes such as young herring, mackerel, menhaden, alewive, sand lance, or silversides, as well as crustaceans and squids. Silver hake are an important prey for other hake species, pelagic fish, cod, spiny dogfish, squid, and some marine mammals.

Habitat Characteristics
The overall distribution of silver hake is from the Gulf of St. Lawrence to Cape Hatteras. The areas of highest abundance are the southern edge of the Grand Bank, the Scotian Shelf, the Gulf of Maine, Georges Bank, and the Middle Atlantic Bight off Long Island.

Silver hake eggs are abundant in the deeper parts of Georges Bank (> 60 m) and the shelf off southern New England. Distribution of silver hake larvae from Cape Hatteras, North Carolina to Nova Scotia based on 50 ichthyoplankton surveys in the NEFSC MARMAP series (1977-1984), reveal considerable year-to-year differences in the temporal and spatial patterns of abundance. The overall pattern of distribution is similar to the distribution of eggs, wherein the center of abundance is on Georges Bank. A secondary center is in southern New England. The bottom depths where eggs were captured ranged from 10-1250 m, however most eggs were collected between 50-150 m. Eggs were found in shallower waters during spring. Average depth of egg occurrences declined from about 100 m in spring to about 60 m in summer. Larvae occur in shallower water than eggs based on NMFS MARMAP surveys. The bottom depths where larvae were captured ranged from 10-1250 m, however most occurred between 50-130 m. Peak abundance of larvae occurred from July to October. During these months most larvae were found in temperatures of 11-16°C. Silver hake juveniles and adults are found over wide temperature and depth ranges in U.S. continental shelf waters. In spring, they were found in waters between 2-16ºC, with the majority at about 4-8ºC. During that season they were found over a depth range of 1-400 m. Juveniles were found at salinities between 30-36 ppt, with most between 33-34 ppt. During autumn, juvenile silver hake were found over a temperature range of 4-21°C, with most caught between 6-13°C. During this time, they were found over depths ranging from 1-400 m. Hake were found at salinities ranging from about 32-36 ppt, with the majority between 33-34 ppt. Auster *et al*. (2003) studied the small scale spatial distributions of both juvenile and adult silver hake within sand wave habitats and the diel patterns of habitat use on the southern side of Georges Bank and on Stellwagen Bank. Silver hake were not randomly distributed within sand wave habitats; there was a positive relationship between fish length and sand wave period. However, other factors, such as currents and available prey, may also influence their distribution in these habitats.

In the spring, adult silver hake are typically found over a temperature range of 2-15°C, with the majority found between 6-12°C. They were found in depths ranging from 11-500 m. Adults were found in salinities ranging from 32-36 ppt with most spread between 33-35 ppt. During the autumn, adults can be found over a temperature range of 4-17°C, with greatest percentages between 7-10°C over a depth range of 21-400 m. Adults have been captured within a salinity range of between 32-36 ppt, with most between 33-35 ppt. Adult silver hake on the Scotian Shelf occurred on all bottom types from gravel to fine silt and clay, but were mainly associated with silts and clays.

Time-Series Analysis

Based on the NMFS trawl surveys, silver hake are one of the most abundant and ubiquitous fish species in the Gulf of Maine. During spring adults and juveniles occurred in half to two-thirds of all trawl samples (Figures 3.3.33 and 3.3.34). Patterns of high abundance are widespread, but in general, most adults are found in the central Gulf of Maine, the deeper edges of Georges Bank, southern New England, and within Massachusetts and Cape Cod Bays. During the fall, adult (Figure 3.3.35) and juvenile (3.3.36) frequency of occurrence was higher than in the spring with similar distribution patterns.

Within the Sanctuary, silver hake were highly abundant and were captured in over 75% of trawl samples. Frequency of occurrence was similar compared between spring and fall, however mean abundance was higher in the fall (Table 3.3.9). Mean standard length for adults was similar during spring and fall, ranging from 29-33 cm. Mean standard length for juveniles was slightly larger during the fall. Depth at capture was similar for adults during spring and fall with catches occurring at depths between 27-150 m, while the highest abundance was centered at depths between 50-110 m. Juveniles were captured at depths between 27-150 m, and highest abundance was captured between 50-105 m.

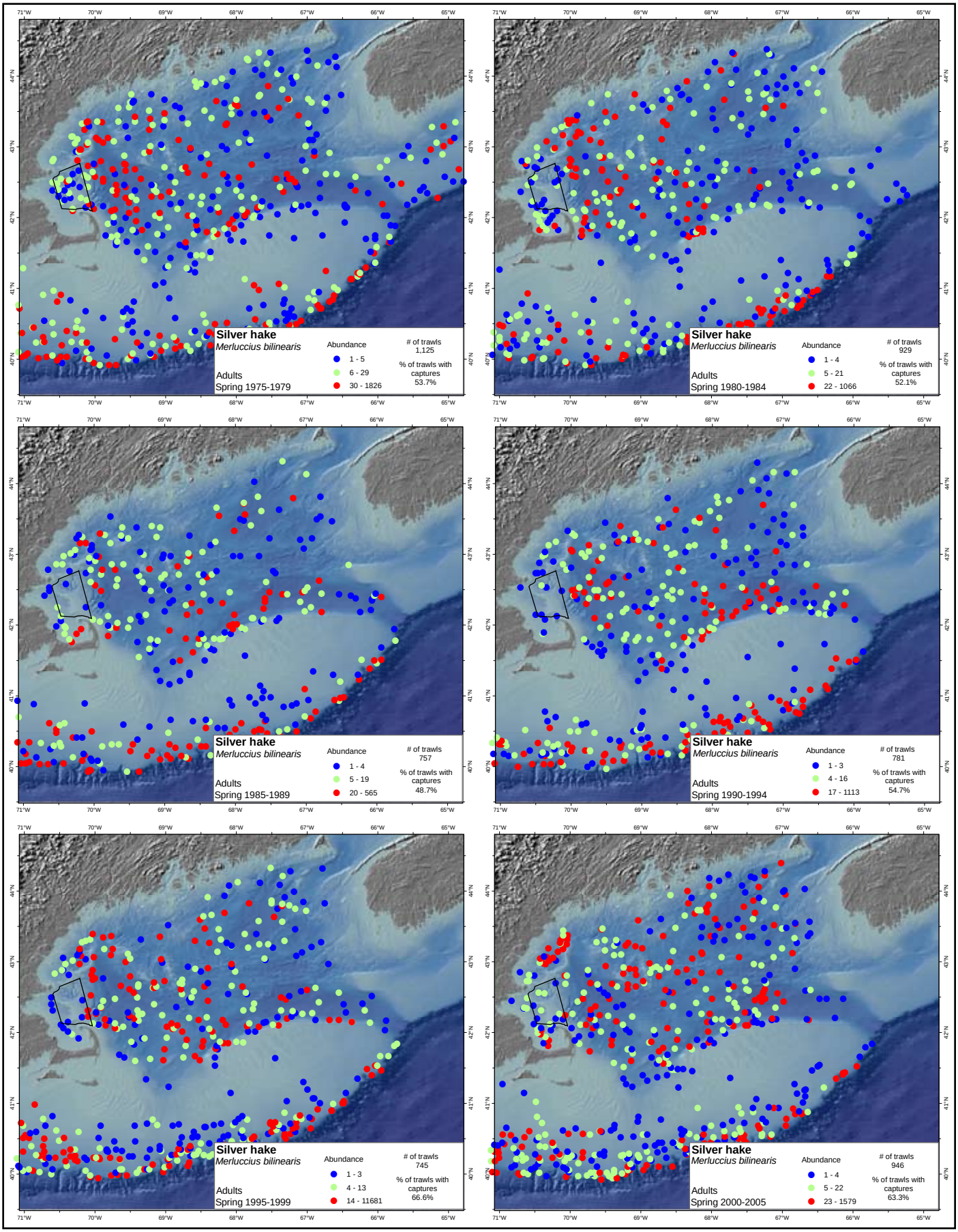

Figure 3.3.33. Abundance and distribution of adult silver hake (*Merluccius bilinearis*) within the Gulf of Maine, Spring 1975-2005.

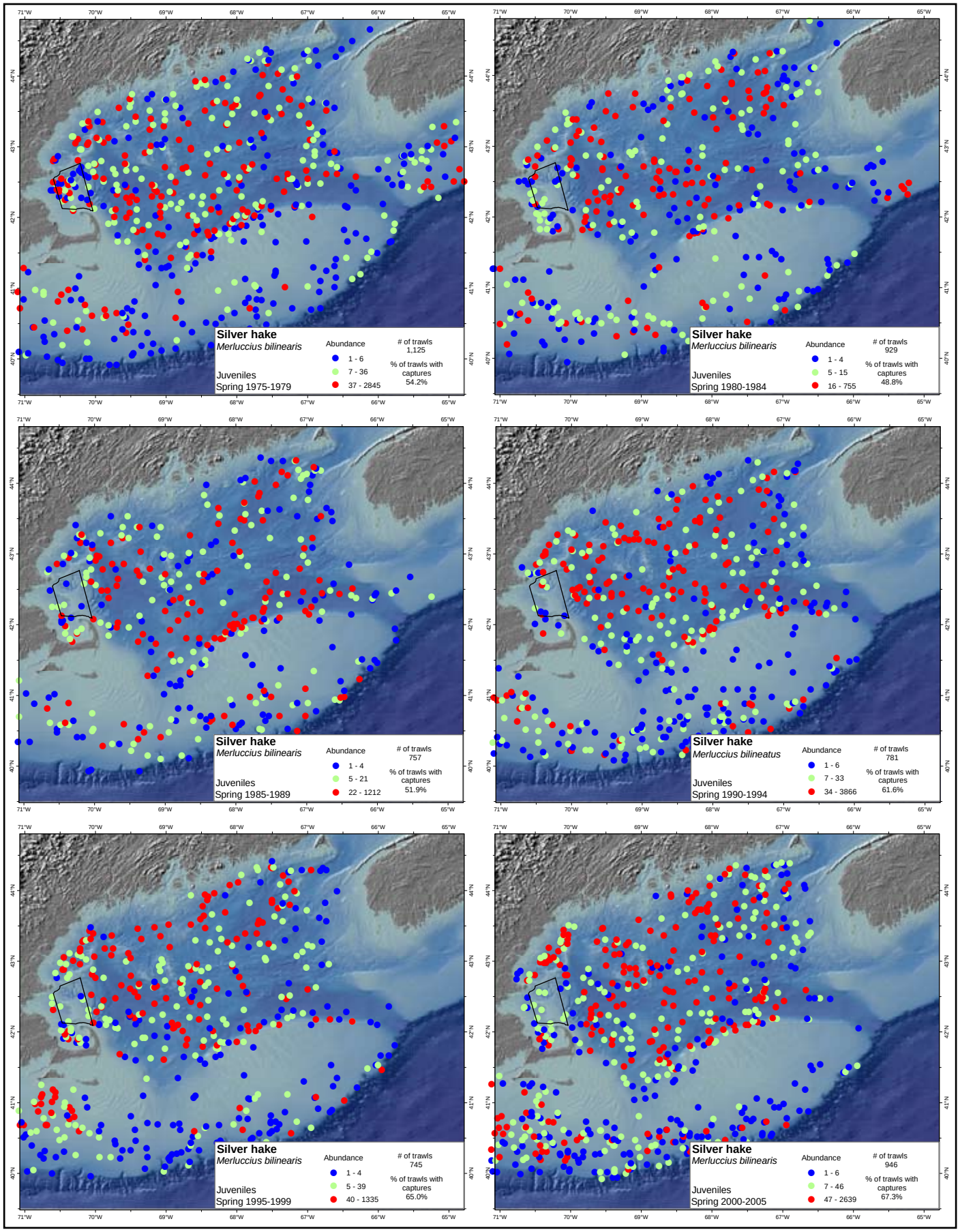

Figure 3.3.34. Abundance and distribution of juvenile silver hake (*Merluccius bilinearis*) within the Gulf of Maine, Spring 1975-2005.

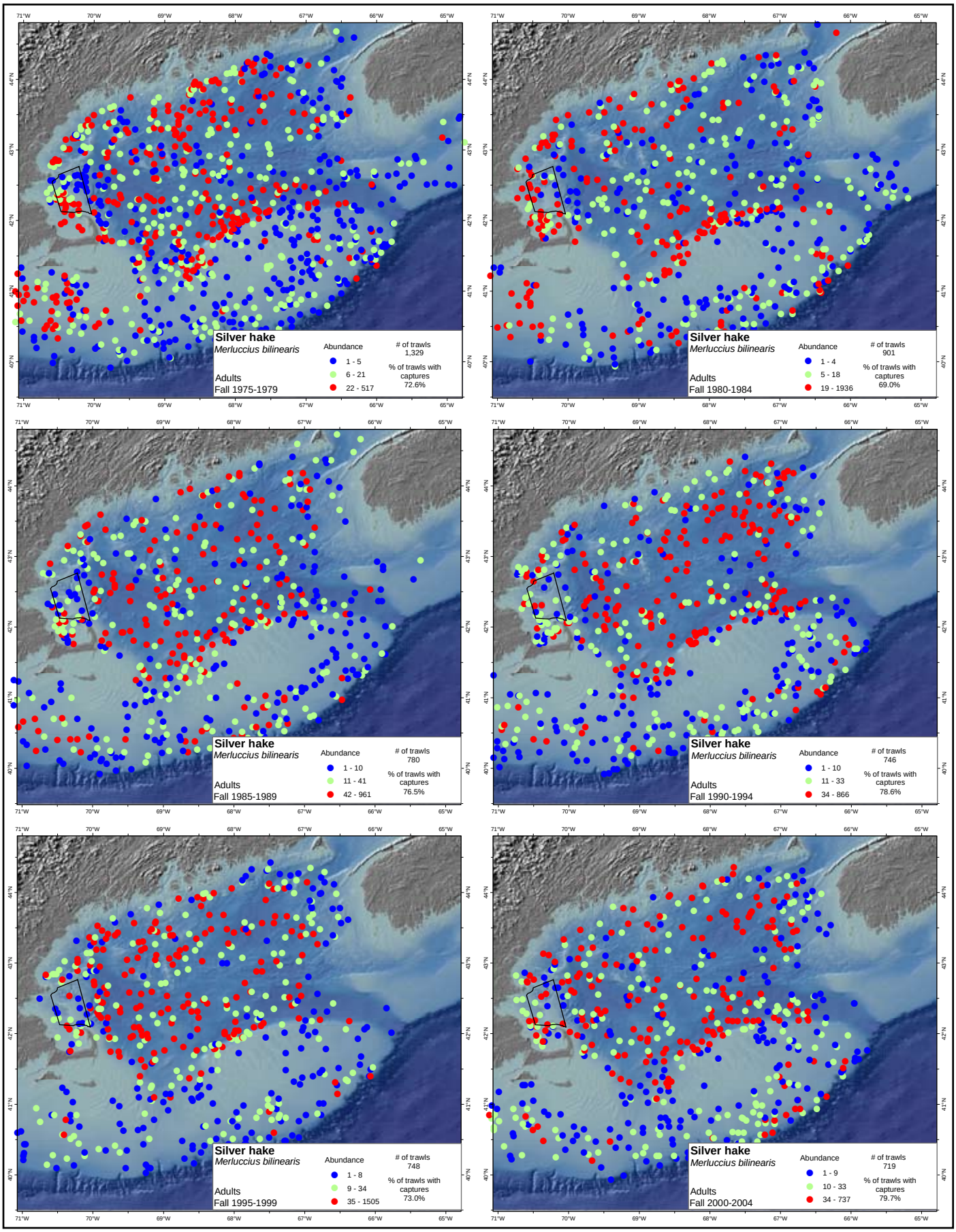

Figure 3.3.35. Abundance and distribution of adult silver hake (*Merluccius bilinearis*) within the Gulf of Maine, Fall 1975-2004.

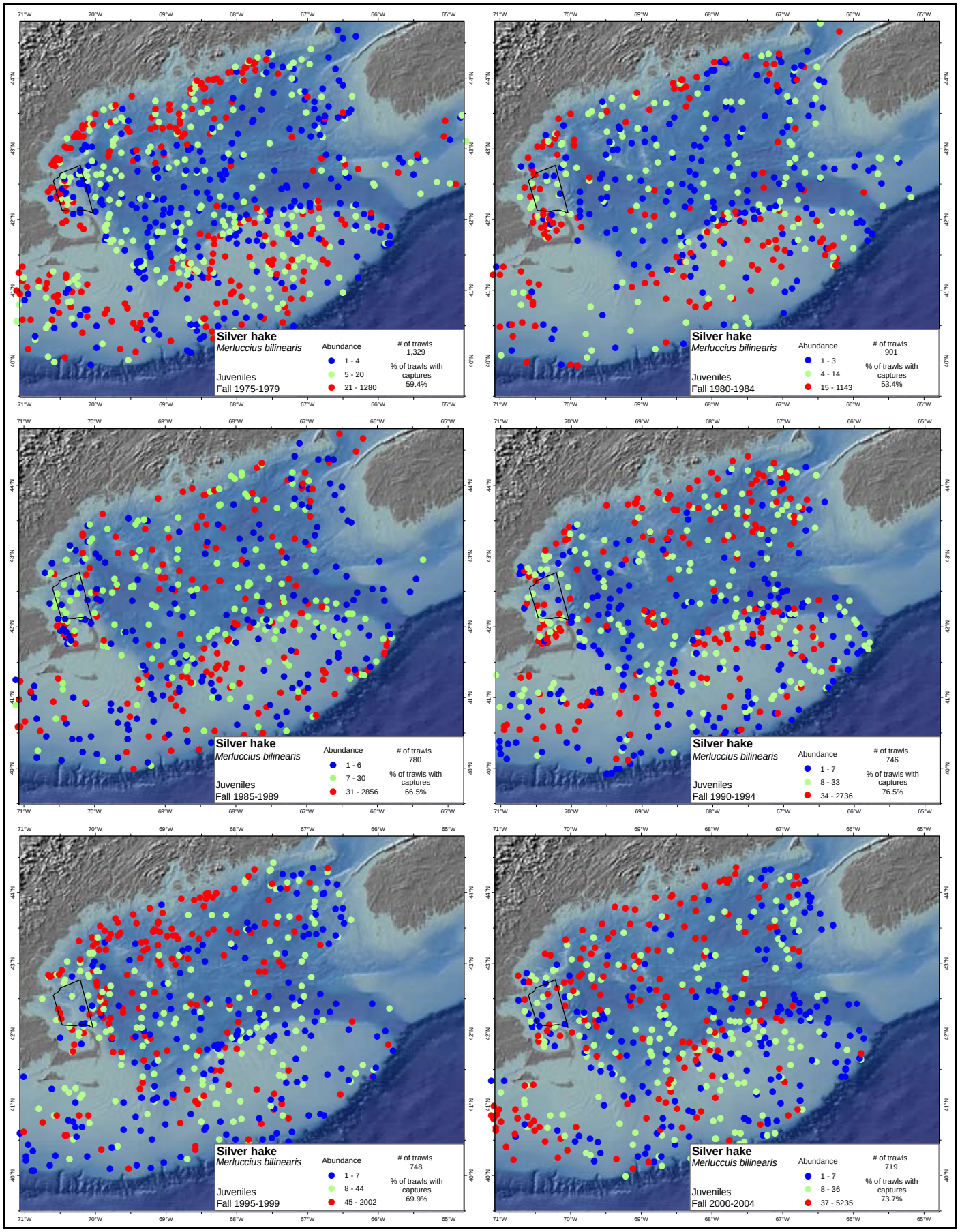

Figure 3.3.36. Abundance and distribution of juvenile silver hake (*Merluccius bilinearis*) within the Gulf of Maine, Fall 1975-2004.

Table 3.3.9. Frequency of occurrence and abundance for all silver hake captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	71.43	61.89	31.97	52	38-133	13.8712	7	38-133
	80-84	22	63.64	6.91	29.14	51	58-105	14.4444	6	64-105
	85-89	16	75.00	5.81	31.43	42	57-126	13.1724	9	54-126
	90-94	21	47.62	18.57	28.28	39	65-120	13.5	6	62-120
	95-99	17	82.35	15.65	31.36	48	41-123	13.8971	6	64-123
	00-05	17	82.35	13.82	28.79	64	36-144	16.3710	9	56-144
Fall	75-79	61	32.79	6.23	35.31	68	30-105	16.1875	4	37-104
	80-84	22	77.27	27.59	32.42	64	29-101	15.2267	4	58-101
	85-89	20	95.00	17.80	31.86	50	43-138	14.8929	4	46-138
	90-94	19	89.47	76.79	30.08	50	44-117	15.9149	4	44-117
	95-99	18	100.00	41.61	33.97	59	32-95	14.3486	4	48-95
	00-04	16	93.75	56.19	29.99	53	45-149	14.1647	5	45-149

Spiny dogfish (*Squalus acanthias)*

The spiny dogfish is a coastal squaloid shark with a circumboreal distribution. Within the Gulf dogfish are abundant predators that feed primarily on fish. Spiny dogfish are the most abundant shark in the western North Atlantic. Dogfish produce live young and reach maturity at large size and populations are sensitive to exploitation. Dogfish exhibit wide seasonal variations in abundance in the Gulf and Stellwagen Bank NMS. Spiny dogfish are managed by the Mid-Atlantic Fishery Management Council. The management unit is the entire spiny dogfish population along the Atlantic coast of the United States (MAFMC, 1998). The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of spiny dogfish inhabiting U.S. waters, primarily in the Gulf of Maine (McMillan and Morse, 1999).

Life History

Estimates of size at maturity for spiny dogfish females have varied temporally and geographically. The median length at which 50% of individuals are mature is 83 cm for females and 60 cm for males. Spiny dogfish school by size until they mature and then they school by size and sex. Schools are often composed of very large, mature females; medium-sized individuals, either all mature males or all immature females; or small immature individuals of both sexes in equal numbers. Fertilization takes place internally and development is ovoviviparous. Internal development takes place over 18-22 months. Parturition occurs offshore in the winter. Litter sizes range from 1-15 pups, but usually average 6-7. The size at birth for both sexes ranges from 20-33 cm.

The maximum age of males has been estimated at 35 years and the maximum age of females at 40 years in the northwest Atlantic Ocean. Females grow larger than males and may reach a maximum length of 125 cm and weight of 10 kg.

Spiny dogfish are voracious and opportunistic predators. Swimming in large groups they will attack schools of fish including cod, haddock, capelin, mackerel, herring, and sand lance. Their opportunistic nature is supported by their consumption of flatfish, blennies, sculpin, ctenophores, jellyfish, polychaetes, sipunculids, amphipods, shrimp, crabs, snails, octopods, squids, and sea cucumbers.

Spiny dogfish migrate northward in the spring and summer and southward in the fall and winter. Fish that spend the summer north of Cape Cod move south to Long Island in the fall and as far south as North Carolina in the winter. Seasonal inshore-offshore movements and coastal migrations are related to water temperature. Generally, spiny dogfish spend summers in inshore waters and overwinter in deeper offshore waters. They are usually

epibenthic, but occur throughout the water column and are found from nearshore shallow to offshore shelf waters to 900 m.

Habitat Characteristics

In the spring, juveniles and adults occur in deeper, generally warmer waters on the outer shelf from North Carolina to Georges Bank. In the fall, they occur in the shallower, moderately warm waters from southern New England into the Gulf of Maine. Their seasonal distribution is similar in coastal areas. Dogfish are transient visitors to estuaries where they prefer higher salinities.

Time-Series Analysis

Spiny dogfish frequency of occurrence was comparable between spring and fall, however abundance was significantly greater during fall. During spring, frequency of occurrence was high ranging between 39-70%. Most of the spiny dogfish occurrences were in the southern portion of the study area (southern Georges Bank and southern New England), however some areas of high abundance were in the central Gulf (Figure 3.3.37). Juvenile frequency of occurrence was lower than adults (17-47%) and centers of abundance were also found on Georges Bank and southern New England. Catch north of Cape Cod was sporadic (Figure 3.3.38). During fall, adult distribution was more widespread than spring with centers of abundance located within Massachusetts and Cape Cod Bays, Georges Bank, and southern New England (Figure 3.3.39). Juvenile abundance increased during fall, but their distribution was centered on Georges Bank and southern New England (Figure 3.3.40) and sporadic high abundance within the northern Gulf.

Spiny dogfish juveniles were uncommon within Massachusetts Bay and SBNMS. Abundance was low within the Sanctuary during spring and was significantly greater during fall, in particular 1995-2004 (Table 3.3.10). No spiny dogfish were captured in the Sanctuary during spring 1985-1994. Mean length of adult dogfish ranged between 85-95 and maximum size ranged between 88-108. Adults were found at depths between 27-101 m during fall, with most abundance occurring between 30-80 m. During spring adults were captured at depths between 28-138 m, with abundance greatest at depths between 35-85 m.

Juveniles ranged in size from 67-75 cm and smallest individuals ranged in size from 25-70 cm. Juveniles were captured in similar depth ranges as adults: 27-145 m during spring and 27-150 m during fall. Juvenile abundance was greatest at depths between 30-85 m during both seasons.

Table 3.3.10. Frequency of occurrence and abundance for all spiny dogfish captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	21.43	5.46	90.38	101	37-96	75.18	57	37-96
	80-84	22	18.18	10.77	95.40	107	37-101	75.33	70	37-75
	85-89	16	NC	-	-	-	-	-	-	-
	90-94	21	NC	-	-	-	-	-	-	-
	95-99	17	64.71	2.59	87	88	41-83	70.91	63	41-115
	00-05	17	47.06	5.59	86.2	90	27-84	71.94	27	27-144
Fall	75-79	61	54.10	11.20	90.22	102	30-118	74.30	54	30-118
	80-84	22	40.91	1.82	96.07	101	28-84	72.83	58	28-84
	85-89	20	90.00	14.90	92.32	103	43-138	71.29	52	43-138
	90-94	19	89.47	7.63	89.07	108	44-111	67.72	47	44-116
	95-99	18	88.89	142.61	85.39	90	32-95	69.14	28	32-95
	00-04	16	181.25	155.94	85.05	91	45-118	72.40	25	45-149

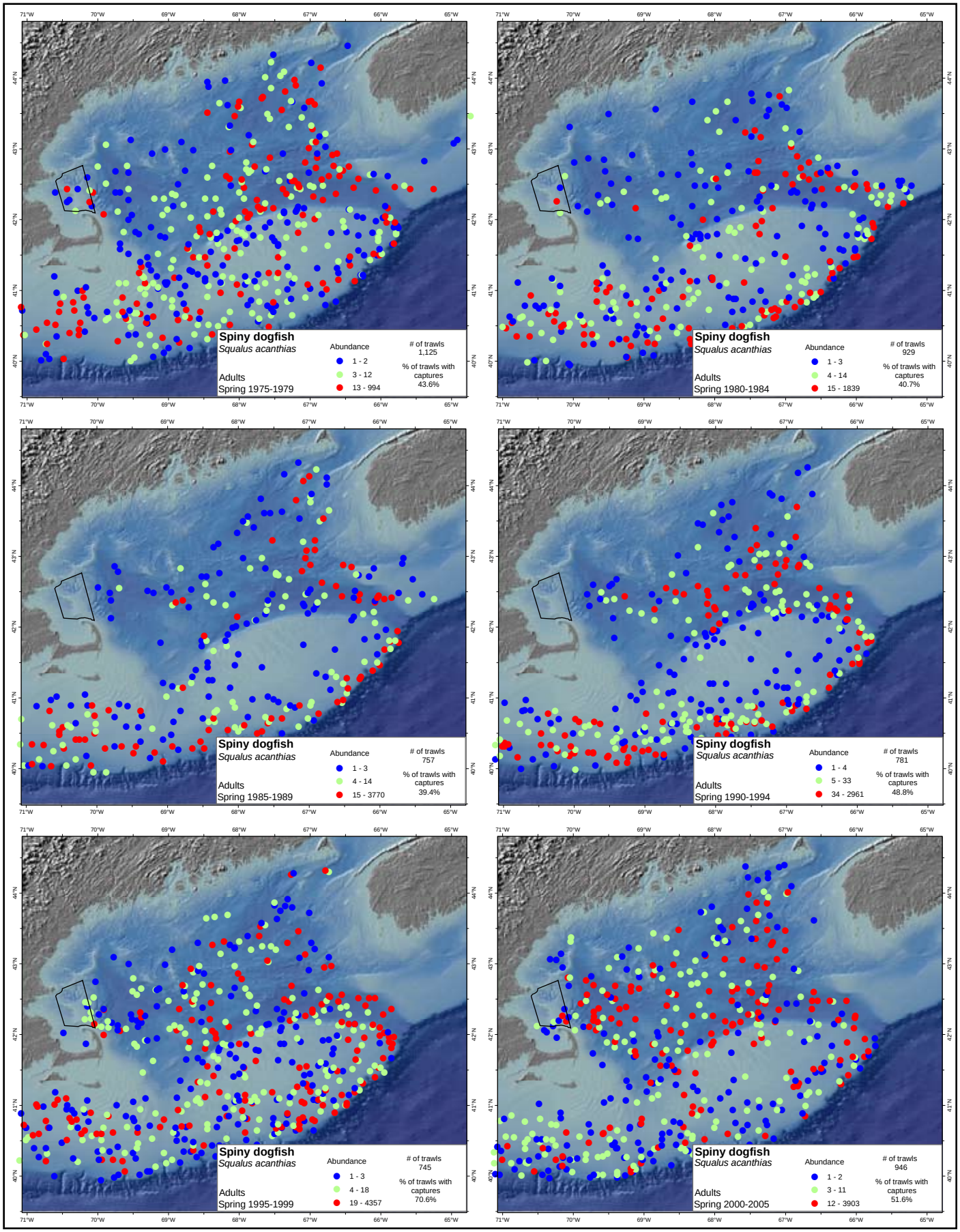

Figure 3.3.37. Abundance and distribution of adult spiny dogfish (*Squalus acanthias*) within the Gulf of Maine, Spring 1975-2005.

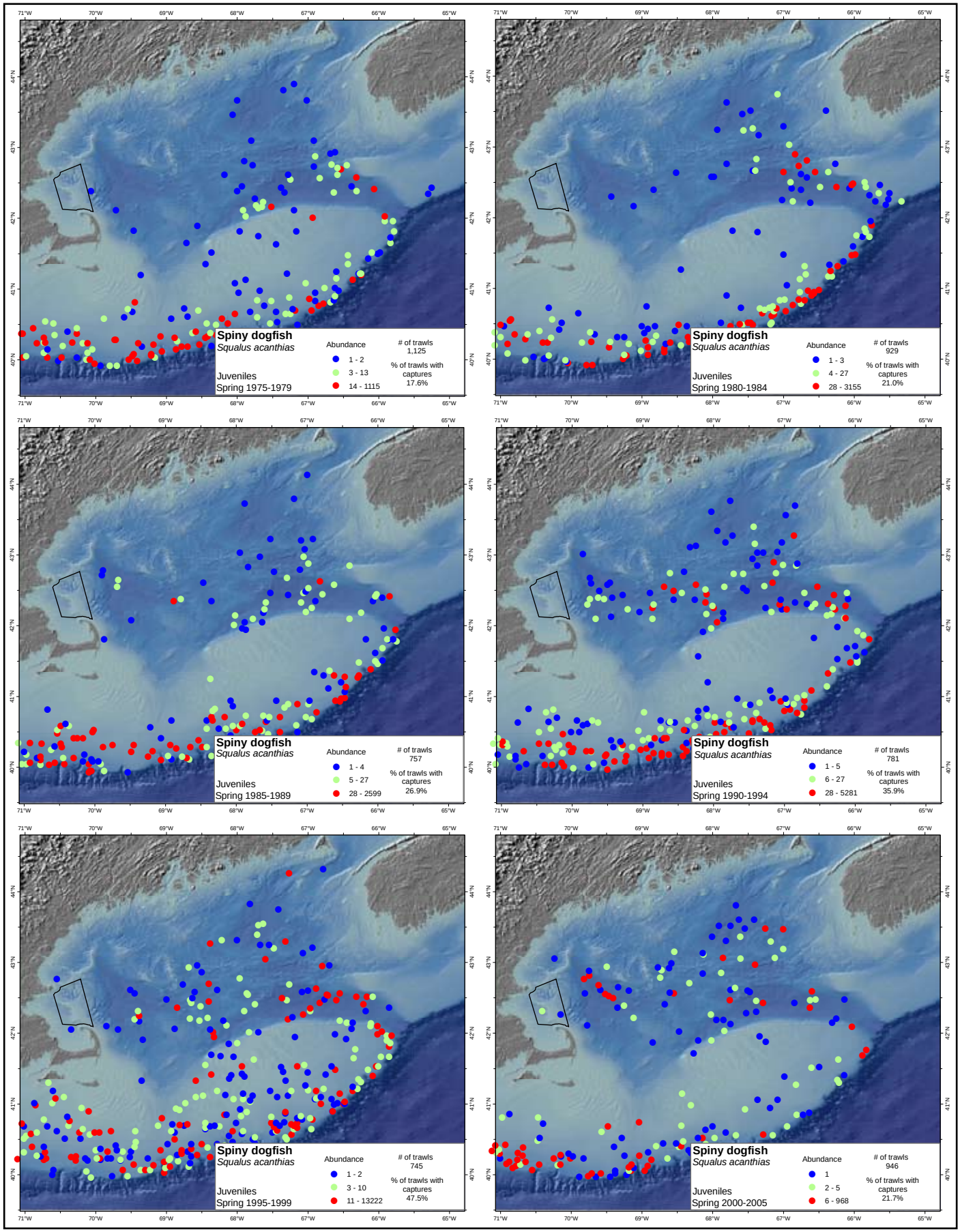

Figure 3.3.38. Abundance and distribution of juvenile spiny dogfish (*Squalus acanthias*) within the Gulf of Maine, Spring 1975-2005.

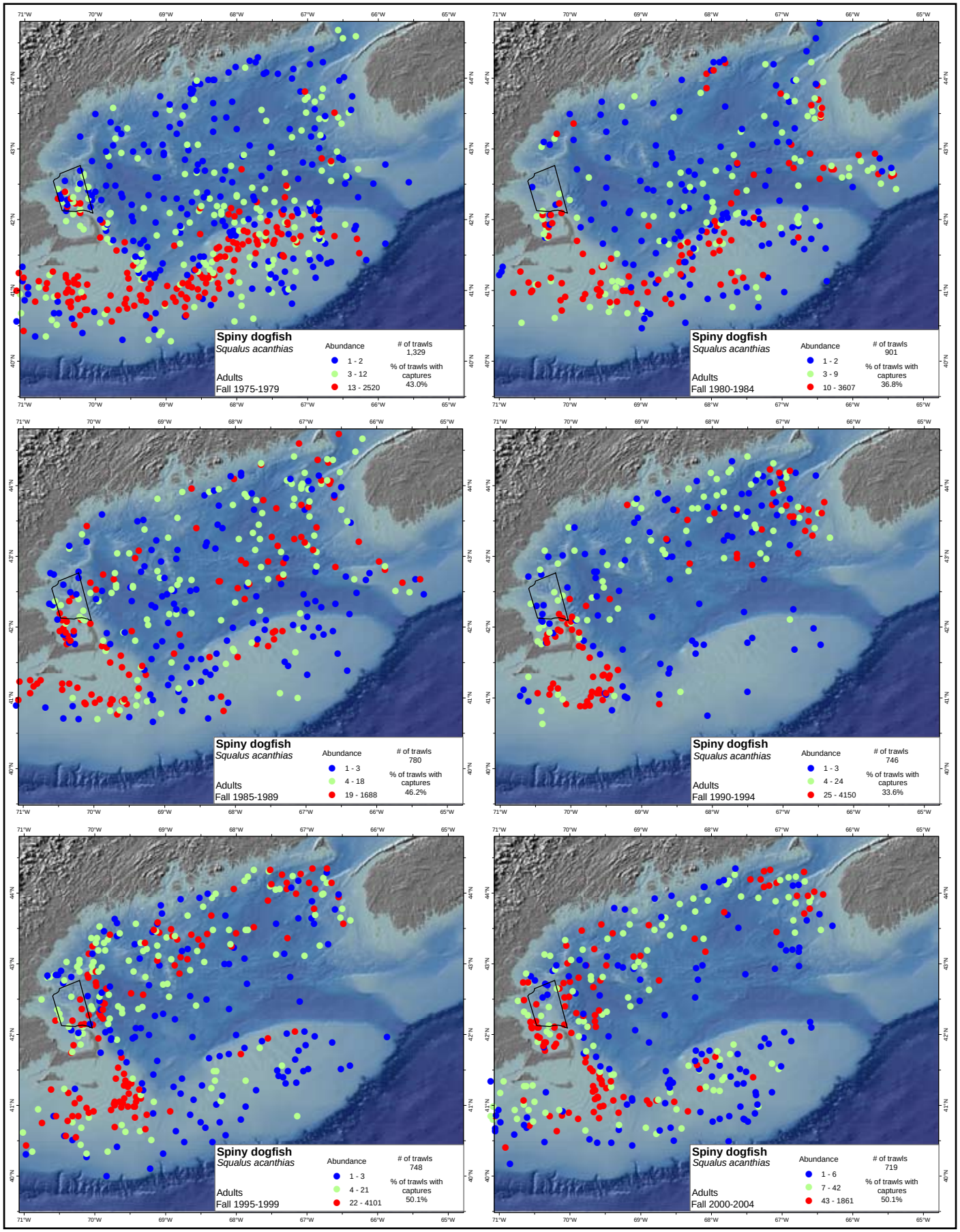

Figure 3.3.39. Abundance and distribution of adult spiny dogfish (*Squalus acanthias*) within the Gulf of Maine, Fall 1975-2004.

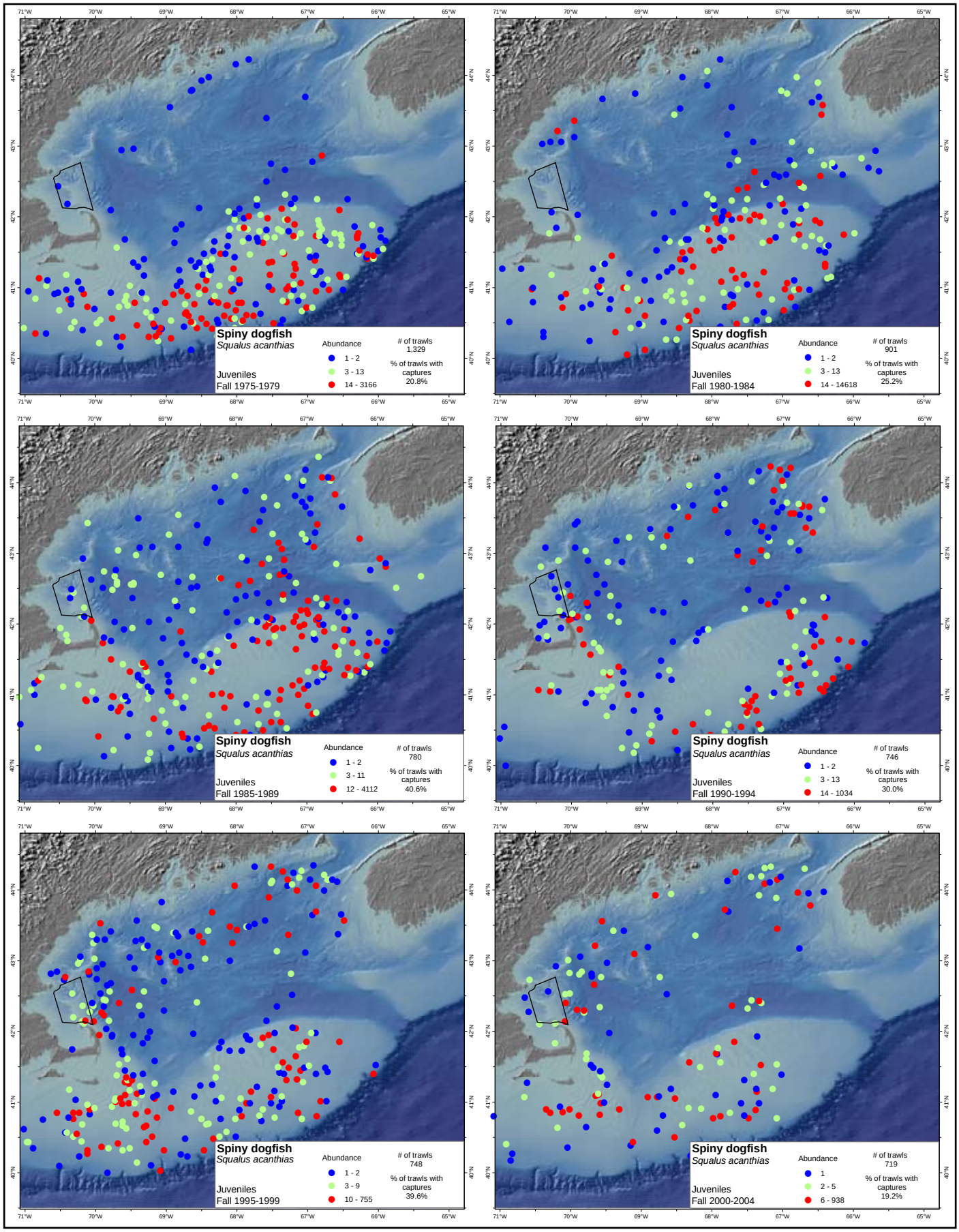

Figure 3.3.40. Abundance and distribution of juvenile spiny dogfish (*Squalus acanthias*) within the Gulf of Maine, Fall 1975-2004.

Thorny skate (*Amblyraja radiata)*
In 2004 thorny skate were listed as a species of concern under the ESA based on low population numbers from overexploitation. The thorny skate occurs on both sides of the Atlantic and are found over a wide variety of habitats within the Gulf. Thorny skate is one of the most abundant skate encountered in the Gulf of St. Lawrence, off northeastern and southeastern Nova Scotia, and in the Gulf of Maine. Skate are frequently taken as bycatch during groundfish trawling and scallop dredge operations and are managed under the New England Fishery Management Council's Northeast Multispecies Fishery Management Plan. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of thorny skate inhabiting U.S. waters, primarily in the Gulf of Maine (Packer *et al*., 2003).

Life History
Females with fully formed egg capsules are captured the entire year, although the percentage of mature females with capsules is higher during the summer. Females with ripe eggs have been taken in Nova Scotian waters or in the Gulf of Maine in April, June, July, and September. Size and age at maturity has been estimated to occur at 83 cm and 7 years.

Thorny skate is an opportunistic feeder on the most abundant and available prey species in an area. Thorny skate prey on hydrozoans, aschelminths, gastropods, bivalves, squid, octopi, polychaetes, pycnogonids, copepods, stomatopods, cumaceans, isopods, amphipods, mysids, euphausiids, shrimp, hermit crabs, crabs, holothuroideans, and fish in the western North Atlantic. Thorny skate is eaten, at least as embryos within the egg capsules, by halibut, goosefish, and Greenland sharks, as well as predatory gastropods (e.g. naticid and muricid gastropods). Adult and juvenile thorny skate are preyed upon by seals, shark, and halibut.

Habitat Characteristics
The depth range of thorny skate is from approximately 18-1200 m and is most common at 50-100 m in the northeast Atlantic and 37-108 m on the Scotian Shelf. The temperature range of thorny skate from Nova Scotia to Cape Hatteras is from -1.3°C to 14°C, although it has been recorded down to -1.4°C off Labrador. On the Nova Scotian shelf skate have a temperature preference of 2-5°C. The spring and fall 1963-2002 NEFSC trawl surveys from the Gulf of Maine to Cape Hatteras collected juveniles and adults over a temperature range of about 2-16°C, with most found between about 4-9°C. Adults and juveniles are found over a wide variety of bottom types from sand, gravel, broken shell, pebbles, to soft mud.

Time-Series Analysis
Overall, adult thorny skate were infrequent within the study area. During spring adults were more frequent in the early portion of the time-series (1975-1984), but captures were uncommon through 2005 (Figure 3.3.41). Juveniles were widely distributed throughout the Gulf and more abundant than adults (Figure 3.3.42). Similar to adults, juvenile capture frequency was highest in the beginning of the time-series with frequency steadily declining through 2005.

Adult skate were also infrequent within the Gulf during fall (Figure 3.3.43), although captures were slightly higher than in spring. Capture frequency of juveniles was similar during fall compared to spring and exhibited a steady decline through the time series (Figure 3.3.44). High concentrations of adults or juveniles was not observed.

Adults and juveniles were common in trawl samples within the Sanctuary (Table 3.3.11) during the first 15 years of the time-series and were less common more recently. No adults were captured within the Sanctuary between 1995-2005. Abundance of both adults and juveniles were greater in the fall than in the spring. Adults were less abundant than juveniles and mean length ranged from 84-99 cm. Adults were captured at depths between 47-112 m, but most were caught at depths less than 90 m. Juvenile mean length was slightly larger in the fall than spring. Juveniles were captured within the same depth range as adults (30-135 m) with abundance greater at depths between 50-85 m.

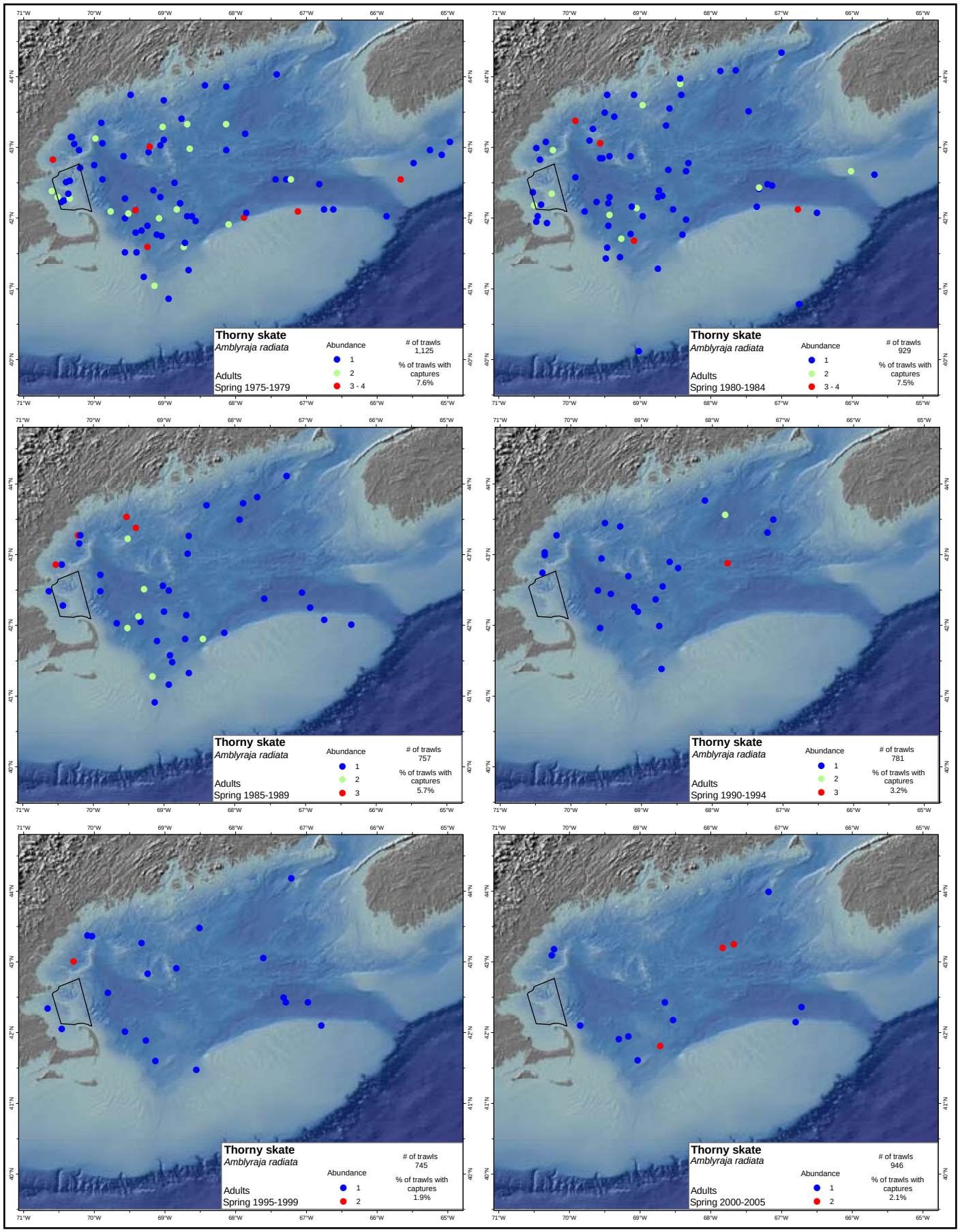

Figure 3.3.41. Abundance and distribution of adult thorny skate (*Amblyraja radiata*) within the Gulf of Maine, Spring 1975-2005.

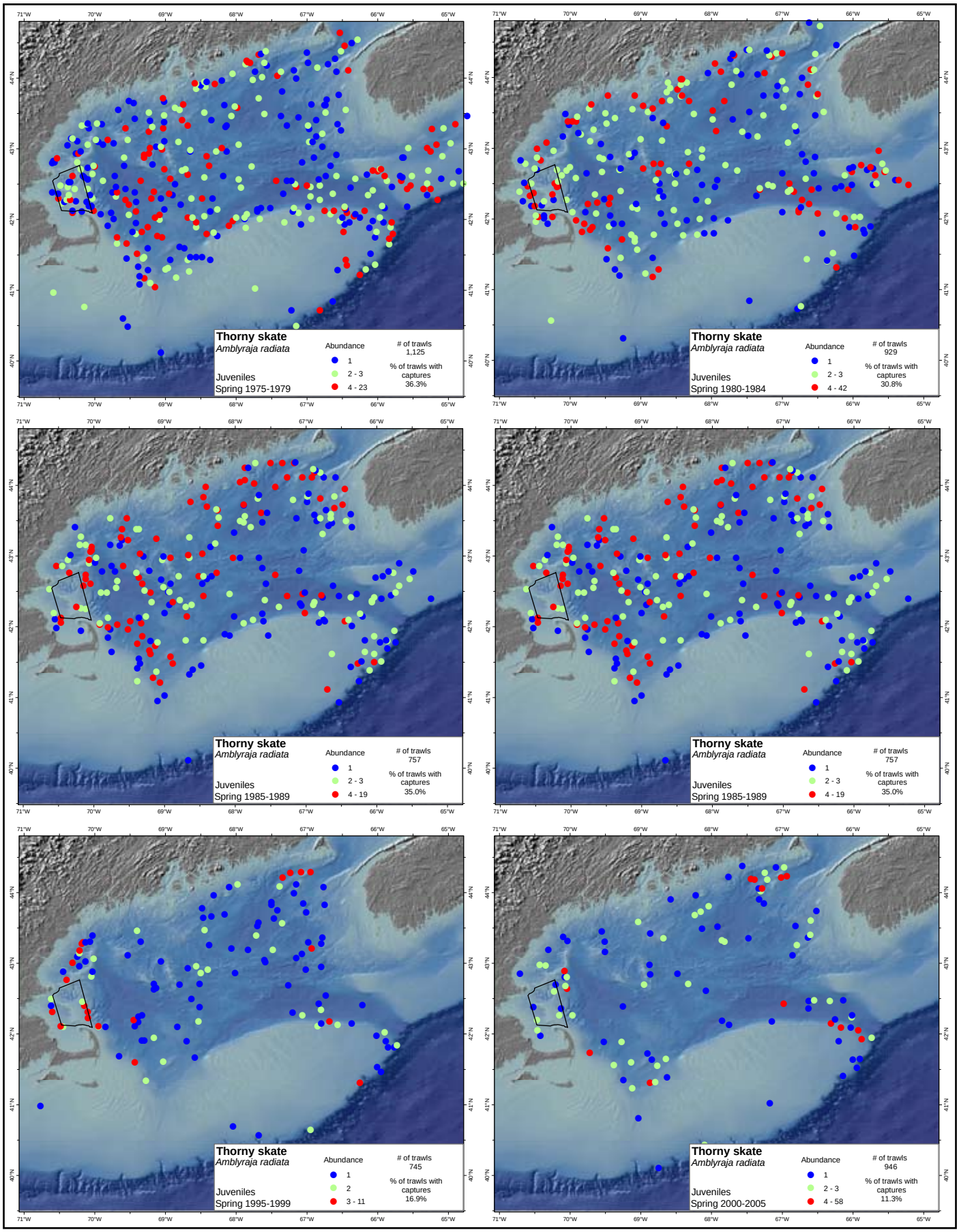

Figure 3.3.42. Abundance and distribution of juvenile thorny skate (*Amblyraja radiata*) within the Gulf of Maine, Spring 1975-2005.

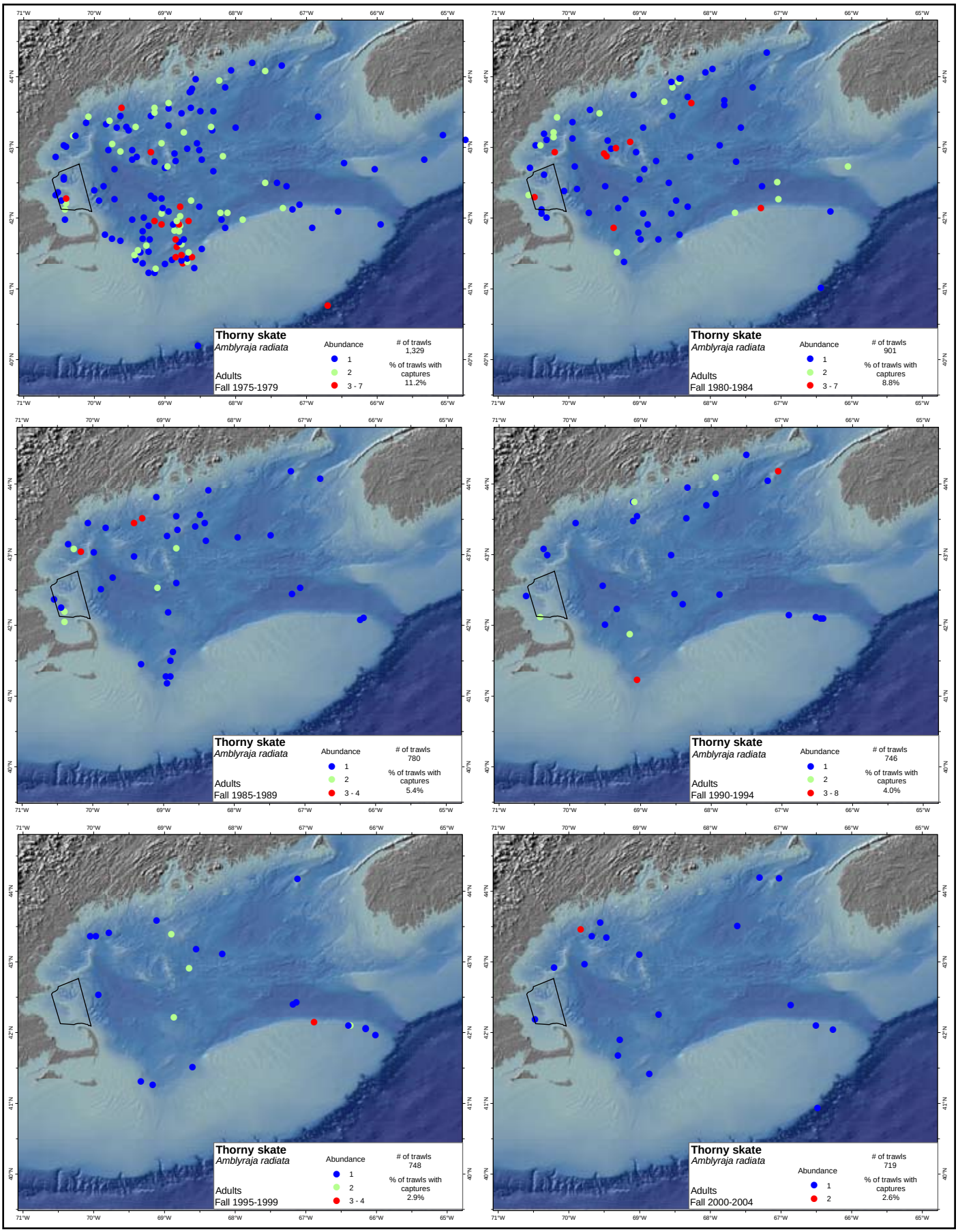

Figure 3.3.43. Abundance and distribution of adult thorny skate (*Amblyraja radiata*) within the Gulf of Maine, Fall 1975-2004.

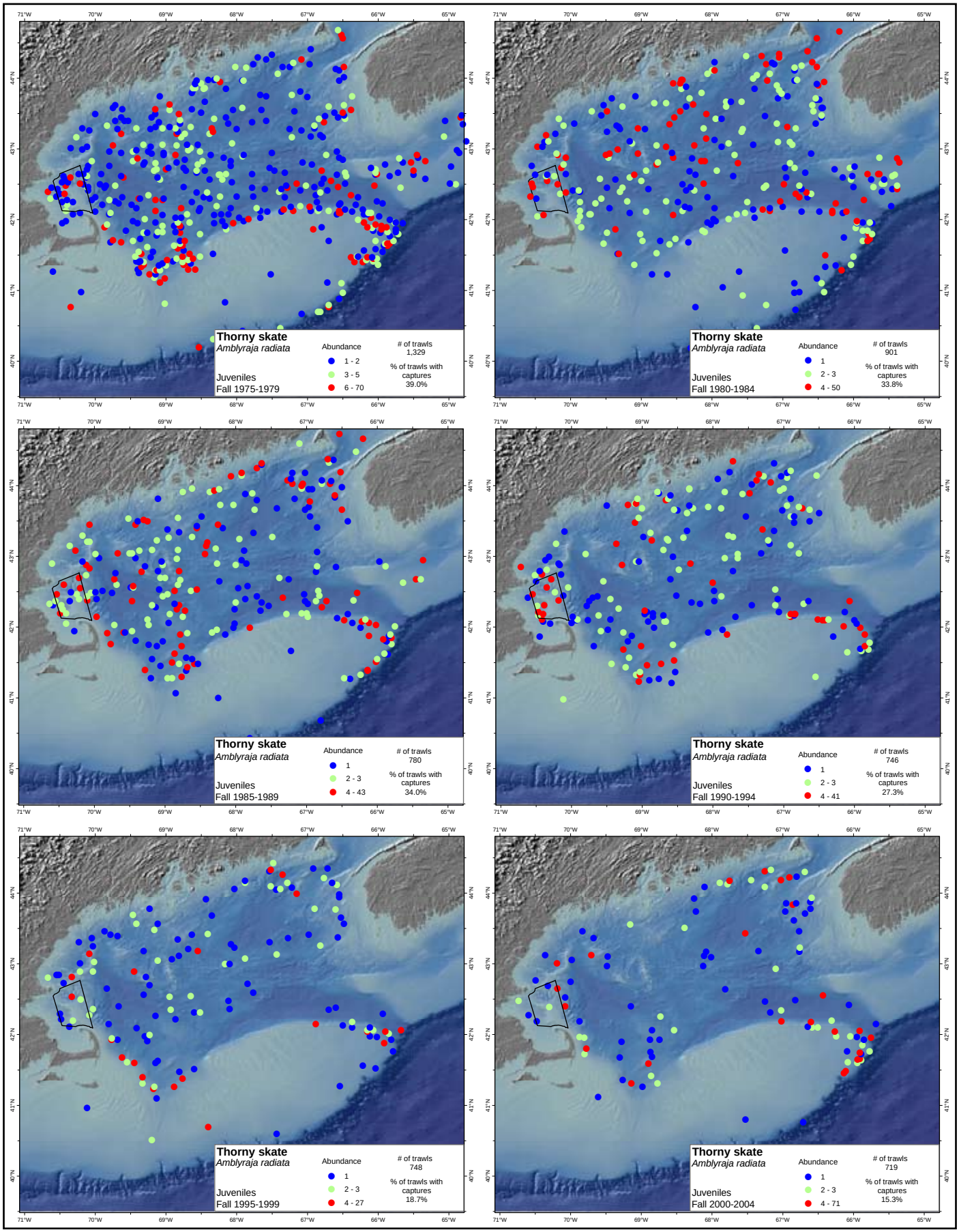

Figure 3.3.44. Abundance and distribution of juvenile thorny skate (*Amblyraja radiata*) within the Gulf of Maine, Fall 1975-2004.

Table 3.3.11. Frequency of occurrence and abundance for all thorny skate captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	53.57	1.57	92.50	101	68-112	39.54	13	35-133
	80-84	22	72.73	4.73	89.00	93	47-88	39.96	12	37-121
	85-89	16	68.75	3.31	84.00	84	88	50.37	15	33-106
	90-94	21	57.14	1.24	99.00	99	93	36.76	15	62-120
	95-99	17	58.82	2.88	N/A	N/A	N/A	32.05	12	75-115
	00-05	17	35.29	0.71	N/A	N/A	N/A	39.00	19	72-97
Fall	75-79	61	50.82	1.67	92.83	103	62-104	44.85	10	42-118
	80-84	22	59.09	3.00	96.00	102	61-88	46.37	13	58-101
	85-89	20	80.00	4.25	94.00	100	65-89	38.60	13	53-138
	90-94	19	89.47	5.74	94.67	99	60-81	33.96	13	59-117
	95-99	18	50.00	1.39	N/A	N/A	N/A	45.42	22	32-95
	00-04	16	37.50	1.13	N/A	N/A	N/A	42.71	13	45-118

Yellowtail flounder (*Limanda ferruginea)*

The yellowtail flounder is a small-mouthed, thin bodied pleuronectid that inhabits waters along the Atlantic coast of North America from the Gulf of St. Lawrence, Labrador, and Newfoundland to the Chesapeake Bay. Yellowtail flounder are a highly abundant benthivore at depths less than 150 m throughout the Gulf. Yellowtail are most abundant on the western half of Georges Bank, the western Gulf of Maine, east of Cape Cod, and southern New England. Yellowtail flounder became a key constituent of the U.S. demersal fishery in the early 1930s when the stock of winter flounder declined and is in high demand today. Yellowtail flounder are managed under the New England Fishery Management Council's Northeast Multispecies Fishery Management Plan. The information that follows is a summary of the Essential Fish Habitat source document for this species which provides life history information and habitat requirements of yellowtail flounder inhabiting U.S. waters, primarily in the Gulf of Maine (Johnson *et al*., 1999).

Life History

In the northwest Atlantic, spawning occurs from March through August at temperatures of 5-12^{o}C. Yellowtail spawn buoyant, spherical, pelagic eggs. Eggs hatch approximately five days after fertilization at temperatures of 10-11^{o}C. Larvae hatch with unpigmented eyes at lengths of 2.0-3.5 mm TL. Caudal rays develop at 10 mm. Body flexion begins at 5-10 mm notochord length (NL); transformation is completed at an average length of 14 mm. Larvae normally do not become benthic until ossification of fin rays is complete at approximately 14 mm SL. Juveniles range in size between 17 mm to <26 cm and are present in the Gulf during all seasons. Yellowtail attain sexual maturity around 26 cm SL and reach maximum size of 60 cm SL. Adults are found within the Gulf during all seasons.

Habitat Characteristics

Adults spawn along continental shelf waters around Georges Bank, northwest of Cape Cod, and throughout southern New England. Spawning typically takes place with water temperatures ranging between 2-17^{o}C. Eggs are found throughout these regions and are pelagic. Larvae are pelagic and movement is regulated by water currents. Juveniles are benthic and found on sand or sand/mud bottom features. Concentrations occur between Massachusetts Bay, Cape Cod and the southern edge of Georges Bank during spring. Juveniles are more widely distributed during the fall where their distribution is shifted north to the Great South Channel and in deeper waters along the southern flank of Georges Bank. Adults are also found on sand or sand/mud substrates and are widely distributed from the Strait of Belle Isle to Chesapeake Bay. Adults are abundant around Cape Cod during both spring and fall.

Time-Series Analysis

Adults were abundant within the study area, with catches concentrated to the shallower regions (to 230 m) within Massachusetts Bay, Georges Bank, southwestern Nova Scotia, and southern New England. Adults were frequently captured in spring, 29-44% of trawls (Figure 3.3.45). Juveniles were captured within the same regions as adults, although at slightly shallower depths and less frequently, 8-17% of trawls (Figure 3.3.46). The same general patterns were observed for adults and juveniles during the fall, although adult capture frequency was lower, 20-32% of trawls (Figure 3.3.47). Juvenile capture frequency was slightly higher during the fall compared to spring, 10-18% of trawls (Figure 3.3.48).

Adult and juvenile yellowtail flounder were frequently captured within the Sanctuary during both spring and fall and abundance was highest during fall (Table 3.3.12). Adult mean lengths were similar between spring and fall (31-37 cm SL) and maximum size declined slightly throughout the time-series. Adults were captured at depths between 27-135 m during both seasons, but abundance was highest between 50-85 m during the spring and 30-70 m during the fall. Juveniles were captured at slightly shallower depths during both seasons, 30-95 m during the spring and 25-105 m during the fall. Juveniles were most abundant at depths between 35-65 during the spring and 30-60 m during the fall.

Table 3.3.12. Frequency of occurrence and abundance for all yellowtail flounder captured in NMFS trawl surveys within Stellwagen Bank NMS. Where available, length and depth ranges are displayed for adults and juveniles.

					Adult			Juvenile		
	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Max length (cm)	Depth range (m)	Mean length (cm)	Min length (cm)	Depth range (m)
Spring	75-79	56	44.64	5.52	35.10	56	35-133	19.04	7	33-87
	80-84	22	59.09	6.32	34.85	52	33-92	22.60	18	33-88
	85-89	16	50.00	5.69	37.27	54	30-106	19.56	7	30-76
	90-94	21	71.43	8.10	31.40	51	30-116	21.31	14	30-82
	95-99	17	64.71	5.06	32.33	44	41-123	21.86	17	41-83
	00-05	17	70.59	13.18	33.33	49	27-135	21.40	14	36-91
Fall	75-79	61	39.34	7.33	34.10	50	30-97	20.37	11	30-97
	80-84	22	50.00	13.77	35.67	52	28-66	20.03	13	28-89
	85-89	20	45.00	6.70	33.56	51	43-86	18.42	13	43-86
	90-94	19	63.16	10.21	32.20	42	44-116	19.12	9	44-101
	95-99	18	44.44	14.94	33.98	46	32-90	17.64	6	32-70
	00-04	16	31.25	1.81	34.63	40	45-127	16.67	13	45-52

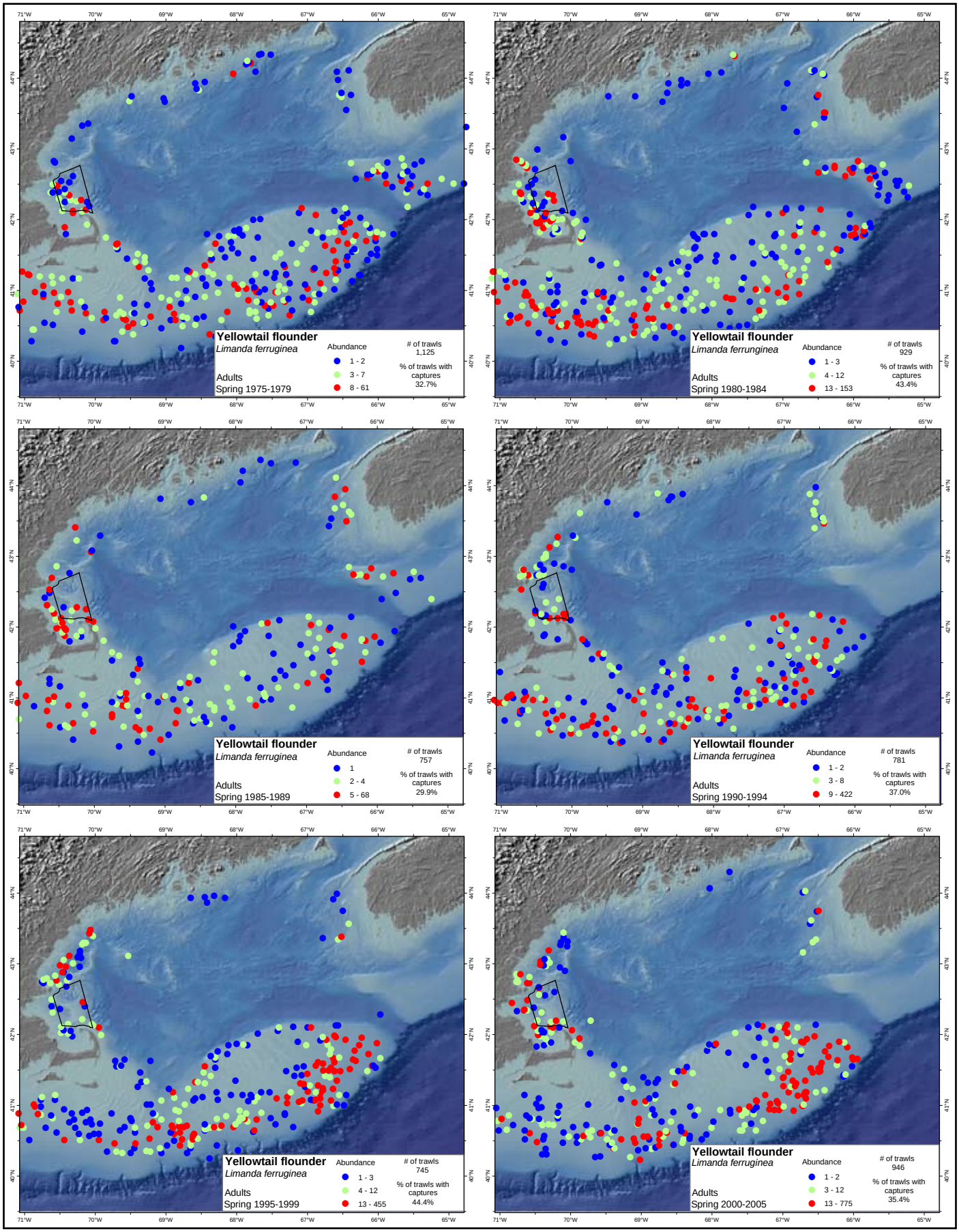

Figure 3.3.45. Abundance and distribution of adult yellowtail flounder (*Limanda ferruginea*) within the Gulf of Maine, Spring 1975-2005.

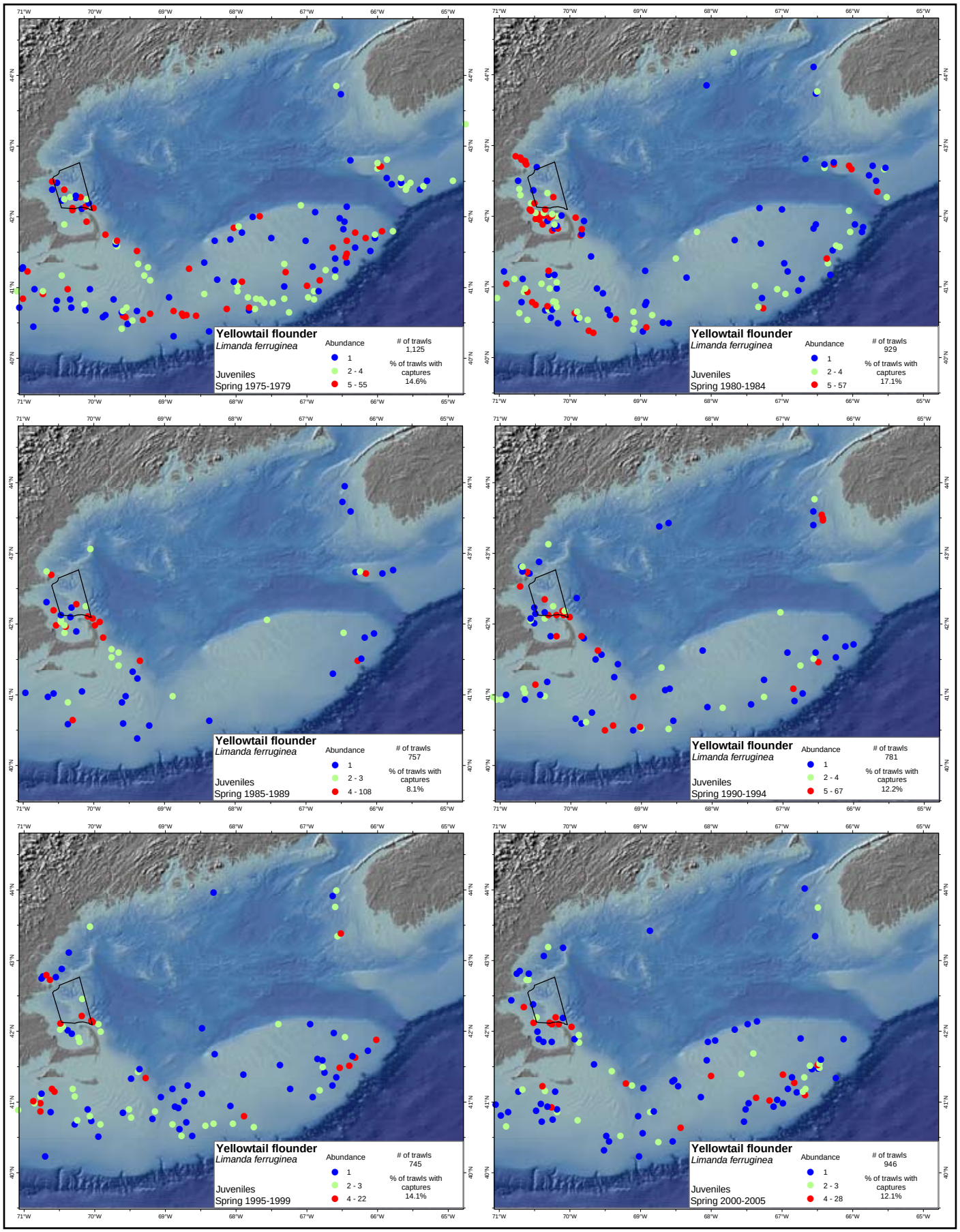

Figure 3.3.46. Abundance and distribution of juvenile yellowtail flounder (*Limanda ferruginea*) within the Gulf of Maine, Spring 1975-2005.

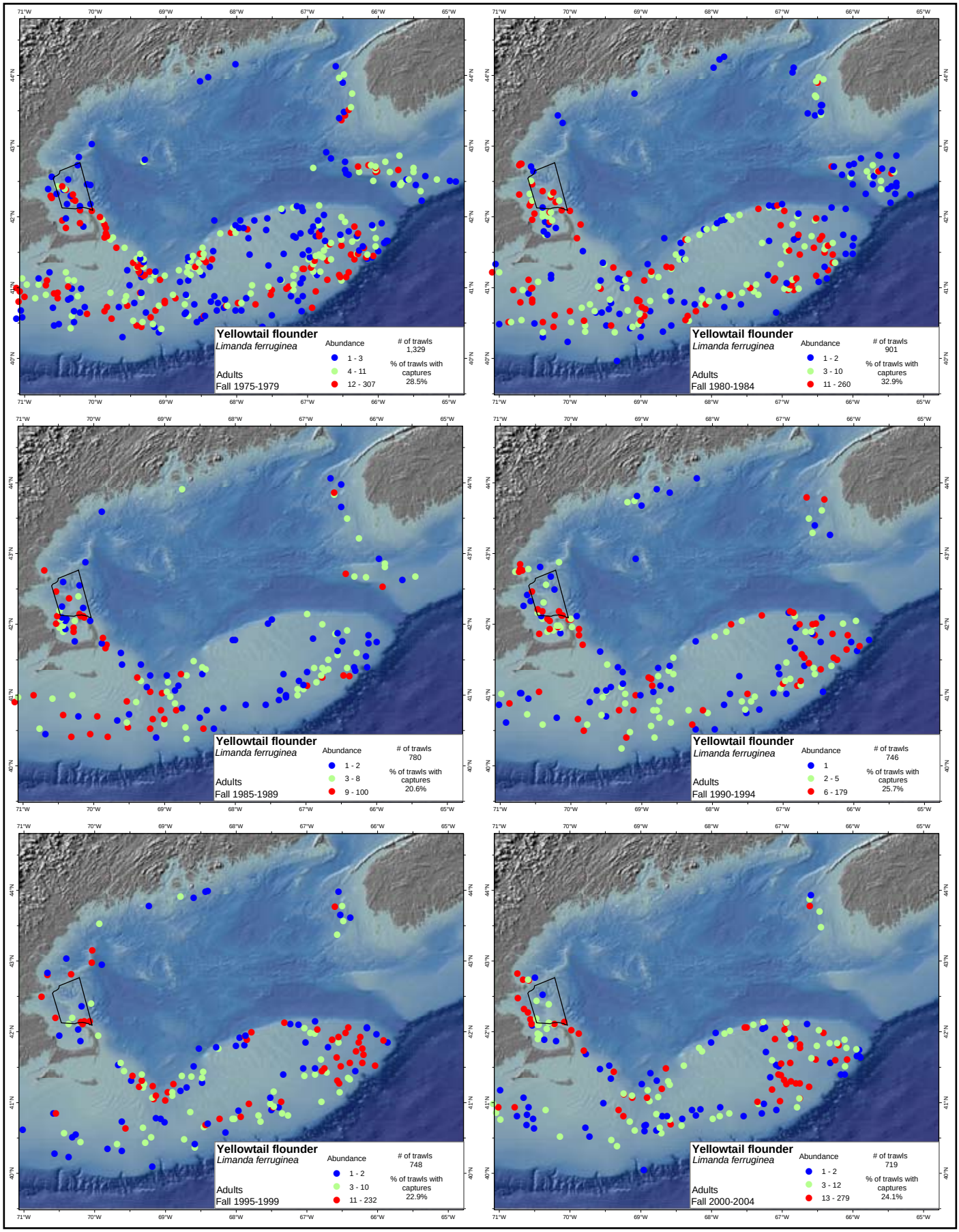

Figure 3.3.47. Abundance and distribution of adult yellowtail flounder (*Limanda ferruginea*) within the Gulf of Maine, Fall 1975-2004.

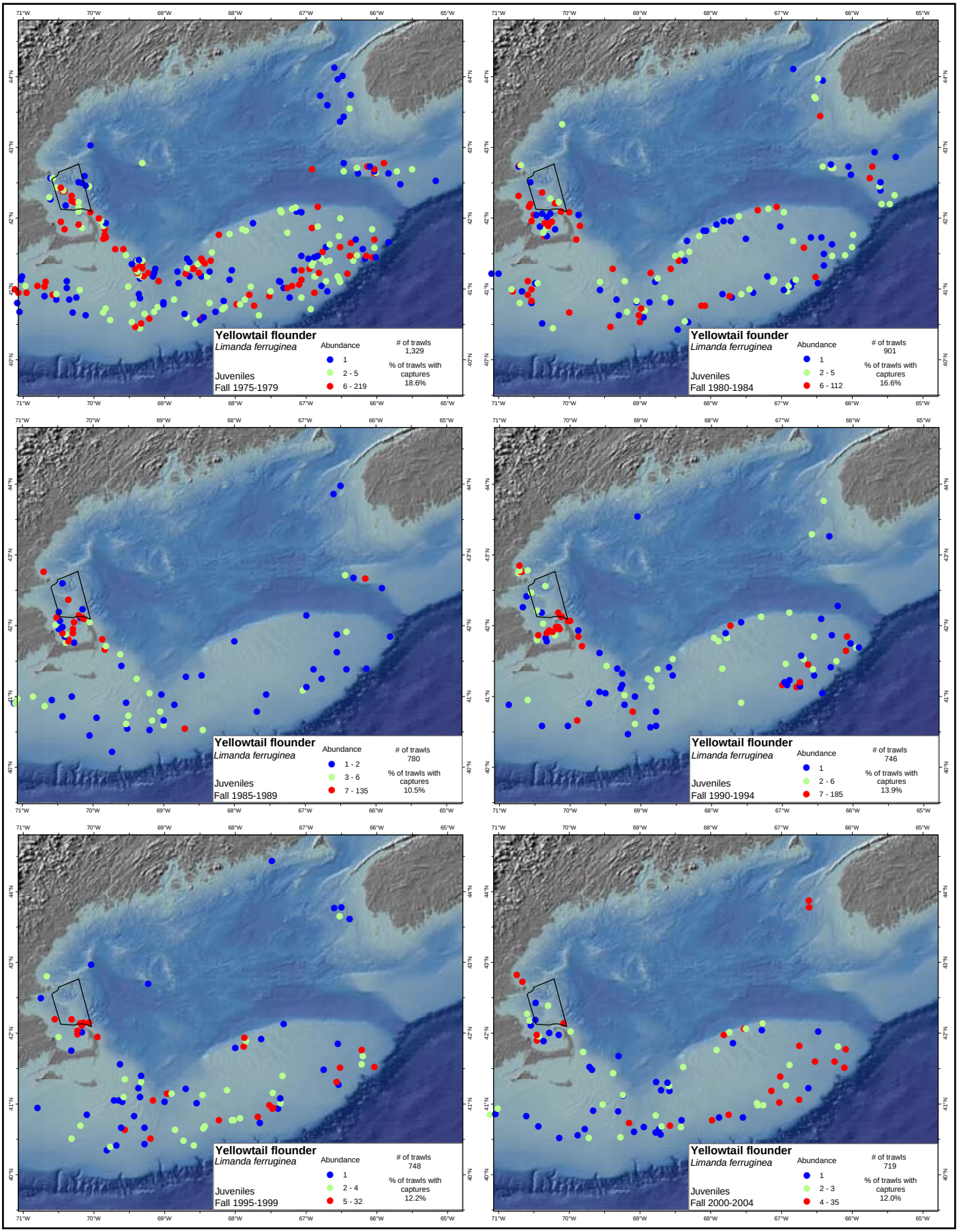

Figure 3.3.48. Abundance and distribution of juvenile yellowtail flounder (*Limanda ferruginea*) within the Gulf of Maine, Fall 1975-2004.

Alligatorfish (*Aspidophoroides monopterygius)*

Life History

Alligatorfish are one of two Atlantic representatives of a diverse group of poachers that are primarily distributed in the North Pacific. Alligatorfish have localized distributions within the Gulf and are frequently found on sandy or muddy habitats within Stellwagen Bank NMS. Little is known about the life history of the alligatorfish. Limited information has been collected regarding egg size and fecundity (Scott and Scott, 1988). Alligatorfish have been collected in trawls from Greenland to Cape Cod, with rare occurrences as far south as New Jersey. Alligatorfish is typically a deep, cold water species and is common in Massachusetts Bay (Bigelow and Schroeder, 1953).

Habitat Characteristics

Historical trawl records indicate that alligatorfish have been taken over pebbly bottom, sand and broken shell, and on mud at depths no shallower than 20-30 m (Bigelow and Schroeder, 1953).

Time-Series Analysis

Approximately 1,224 individual alligatorfish, ranging in size from 4-22 cm total length, were collected during the 30 year time-series. Typically, frequency of occurrence was low per seasonal year-bin (< 5.5%) and abundance was generally low per tow (mean=2.6 individuals/tow). Depth of captures ranged between 15.5-322 m and abundance was comparable during spring and fall. Locations of captures during spring (Figure 3.3.49) and fall (Figure 3.3.50) typically occurred in the same regions: Massachusetts Bay, offshore west of Cape Sable, around the inner rim of Georges Bank, and Browns Bank. A large percentage of the captures of alligatorfish occurred within or in waters close to SBNMS.

Within the Sanctuary, alligatorfish were more frequent and abundant during spring (Table 3.3.13). Captures generally occurred within the deeper portions of the Sanctuary, ranging from 35-138 m.

Table 3.3.13. Frequency of occurrence and abundance for all alligatorfish captured in NMFS trawl surveys within Stellwagen Bank NMS.

	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Depth range (m)
Spring	75-79	56	28.57	1.57	9.71	35-133
	80-84	22	31.82	2.82	10.40	67-101
	85-89	16	18.75	0.56	12.80	46-76
	90-94	21	47.62	1.86	11.17	48-120
	95-99	17	23.53	0.59	8.88	64-102
	00-05	17	17.65	0.18	12.33	94-135
Fall	75-79	61	9.84	0.21	10.80	74-100
	80-84	22	22.73	0.45	10.30	58-101
	85-89	20	15.00	0.20	10.00	64-138
	90-94	19	31.58	0.84	11.83	62-117
	95-99	18	38.89	0.67	11.80	59-95
	00-04	16	6.25	0.06	9.00	55

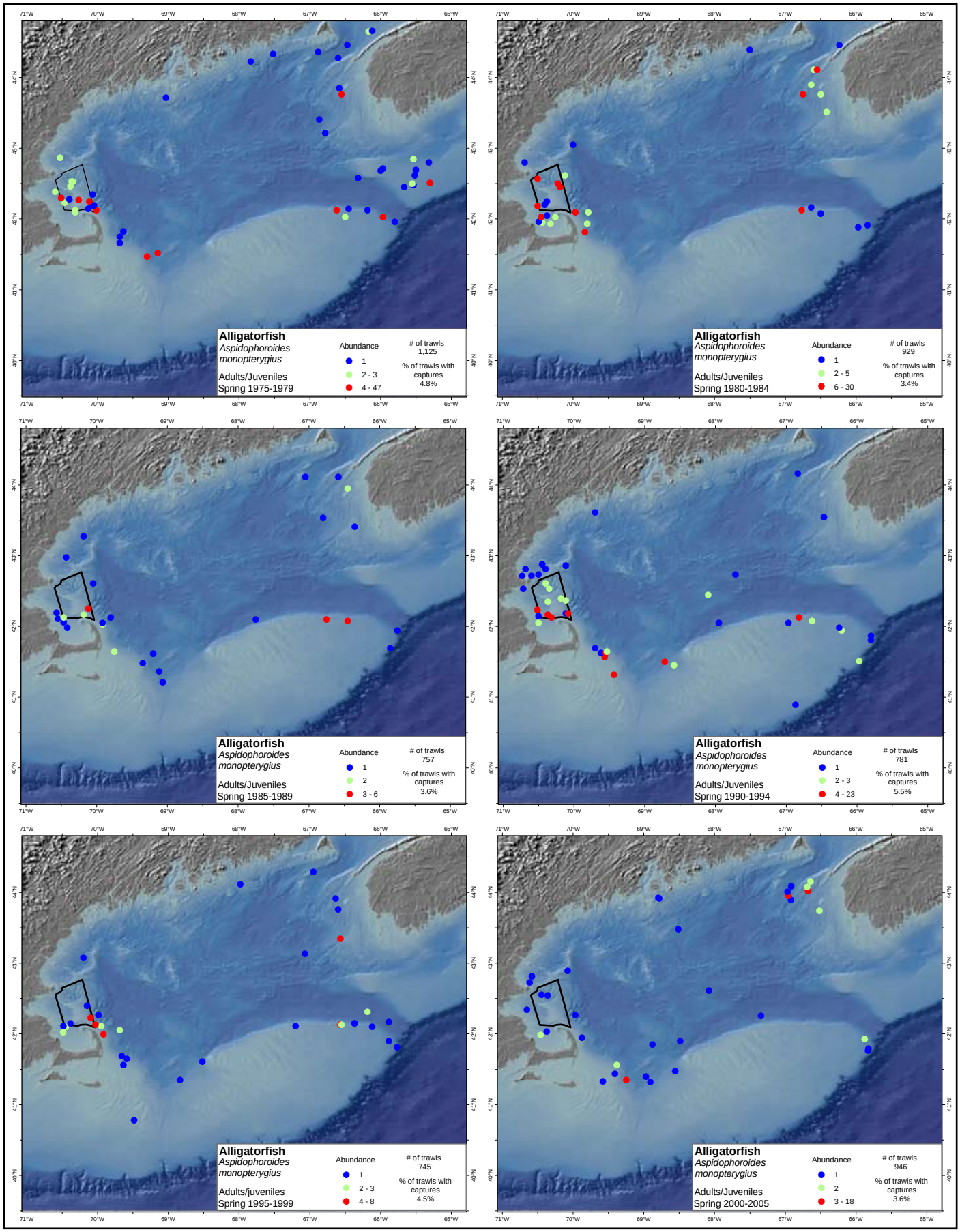

Figure 3.3.49. Abundance and distribution of adult and juvenile alligatorfish (*Aspidophoroides monopterygius*.) within the Gulf of Maine, Spring 1975-2005.

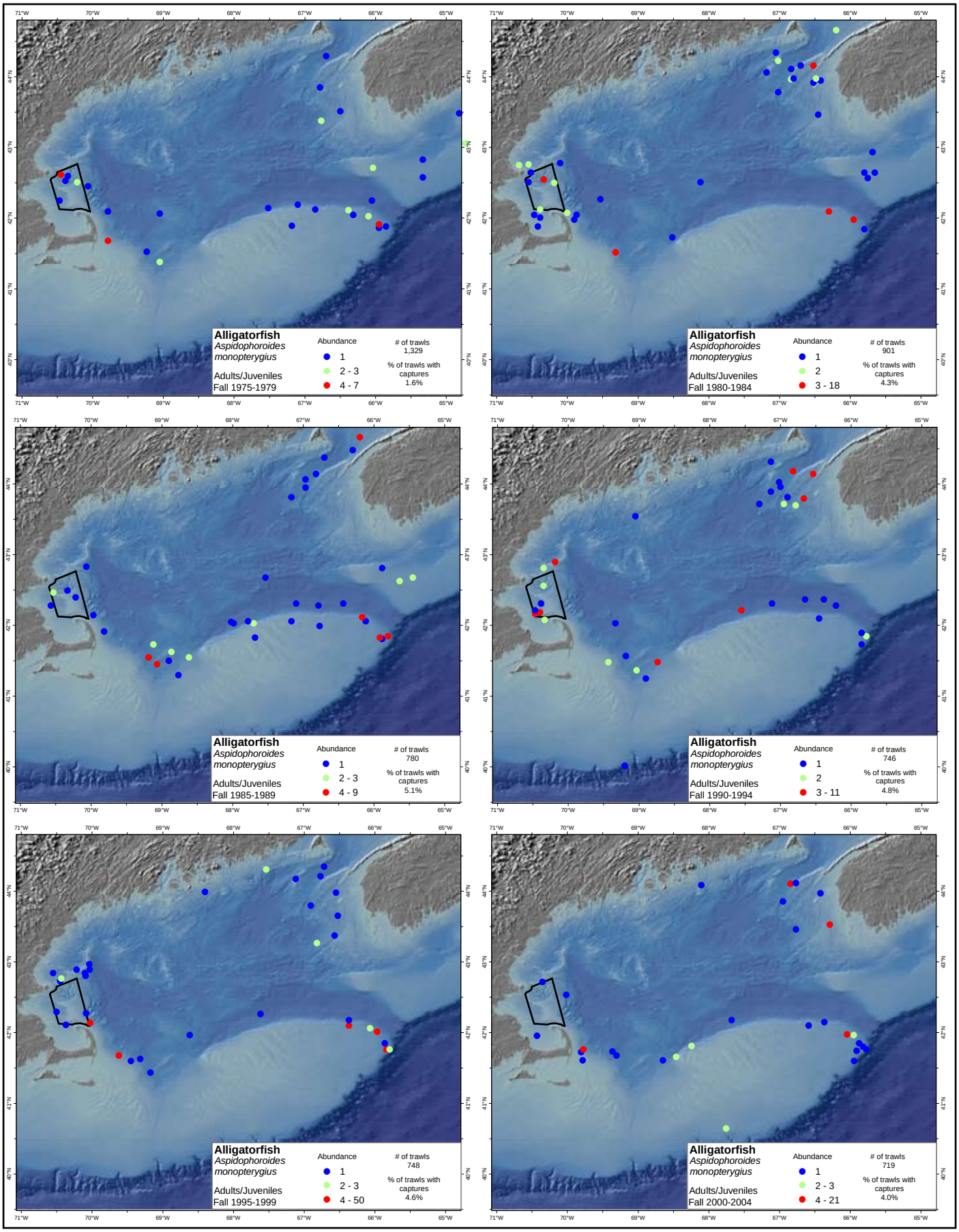

Figure 3.3.50. Abundance and distribution of adult and juvenile alligatorfish (*Aspidophoroides monopterygius*.) within the Gulf of Maine, Fall 1975-2004.

Cusk (*Brosme brosme)*
Cusk are slow growing and attain maturity at late ages and populations are susceptible to exploitation. Biomass indices have exhibited a declining trend since the late 1960s and has reached all-time lows most recently. As a result, cusk have been on the ESA's species of concern list since 2004. The cusk is a year-round resident with localized populations on boulder reefs and bank ledges within the western Gulf and SBNMS. The cusk fishery is not currently managed and little is known about sustainability levels. Annual landings have declined since 1981, and mean length of cusk caught in NEFSC surveys has declined from 62 cm during 1964-1987 to 50 cm during 1988-1998. Prior to 1993, 60 to 80% of the U.S. catch was taken from the Gulf of Maine (O'Brien, 2000).

Life History
Cusk are slow growing, late maturing, sedentary and solitary bottom dwellers. Spawning occurs in spring and early summer. Eggs rise to the surface where hatching and larval development occur. Juveniles settle on the bottom at about 5 cm in length. Adults reach sexual maturity by ages 5 (males) and 7 (females) and attain lengths up to 90 cm and weights up to 9.0 kg Size at 50% sexual maturity has been estimated at 50 cm (O'Brien, 2000). The reproductive biology of the cusk is not widely known for the northwest Atlantic. It is suggested that spawning takes place from May to August, but that most spawning occurred in the last two weeks of June, and usually occurred in depths less than 183 m. In the Gulf of Maine spawning is somewhat earlier, April-July. It was reported that 100,000 eggs were found in a fish 56 cm TL and 3,927,000 eggs for one 90 cm (Oldham, 1972). Cusk eat crustaceans, soft-bodied invertebrates and mollusks.

Habitat Characteristics
Cusk are found throughout the Gulf of Maine, the Scotian Shelf, and waters around Iceland and Norway on hard bottom habitats deeper than 20 m with rocks, ledges or gravel. Found in small shoals on rough, rock, gravel, or pebble bottoms, cusk generally keep far from the shore, near the bottom, mostly between 150 and 450 m in the northeastern Atlantic, and between 18 and 550 m in the northwestern Atlantic. Cusk occur at a temperature range of 0°-10° C and are usually solitary or occur in small groups (Fishbase, 2006). Along the Scotian Shelf cusk are found on hard, rough or rocky bottom, usually at depths of 73-363 m, temperatures of 2-12° C and salinities of 32-34 ppt. The preferred depth, temperature, and salinity ranges are 128-144 m, 6-10° C, and 34 ppt, respectively (Oldham, 1972).

Time-Series Analysis
Adult cusk were more common than juveniles in trawl samples, but overall, capture frequencies were low. Highest capture frequency was observed during spring 1975-1979, where adults were found in 12.4% of trawl samples (Figure 3.3.51). Abundance of cusk/trawl was low with typically one or two fish per sample, rarely exceeding three or more. The frequency of occurrence and overall abundance of adult cusk during spring was lowest between 1995-2005. Adults were found in the deeper portions of the central Gulf and southern edge of Georges Bank (42-360 m) with most occurring between 90-220 m. Juvenile cusk were uncommon in spring trawl samples (Figure 3.3.52). Abundance was generally low, with most samples containing one or two cusk per sample. Juvenile frequency of occurrence was highest (3-4%) between 1975-1984 and declined through the remaining time-series. During spring, juveniles were found primarily in the central Gulf.

Similar patterns of adult and juvenile abundance and distribution were observed during fall. Adult frequency of occurrence was highest during the first ten years of the time-series and declined through the successive years (Figure 3.3.53). Juveniles were less abundant that adults during the time-series and frequency of occurrence maintained a stable ratio of 2-3% per year-bin (Figure 3.3.54). Both adults and juveniles were primarily found in the central Gulf and southern edge of Georges Bank during fall.

Adult and juvenile cusk were uncommon in trawl samples within the Sanctuary (Table 3.3.14). Adults were more abundant than juveniles throughout the 30-year time period, however, abundance overall was low. Mean length of individuals declined slightly during spring and fall through the time-series. Cusk were captured at depths between 30-144 m within the Sanctuary.

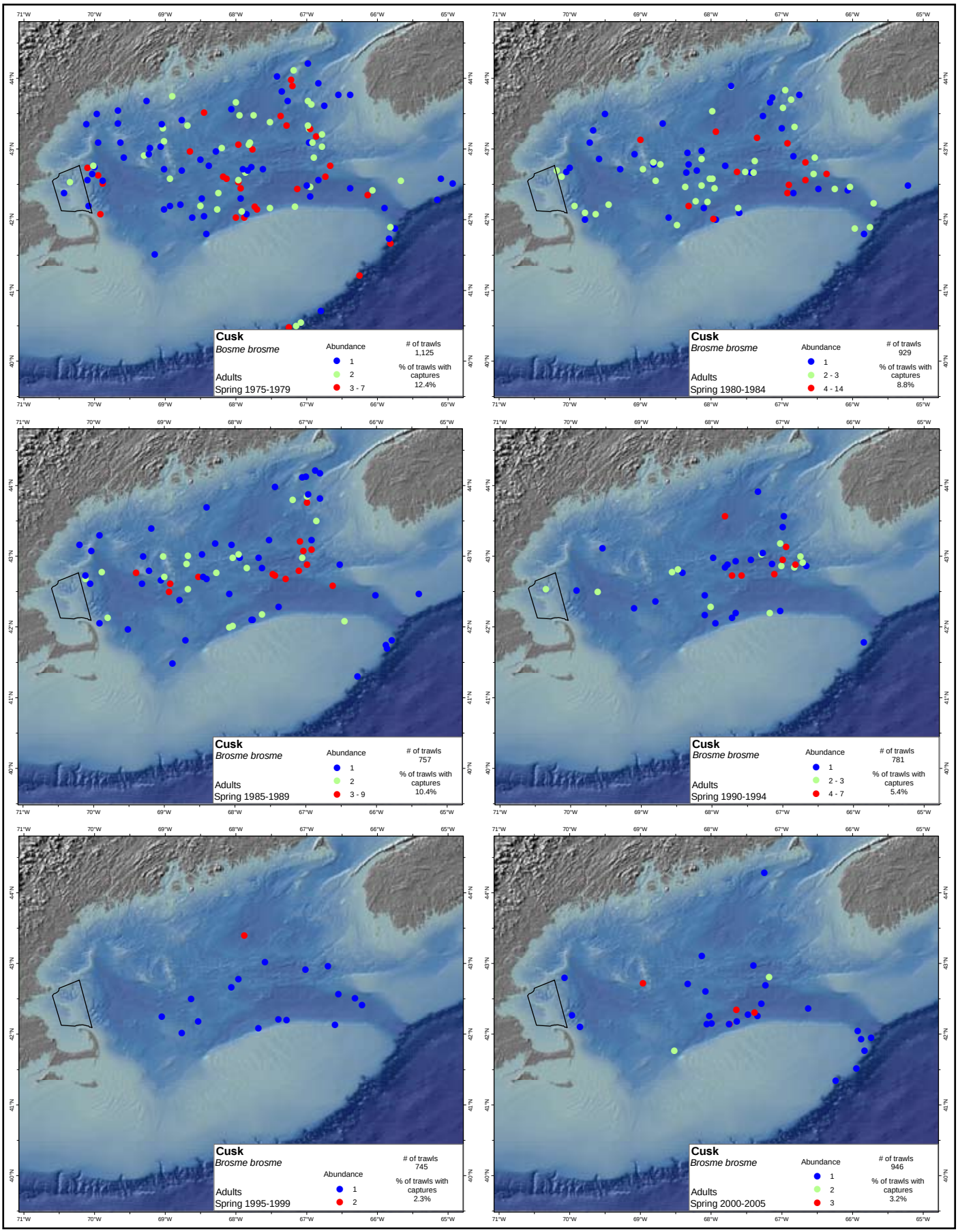

Figure 3.3.51. Abundance and distribution of adult cusk (*Brosme brosme*) within the Gulf of Maine, Spring 1975-2005.

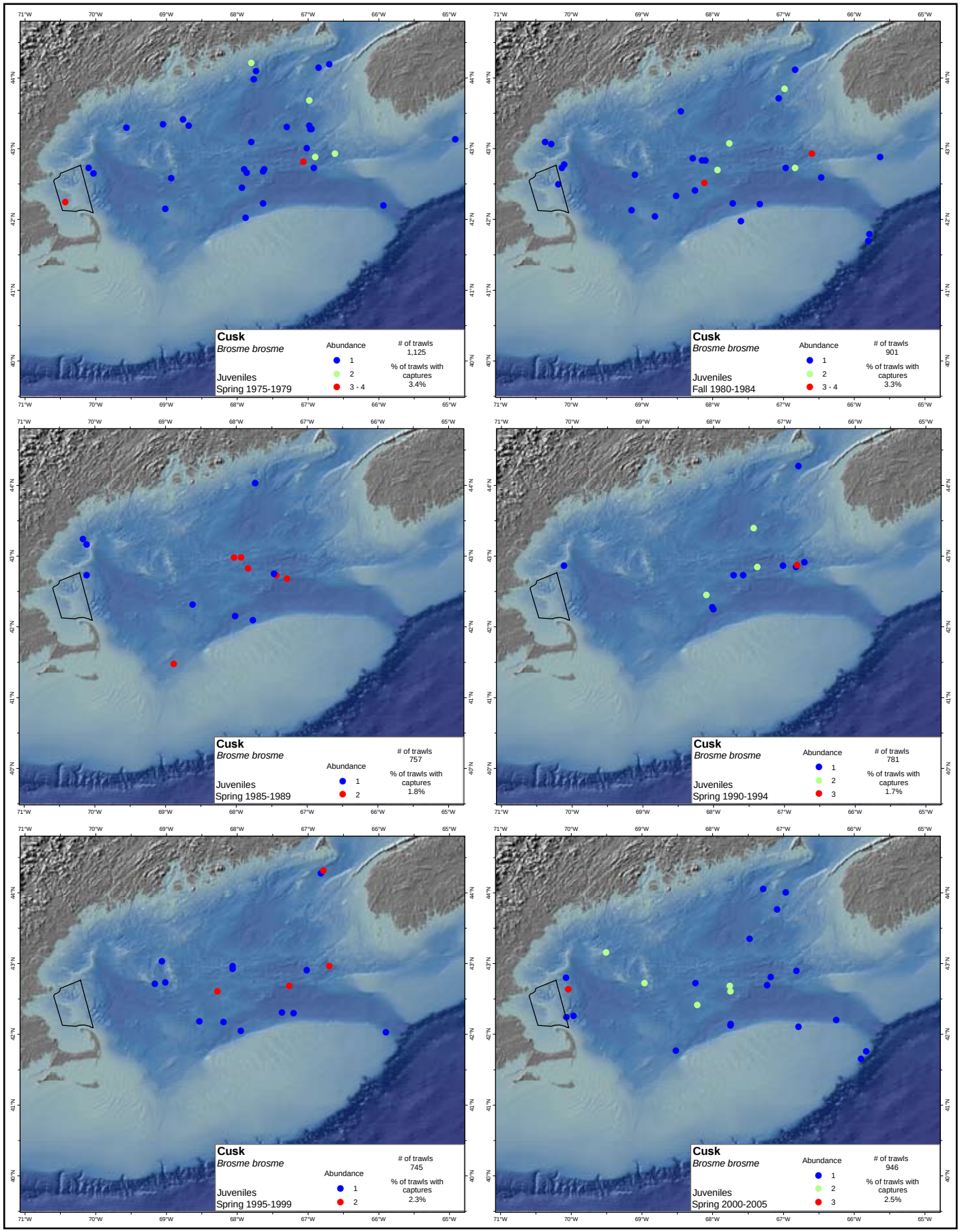

Figure 3.3.52. Abundance and distribution of juvenile cusk (*Brosme brosme*) within the Gulf of Maine, Spring 1975-2005.

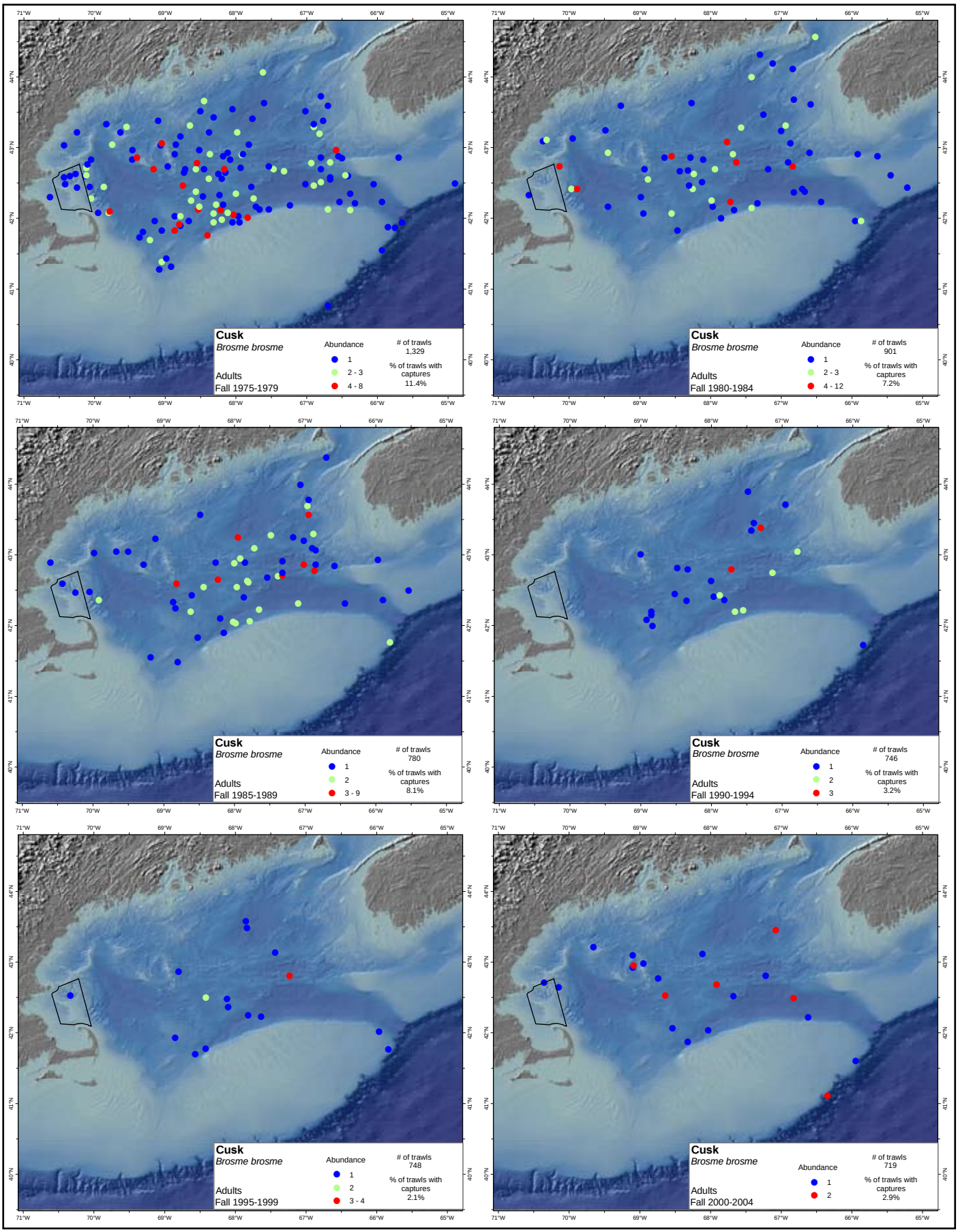

Figure 3.3.53. Abundance and distribution of adult cusk (*Brosme brosme*) within the Gulf of Maine, Fall 1975-2004.

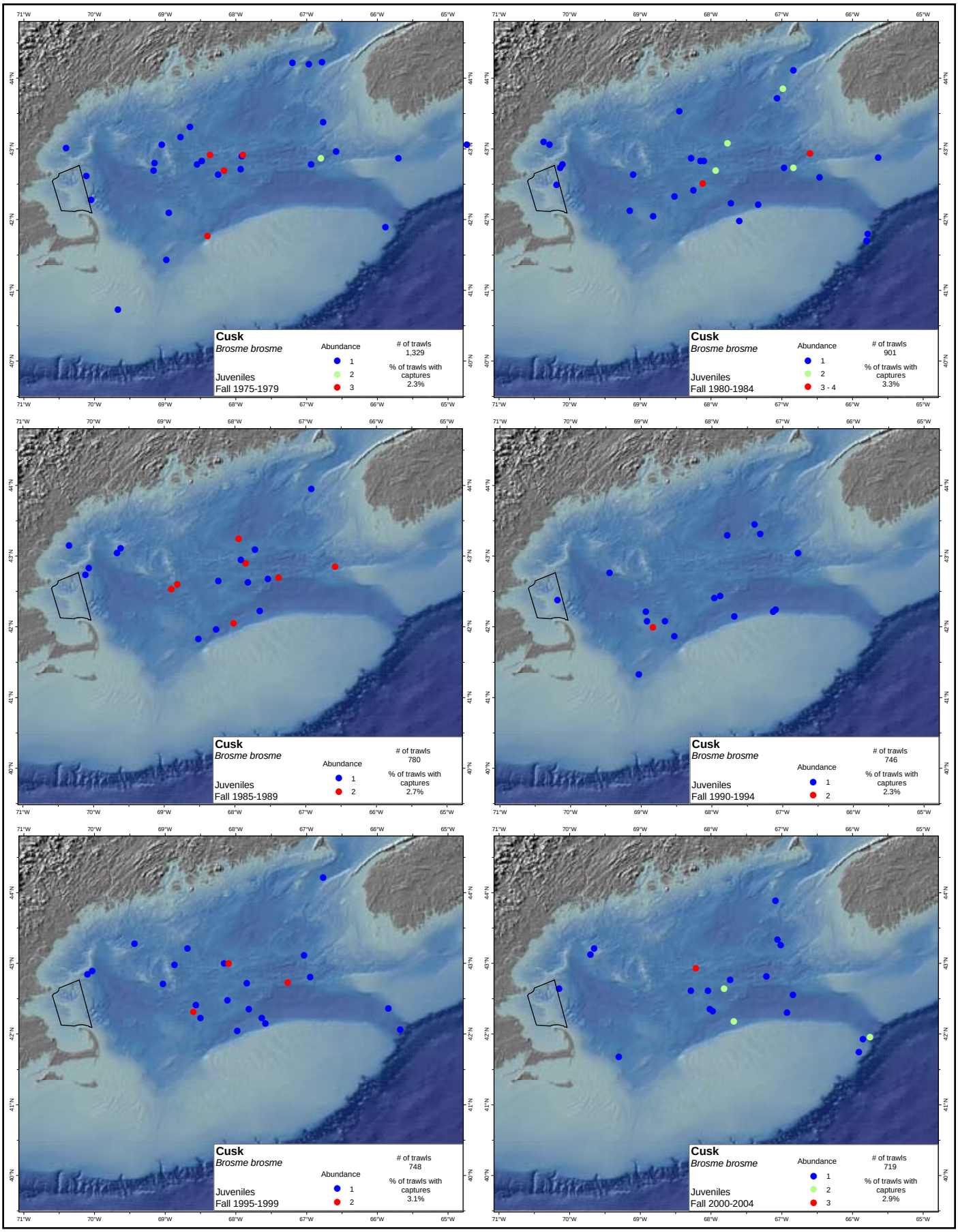

Figure 3.3.54. Abundance and distribution of juvenile cusk (*Brosme brosme*) within the Gulf of Maine, Fall 1975-2004.

Table 3.3.14. Frequency of occurrence and abundance for all cusk captured in NMFS trawl surveys within Stellwagen Bank NMS.

	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Depth range (m)
Spring	75-79	56	10.71	0.21	56.83	30-112
	80-84	22	9.09	0.32	62.86	101-105
	85-89	16	12.50	0.13	75.00	76-106
	90-94	21	4.76	0.10	67.00	120
	95-99	17	NC	-	-	-
	00-05	17	5.88	0.06	47.00	144
Fall	75-79	61	18.03	0.25	61.50	71-105
	80-84	22	9.09	0.09	51.50	66-78
	85-89	20	10.00	0.10	65.00	72-86
	90-94	19	5.26	0.05	32.00	77
	95-99	18	5.56	0.06	58.00	95
	00-04	16	12.50	0.19	55.33	55-103

Daubed Shanny (*Leptoclinus maculatus)*
The daubed shanny is a small member of the prickleback family and typically occur in inshore waters during the spring and deeper waters in the fall. Daubed shanny occur in very localized distributions among rocky areas nearshore and among mud/pebble substrates in SBNMS, in particular. They are assumed to have low movement rates are thus sensitive to environmental change. Due to its size, there is no commercial fishery for this species.

Life History
The daubed shanny is a resident in the Gulf of Maine (Auster, 2002) and was classified as a rare species based on low frequency of occurrence in NMFS trawl samples between 1975-2005, however populations are very localized. Some life history information is available for shanny in the Pacific (Eschmeyer and Harold,1983), which state that daubed shanny inhabit sandy, muddy, or pebble substrates in waters less than 170 m. They feed on polychaetes and crustaceans.

Time-Series Analysis
Daubed shanny were infrequently captured in NMFS trawl samples throughout the study area. They were most abundant during spring and frequency of occurrence was higher during spring compared to fall (Figure 3.3.55). During spring, daubed shanny were captured at locations closer to shore than in the fall (Figure 3.3.56) and at slightly shallower depths (14-197 m in the spring, 31-275 during fall). Catch was primarily located between Cape Cod Bay and Penobscot Bay during spring. Fall captures were located primarily in the central Gulf.

Daubed shanny were more commonly caught in Massachusetts Bay and within the Sanctuary compared to the rest of the study area. They were more common in spring than in fall, similar to the broad-scale pattern previously mentioned. Shanny were most abundant during spring 1980-84 and 1995-99 which suggest that they may be locally abundant based on smaller scale habitat requirements (Table 3.3.15). Mean length of daubed shanny ranged between 8-16 cm and captures were taken at depths between 63-133 m. Most of the abundance was captured at depths between 60-85 m.

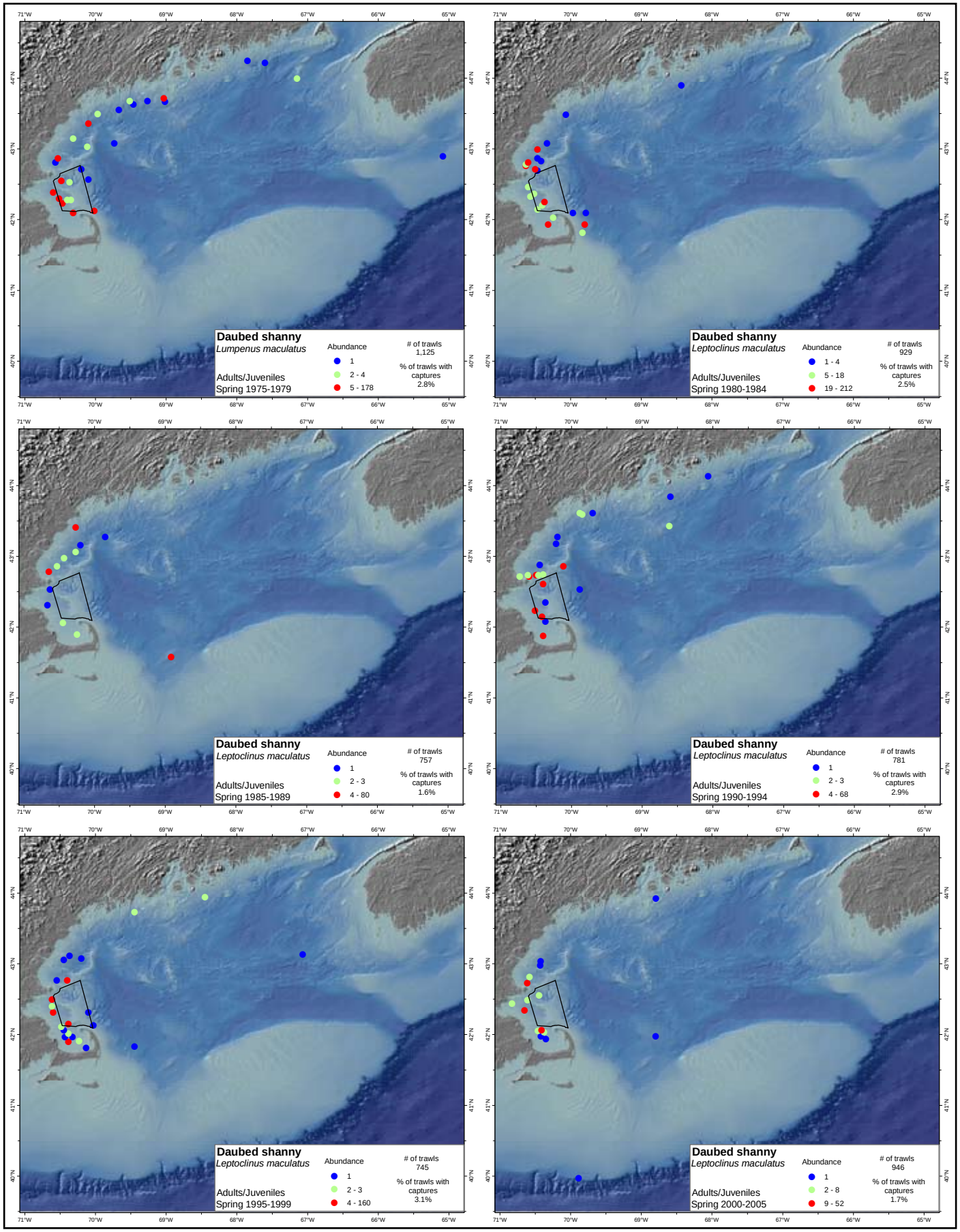

Figure 3.3.55. Abundance and distribution of adult and juvenile daubed shanny (*Leptoclinus maculatus*) within the Gulf of Maine, Spring 1975-2005.

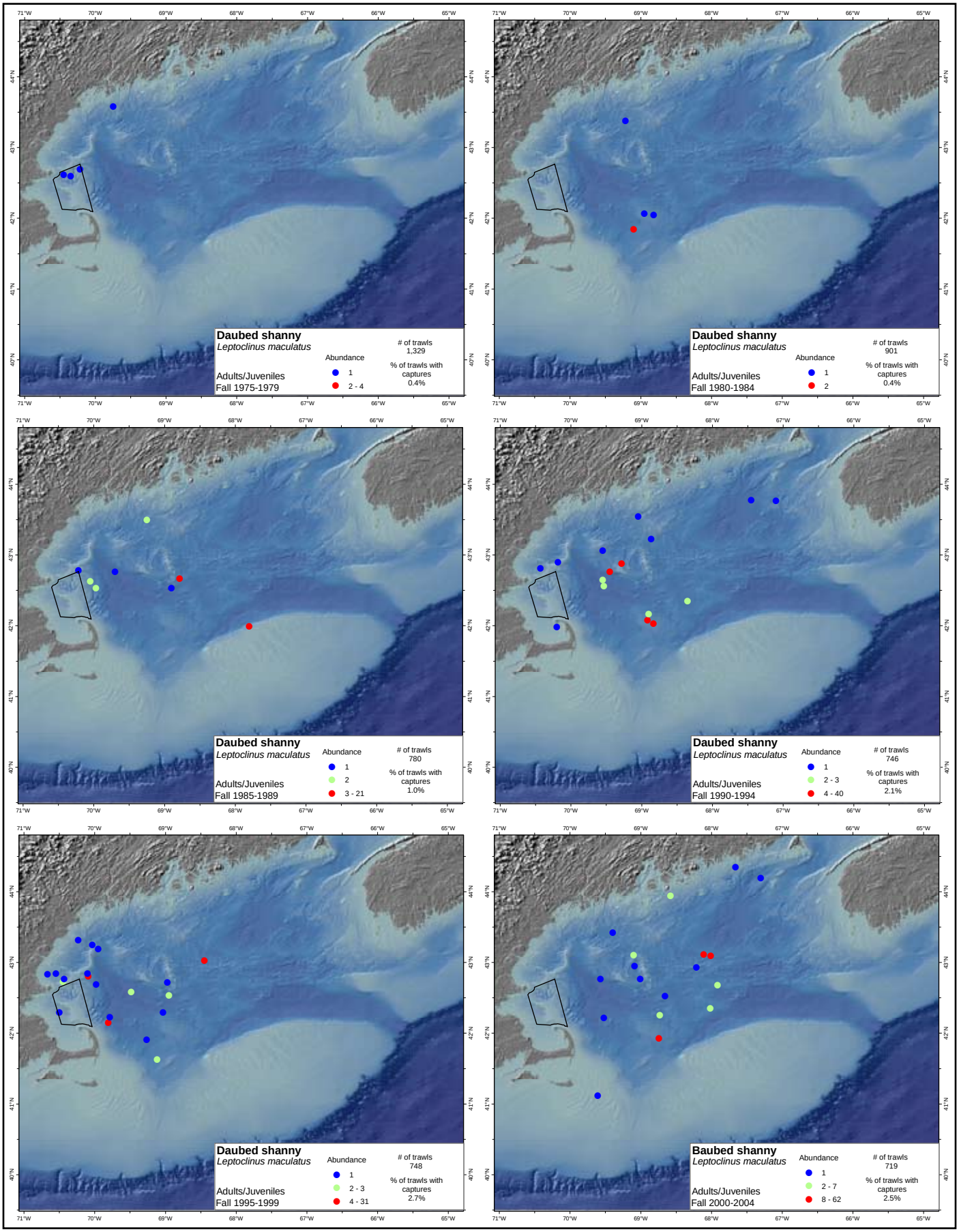

Figure 3.3.56. Abundance and distribution of adult and juvenile daubed shanny (*Leptoclinus maculatus*) within the Gulf of Maine, Fall 1975-2004.

Table 3.3.15. Frequency of occurrence and abundance for all daubed shanny captured in NMFS trawl surveys within Stellwagen Bank NMS.

	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Depth range (m)
Spring	75-79	56	19.64	6.04	15.98	63-133
	80-84	22	27.27	11.73	12.15	97-92
	85-89	16	NC	-	-	-
	90-94	21	28.57	1.95	11.32	65-93
	95-99	17	35.29	11.24	11.54	64-115
	00-05	17	11.76	0.65	10.50	80-116
Fall	75-79	61	4.92	0.05	9.33	85-100
	80-84	22	NC	-	-	-
	85-89	20	5.00	0.05	8.00	63
	90-94	19	5.26	0.05	10.00	111
	95-99	18	16.67	0.28	8.50	82-90
	00-04	16	NC	-	-	-

Northern sandlance (*Ammodytes dubius)*
Sand lance are widespread along the northeast coast of the U.S. and are abundant on muddy or loosely consolidated sand substrates within the Gulf and SBNMS. They are abundant and are an important prey species for many higher level predators, including marine mammals. Sand lance occur in estuarine, open coastal, and offshore habitats. The northern sand lance has been included as a species with strong ecological importance within the Gulf of Maine and SBNMS in particular. The information that follows is a summary of life history and habitat requirements for this species (Auster and Stewart, 1986).

Life History
The northern sand lance is one of among four species of sand lance that occur on the eastern coast of the U.S. Despite morphological differences between the species they basically share similar life history characteristics. Sand lance mature during their first or second year and males reach maturity several months before females. Spawning occurs principally from November to March. Larval fish survey data indicate that spawning principally occurs inshore although evidence exists of some offshore spawning activity. Sand lance lay demersal eggs that are deposited on or in sand substrates or on gravel surfaces. Sand lance larvae are distributed over a wide area of the shelf in winter. Larvae are approximately 3 to 4 mm in length at hatching. After a planktonic stage of 2 to 3 months during which they grow to about 35 mm, they become semi-demersal. Larvae are most abundant at the mouths of major estuaries, but are common to the edge of the continental shelf. Major concentrations of larvae have consistently occurred in the Georges Bank and the Nantucket Shoals to Long Island, New York. Sand lance larvae feed diurnally. Their diet consists of phytoplankton, invertebrate eggs, and copepod nauplii. As the fish increase in size, phytoplankton such as peridinians decrease in importance and copepod nauplii increase. When larvae become about 21 mm long, their diet consists mostly of adult copepods.

Juvenile and adult sand lance have generally been found in schools during the day. School size can range from 100 to tens of thousands of fish. Copepods are the major prey of juvenile and adult sand lance. Sand lance are a major link between zooplankton production and fish of commercial importance. They have been found in the stomachs of a wide variety of species, including Atlantic cod, haddock, silver hake, white hake, yellowtail flounder, and longhorn sculpin. They are also important prey of several marine mammals. Population fluctuations and distribution of these predators are frequently linked to sand lance abundance.

Habitat Characteristics

Sand lance are generally found over sandy substrates and individual fish have been observed to burrow into the sand and remain either partly or totally buried. Sand lance have been collected at temperatures ranging from 2-11°C, but are most abundant between 3-6°C. Juvenile and adult sand lance occur in salinities ranging from 26 to 36 ppt. Sand lance occur throughout the water column over sandy substrates into which they burrow.

Time-Series Analysis

Information regarding sand lance sexual maturity was not available, thus seasonal maps include all individuals captured in NMFS trawls. Northern sand lance were abundant within the study area, but distribution was limited to sandy habitats at depths less than 200 m. The majority of sand lance were captured at depths between 10-95 m within Massachusetts Bay, on Georges Bank, and southern New England.

Frequency of occurrence and abundance of sand lance were considerably greater in the spring (Figure 3.3.57) than fall (Figure 3.3.58). Within both seasons, frequency of occurrence was highest during the early part of the time-series (1975-1989) and was low during recent years.

Sand lance were exceptionally abundant during spring 1975-1989 within the Sanctuary (Table 3.3.16). Abundance during the fall was also high during 1975-1984. Frequency of occurrence was significantly reduced in more recent years during both spring and fall. Mean length of individual sand lance ranged between 15-23 cm at depths ranging from 24-130 m. The majority of sand lance were captured at depths between 20-80 m.

Table 3.3.16. Frequency of occurrence and abundance for all northern sand-lance captured in NMFS trawl surveys within Stellwagen Bank NMS.

	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Depth range (m)
Spring	75-79	56	23.21	390.43	18.76	35-130
	80-84	22	31.82	1371.45	16.42	33-92
	85-89	16	31.25	495.19	16.54	30-97
	90-94	21	14.29	29.71	18.41	24-82
	95-99	17	5.88	0.71	23.50	41
	00-05	17	5.88	0.12	17.00	77
Fall	75-79	61	11.48	214.36	15.67	30-97
	80-84	22	22.73	241.32	16.11	28-58
	85-89	20	5.00	0.05	15.00	53
	90-94	19	NC	-	-	-
	95-99	18	11.11	2.22	17.33	32-82
	00-04	16	NC	-	-	-

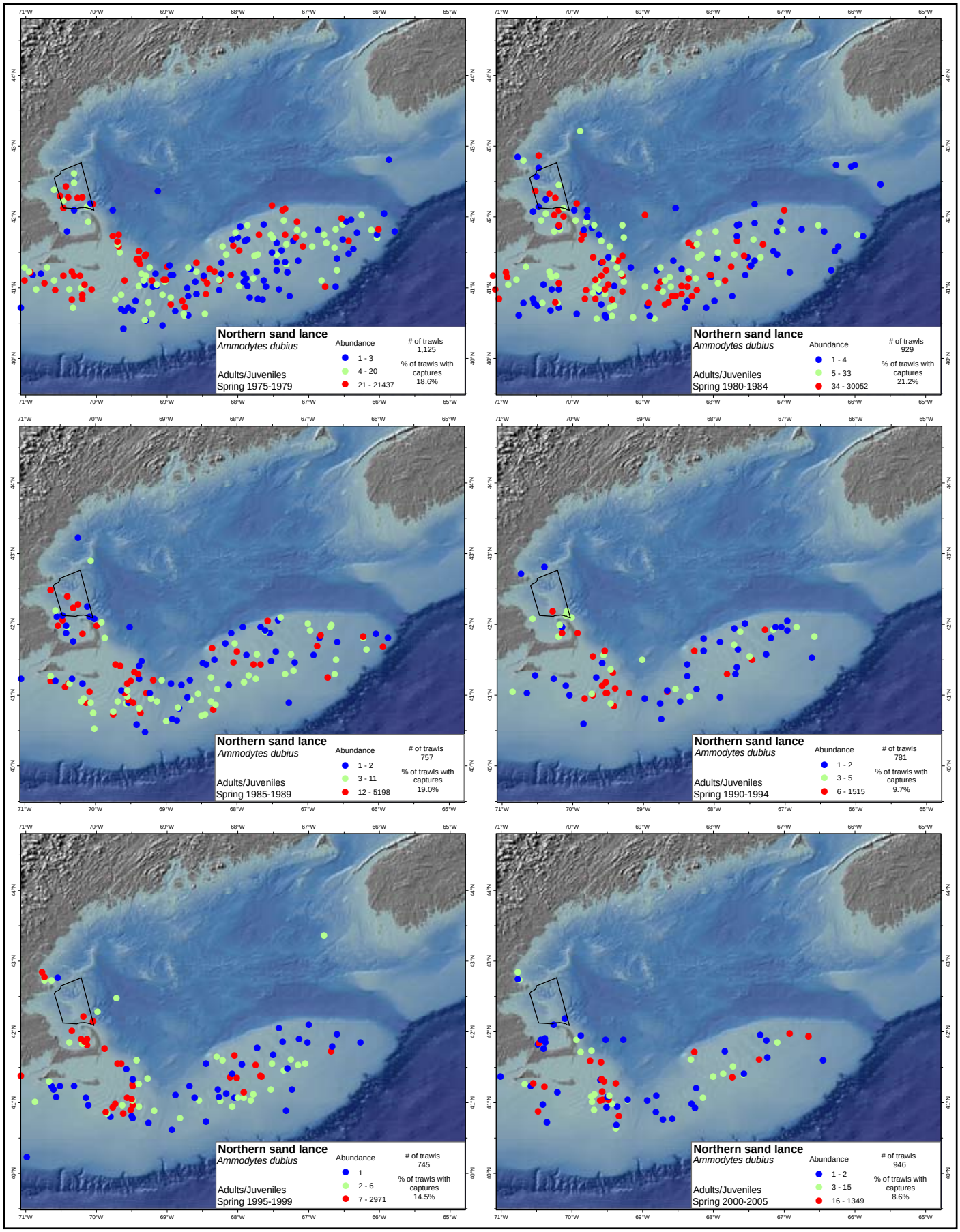

Figure 3.3.57. Abundance and distribution of Northern sand lance (*Ammodytes dubius*) within the Gulf of Maine, Spring 1975-2005.

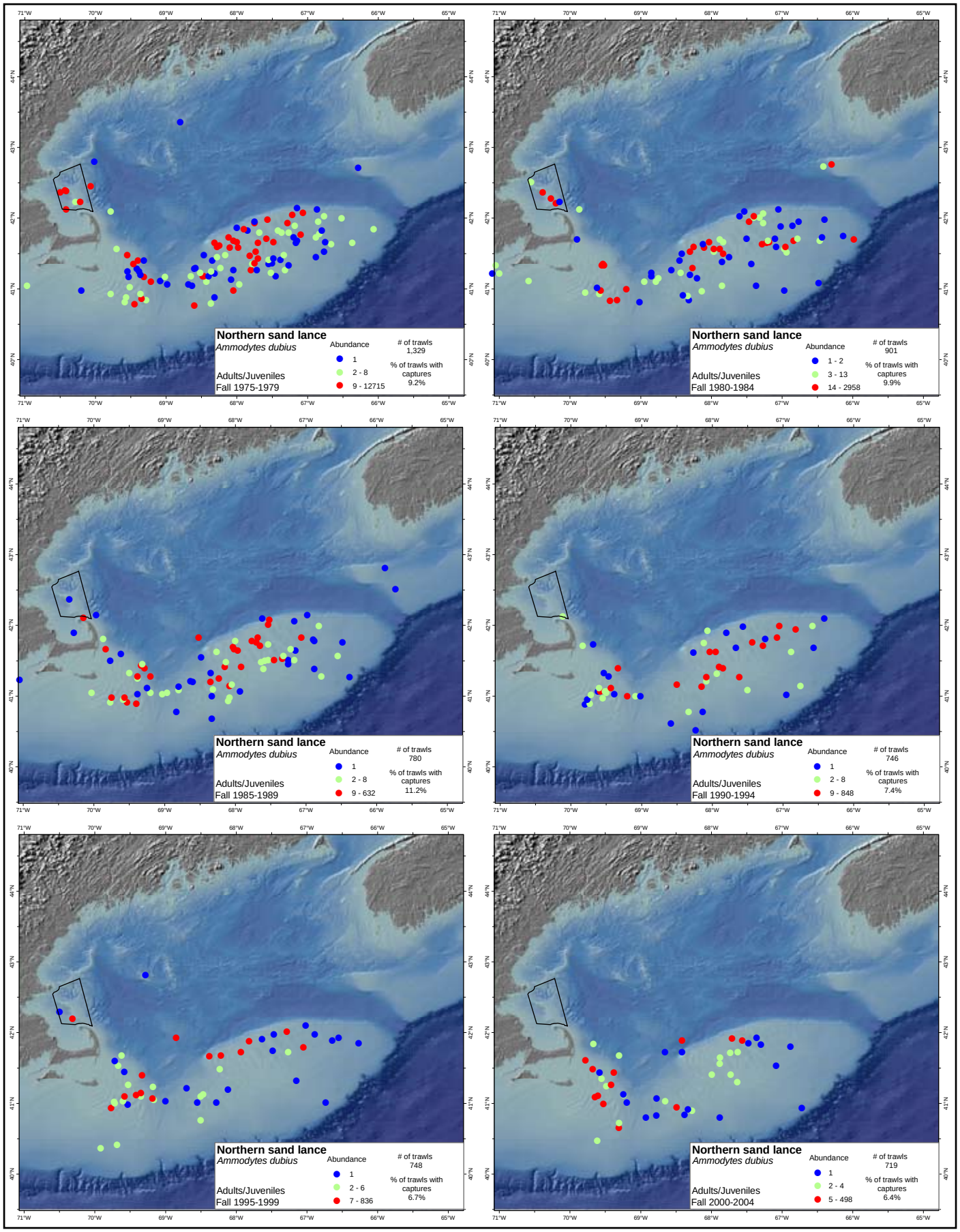

Figure 3.3.58. Abundance and distribution of Northern sand lance (*Ammodytes dubius*) within the Gulf of Maine, Fall 1975-2004.

Snakeblenny (*Lumpenus lumpretaeformis)*
Snakeblenny are found on muddy substrates within the Gulf and SBNMS. In particular, snakeblenny are found in burrows among mud substrate in Stellwagen Basin (Auster *et al*., 1998). Presumably, snakeblenny have low movement rates and are sensitive to localized environmental changes. Snakeblenny distribution in the northwest Atlantic occurs from Labrador and Newfoundland to Massachusetts Bay (Wheeler, 1992), generally found within 80°- 41°N, 71°W - 55°E. Snakeblenny are considered rare within the Gulf of Maine (Auster, 2002).

Life History
Little is known of the habits of the snake blenny on either side of the Atlantic and most information comes from the eastern Atlantic. Snakeblenny live in Y-shaped tubes in the mud in 50-200 m depth (Muus and Nielsen, 1999). They feed on small crustaceans, mollusks, brittle stars and worms (Wheeler, 1992). Snakeblenny matures at three years at about 20 cm length. Spawning takes place from December to January. Drifting larvae have been taken in tow nets from February to March in the Baltic, and from March to May in the Gulf of Maine. Historical records from the Gulf of Maine indicate sporadic catches off Nova Scotia, Maine, Stellwagen Bank, and Massachusetts Bay at 76-132 m (Bigelow and Schroeder, 1953).

Habitat Characteristics
Snakeblenny are probably found on sand or mud substrates at depths less than 200 m (Bigelow and Schroeder, 1953).

Time-Series Analysis
Snakeblenny capture frequency was low in spring (1.7-3.7% of all trawls) and rare in fall (0.4-0.7% of all trawls). Captures occurred in Massachusetts and Cape Cod Bays and along the western edge of the Gulf at depths between 20-330 m during spring (Figure 3.3.59). The majority of snakeblenny captures occurred between 40-150 m. A few captures were taken in the central Gulf. Snakeblenny captures were sporadic in fall (Figure 3.3.60) and consisted of one individual per trawl when captured. Depth of captures ranged from 40-330 m and the majority were captured between 60-200 m.

Snakeblenny capture frequency within the Sanctuary was variable during the spring, usually between 4-15%. Capture frequency was highest during spring 1990-94 and 2000-05 (Table 3.3.17) and abundance was highest during 1980-84. Only two captures within the Sanctuary were recorded during fall. Mean length of snakeblenny captured within the Sanctuary ranged between 15-38 cm in the spring and 34-40 cm in the fall. Depth of capture ranged from 24-135 m during spring, but most were captured between 60-90 m. During fall, catches occurred between 83-90 m.

Table 3.3.17. Frequency of occurrence and abundance for all snakeblenny captured in NMFS trawl surveys within Stellwagen Bank NMS.

	Year	# of trawls	Capture frequency (%)	Mean abundance/ trawl	Mean length (cm)	Depth range (m)
Spring	75-79	56	3.57	0.29	38.00	63-69
	80-84	22	13.64	2.82	37.86	67-87
	85-89	16	12.50	1.25	31.27	60-88
	90-94	21	33.33	1.71	27.64	24-93
	95-99	17	11.76	0.24	23.25	64-80
	00-05	17	41.18	1.94	15.27	73-135
Fall	75-79	61	NC	-	-	-
	80-84	22	4.55	0.05	34.00	83
	85-89	20	NC	-	-	-
	90-94	19	NC	-	-	-
	95-99	18	5.56	0.06	40.00	90
	00-04	16	NC	-	-	-

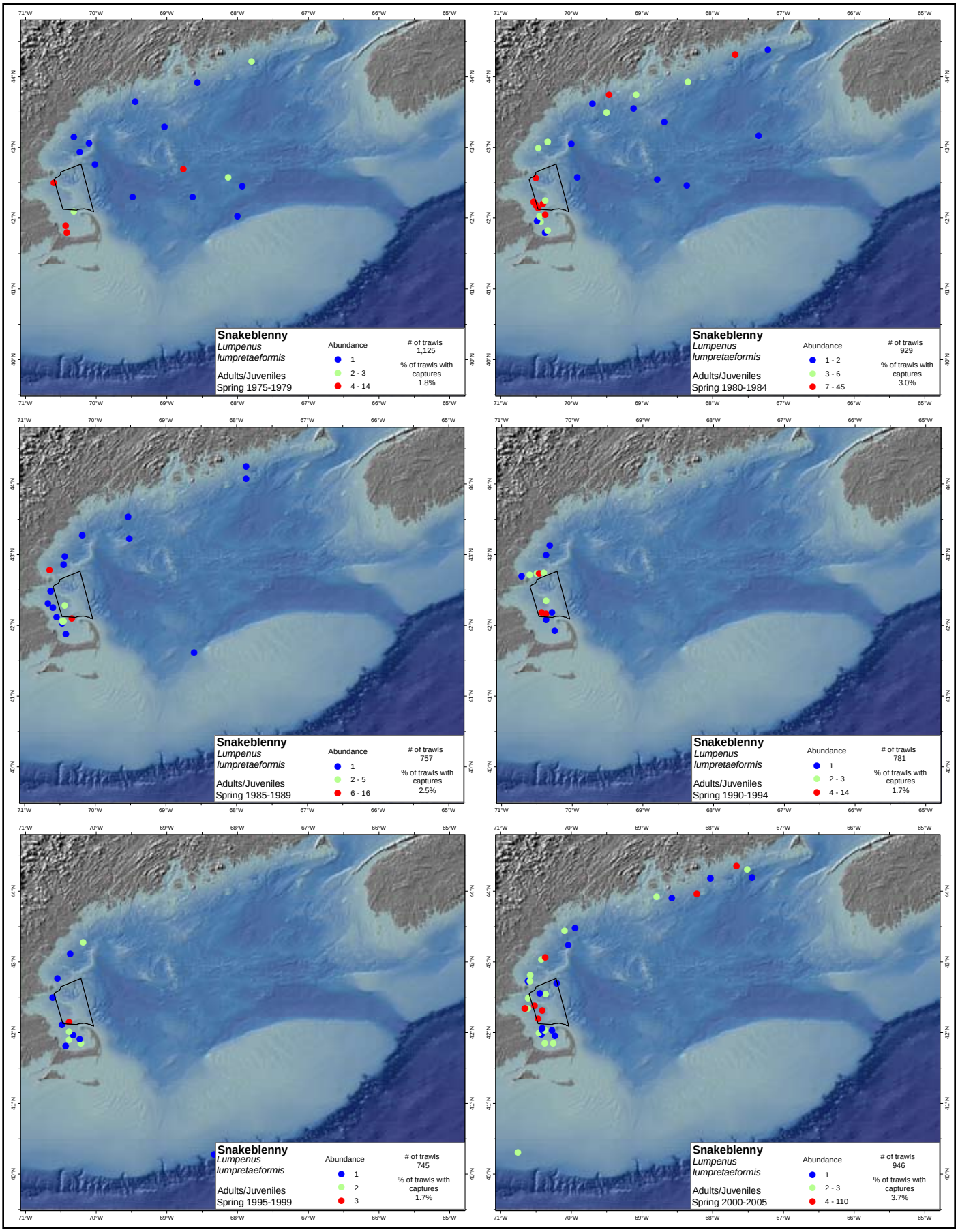

Figure 3.3.59. Abundance and distribution of snakeblenny (*Lumpenus lumpretaeformis*) within the Gulf of Maine, Spring 1975-2005.

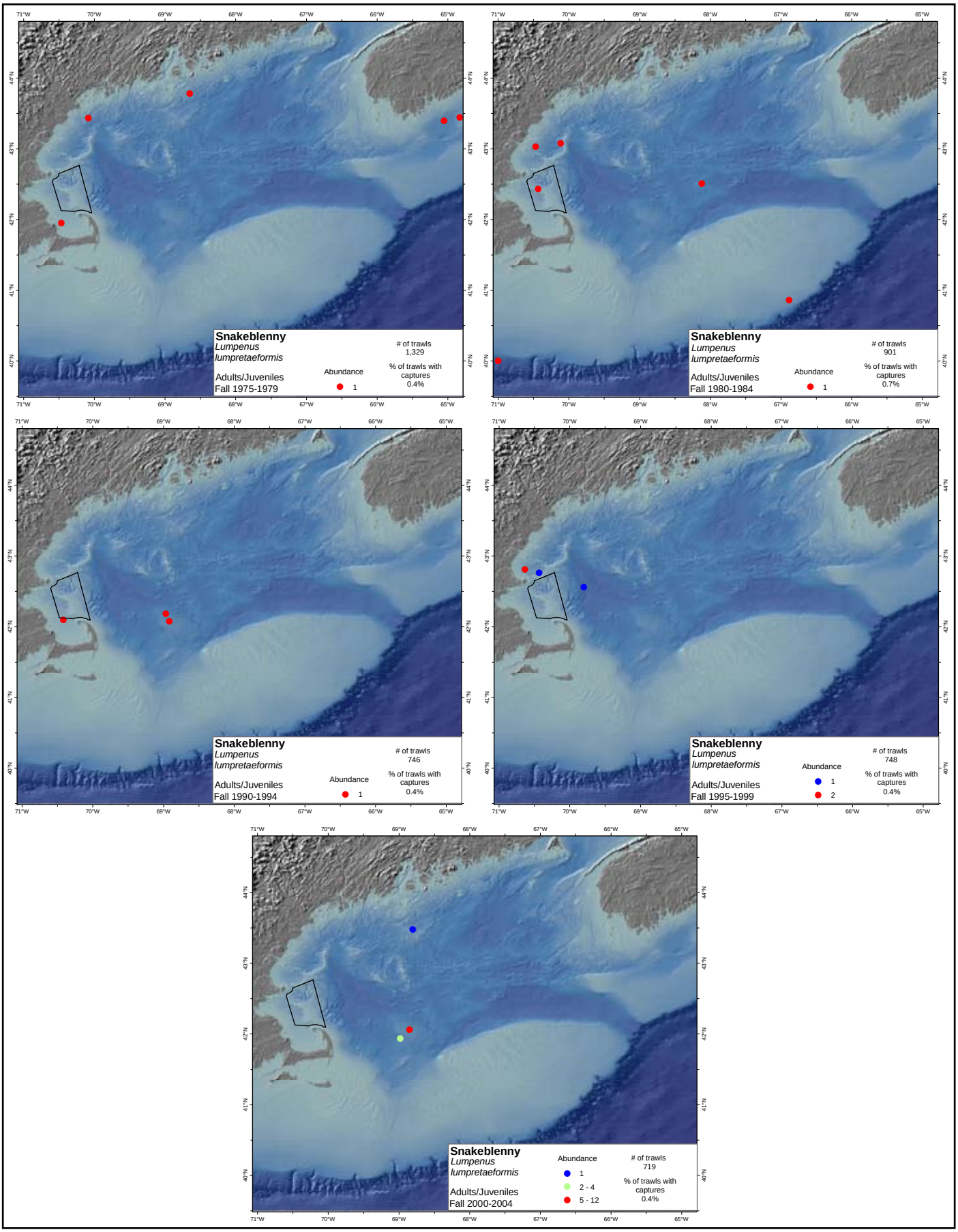

Figure 3.3.60. Abundance and distribution of snakeblenny (*Lumpenus lumpretaeformis*) within the Gulf of Maine, Fall 1975-2004.

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CHAPTER 4 - SEABIRD DISTRIBUTION AND DIVERSITY

Simon Pittman and Falk Huettmann

4.1 INTRODUCTION

Seabirds are defined as birds that spend a large proportion of their lives at sea, feeding either entirely or predominantly on marine organisms, and coming ashore for relatively short periods for resting or breeding (Schreiber and Burger, 2001). Most seabirds are assigned to one of three orders: the Procellariiformes (e.g. shearwaters, fulmars, petrels and albatrosses), the Pelecaniformes (e.g. gannets, pelicans, boobies and cormorants) or the Charadriiformes (e.g. gulls, terns, auks). They are usually numerically abundant, long lived (15-70 years) and feed at a variety of trophic levels (i.e. predators and scavengers). As such, seabirds can be very responsive to changes in their environment. The broad-ranging movements and longevity of seabirds mean that they track environmental changes at spatial and temporal scales that are otherwise difficult to monitor (Diamond and Devlin, 2003; Huettmann and Diamond, 2006). For example, seabird species are useful bioindicators by providing valuable information to define pelagic habitat types (Springer et al., 1996) and assess ecosystem health (Furness and Greenwood, 1993). Changes in seabird distribution and abundance, as well as breeding success, growth rates, survival and diet composition, have been closely linked to regional climate variability (e.g. North Atlantic Oscillations and El Niño/La Niña events) and global climate change (Schreiber and Schreiber, 1989; Aebischer et al., 1990; Brown, 1991; Monaghan, 1992; Montevecchi and Myers, 1997) often due to changes in prey abundance (Cairns, 1987; Hamer et al., 1991; Garthe et al., 1996; Diamond and Devlin, 2003). Seabirds also have the potential to function as indicators of pollutants, particularly since they rapidly bio-accumulate chemicals that are lipid-soluble such as organochlorines (e.g. DDT, PCBs) and organo-metals (e.g. methylmercury) (Chapdelaine et al., 1987; Furness and Camphuysen, 1997).

Seabirds and the Gulf of Maine

The Gulf of Maine region is locally and internationally recognized as an important area for seabirds, with seabird densities that are considerably higher than adjacent oceanic waters (Powers et al., 1980; Powers, 1983; Powers and Brown, 1987; Platt et al., 1995). The shallow banks and shelves, including Brown's Bank, Georges Bank, Cashes Ledge, Cape Cod, and the Grand Manan region, have long been known to support large numbers of seabirds (Powers, 1983; Powers and Brown, 1987; Huettmann and Diamond, 2006). Other known regional seabird hotspots are located at the southern tip of Nova Scotia, the continental shelf edge and the North East Channel.

Many of the seabirds observed in the Gulf of Maine region are seasonal migrants that have traveled vast distances from remote islands in the south Atlantic, where they nest (Brown, 1973). For example, Wilson's Storm- petrel (*Oceanites oceanicus*) migrate to the Gulf of Maine during summer from breeding sites in sub-Antarctic islands. Sooty Shearwaters (*Puffinus griseus*) and Greater Shearwaters (*Puffinus gravis*) are also summer migrants to the Gulf of Maine, from breeding sites on several remote south Atlantic islands (Tristan da Cunha and Gough Island) and sub-Antarctic islands (Hüttmann, 2000). Other birds, including some Arctic Terns (*Sterna paradisaea*) and Red Phalaropes (*Phalaropus fulicaria*) connect the Gulf of Maine with southern and western Africa (Brown, 1979). Black-legged Kittiwakes (*Rissa tridactyla*) and Great Cormorants are winter migrants, typically migrating from more northerly regions along with some auks, especially razorbills. Other seabirds migrate shorter distances (e.g. from Canada) to specific sites within the Gulf that are considered to be important moulting grounds for immature birds (Huettmann and Diamond, 2000; Huettmann et al., in press).

Non-resident seabirds visiting the Gulf of Maine typically exhibit a spring and fall arrival and departure pattern (Powers and Brown, 1987). The majority of shearwater species in the region are migrants and breed outside the study area (Brown, 1988; 1990). Seabirds that have established breeding colonies in the Gulf of Maine region include Atlantic Puffin (*Fratercula arctica*), Black Guillemot (*Cepphus grylle*), Common Murre (*Uria aalge*), Leach's Storm-petrel (*Oceanodroma leucorhoa*), Razorbill (*Alca torda*), Common Eider (*Somateria mollissima*) ,and several species of cormorant, gull and tern. In fact, the islands of Maine provide the only breeding sites in the United States for Atlantic Puffin and Razorbill (one of the rarest breeding Auks in North America) and provide some of the southernmost breeding sites for Leach's Storm-petrel and Common Eider. These breeding sites prompted the U.S. Fish and Wildlife Service (Gulf of Maine Coastal Program) to recognize approximately 300 "nationally significant" seabird nesting islands in the Gulf of Maine.

The auks (Alcidae), terns and some gulls (Laridae), fulmars, shearwaters and Storm-petrels (Procellariiformes), gannets (Sulidae) and cormorants (Phalacrocoraciidae) are key components of the offshore ecosystem, where they form an important group of predators of small fish, squid, and planktonic crustaceans. The primary prey items for most of these seabird species are small fish including Atlantic herring, sand lance, hake and mackerel, although they will also feed on cephalopods, crustaceans, annelids, and some plant material (Powers et al., 1980; Hall et al., 2000; Diamond and Devlin, 2003). Stomach content analysis of 156 individuals of nine seabird species (five species of Procellariiformes; and four gulls, Laridae) collected at sea from the northeastern continental shelf showed that all species fed on fish, with sand lance (*Ammodytes* sp.) being an important prey item for most marine birds throughout the year (Powers et al., 1980). Squid were also a major prey item for many species, particularly Greater Shearwaters, while Euphausiids (pelagic crustaceans) were an important component for Wilson's Storm-petrel.

Conservation Status

Many of the seabird species observed in the Gulf of Maine have large global populations, while considered locally threatened or vulnerable. For instance, Razorbill has a relatively large population within its range (mostly North Atlantic), with some historical evidence of a population decline (del Hoyo et al., 1996). The North American population is only 38,000 breeding pairs, most of which probably winter in the Gulf of Maine (Huettmann and Diamond, 2006). Consequently, the Razorbill has been listed as a bird of conservation concern for the U.S. Atlantic coastal region (U.S. Fish and Wildlife Service, 2002), and the state of Maine has listed the species as threatened under the Maine Endangered Species Act (1975). Least Tern (*Sterna antillarum*) and Black Tern (*Chlidonias niger*) are also listed as endangered under the Maine Endangered Species Act (1975), while Arctic Tern and Atlantic Puffin are listed as threatened. Roseate Tern (*Sterna dougallii*) is listed as both a Federal (U.S. Endangered Species Act, 1973) and state (Maine) endangered species. Although Roseate Tern is considered threatened in some regions globally, populations are not considered to have declined sufficiently for international recognition (IUCN/Birdlife International, 2006). Furthermore, the Great Cormorant (*Phalacrocorax carbo*), which was locally extirpated by the 1880s, but has recently (1980s) re-established breeding colonies on several Maine islands is also being considered for threatened status in Maine. Such designations reflect the local status of populations and are usually based on the number of breeding pairs and historical and current threats to those populations.

In addition, increases of several species have been reported, with some localized population explosions, which may also be an indicator of overall changes to ecosystem health. Several gull species including the Herring Gull (*Larus argentatus*) and Great Black-backed Gull (*Larus marinus*) have experienced substantial population increases in the Northwest Atlantic region (Drury, 1973; 1974). Estimates from Audubon Society Christmas Bird Counts and colony counts suggested that the gull population in the Gulf of Maine had doubled every 12 to 15 years since 1900 (Kadlec and Drury, 1968). Population estimates from both aerial and ground-based surveys of colonies indicate that the number of breeding pairs of terns (Common, Arctic, and Roseate) and Atlantic Puffin have increased steadily since the late 1970s and early 1980s (Gulf of Maine Seabird Working Group – summarized in Cornelison 1998). A comparison of adult bird surveys on and around nesting islands in Maine between 1976-77 and 1994-1995 indicated that Black Guillemot, Atlantic Puffin, Great Black-backed Gull, Laughing Gull, Razorbill, and cormorants had increased in abundance, while Leach's Storm-petrel and Herring Gull populations had declined (Cornelison, 1998). Ronconi and Wong (2003) compared recent (2001) and historical surveys of nine species around Grand Manan Island in the northern Gulf of Maine and estimated from colony counts that populations of Herring Gull, Great Black-backed Gull, Razorbill, and Common Murre had increased.

However, few data are available to accurately determine population trends for pelagic seabirds in the Gulf of Maine. Most population information for the region comes from visual census of breeding pairs at colonies (Drury 1973, 1974, Ronconi and Wong 2003), yet research is insufficient to determine the linkages between local colony counts and pelagic seabird population trends.

Threats to Seabirds

Anthropogenic activity in the Gulf of Maine and worldwide has resulted in a range of direct and indirect threats to seabirds (Tasker and Furness, 2003; Lotze and Milewski, 2004). For example, analyses of changes in seabird populations in the Bay of Fundy (northern Gulf of Maine) since European colonization have shown that approximately 50% of marine and coastal bird species have been severely affected by human activity, with several species extirpated and major colonies abandoned (Lotze and Milewski, 2004). Great Auk (*Pinguinus impennis*)

(Figure 4.1.1) were once frequently sighted in the Gulf of Maine where some populations over-wintered, but was globally extinct by 1844. Great Auk bones have been found in Massachusetts (Martha's Vineyard, East Wareham, Marblehead, Eagle Hill and Plum Island) and at least 10 islands along the Maine coast (Burness and Montevecchi, 1992). With the exception of the Great Auk, re-colonization of abandoned breeding colonies have taken place for most species, albeit relatively slowly with estimated recolonization time considered to take as long as 45 years for Common Murre and 133 years for Northern Gannet (Lotze and Milewski, 2002).

Historically, the main threats to seabirds have been coastal development, predation by humans and other animals, removal of prey through fisheries activity, and pollution of the marine environment. Drury (1973; 1974) describe the extensive harvesting of seabirds for food and feather in New England that resulted in extirpation of many seabird species even from remote outer islands by the turn of the 20th century. Interactions between fisheries and seabirds have been well documented in many regions worldwide, with both increases and declines of seabird populations linked to patterns of fishing activity (Tasker et al., 2000; Tasker and Furness, 2003; Votier et al., 2004). Intense fishing activity can impact seabird populations through reduction of prey abundance and perturbation of prey population and community structure (Pauly et al., 1998; Tasker et al., 2000). Food web changes related to heavy fishing over many years have been found to adversely affect seabirds in the Gulf of Maine (Lotze and Milewski, 2004). In addition, mortality related to entanglement with fishing gear has been reported. Though not well studied, entanglement is currently not considered a major source of seabird mortality in the Gulf of Maine.

Figure 4.1.1. Watercolor painting of the extinct Great Auk (*Pinguinus impennis*) painted in 1839 from a preserved specimen belonging to J.J. Audubon Esq. Archeological evidence indicates that this species was once prevalent as a seasonal migrant in the Gulf of Maine.

Arguably, the greatest threat for many seabirds (particularly terns and auks) is from other seabirds, primarily gulls (Drury, 1965). During the mid-1900s, an increase in fishery discards (and the spread of open landfills) along the Gulf of Maine coastline led to increased Herring and Great Black-backed Gull populations. This in turn led to greater pressure on other seabirds, particularly terns, through competition for prime nesting sites and increased predation by gulls on their eggs and chicks (Drury, 1965; Platt et al., 1995; Anderson and Devlin, 1999).

Industrial contaminants are also a potential threat to seabird populations (Burger and Gochfeld, 2002). For example, elevated PCBs have been found in Roseate Tern chicks at Bird Island (Massachusetts) (Nisbet, 1981) and a wide range of metals have been found in Common Terns at breeding colonies in Massachusetts (Burger et al., 1994). The impact of pollutants on seabirds, including sub-lethal effects has not been adequately assessed for the Gulf of Maine.

Seabird-Environment Linkages

Areas with a high a seabird abundance and richness and areas with major nesting or resting sites are often considered of special interest in marine resource management strategies and in the design of marine protected areas (MPAs) or networks of MPAs. However, determining which areas of the open ocean are most important to seabirds requires, at the very least, quantitative information on the spatial and temporal distribution of seabird species (Huettmann and Diamond, 2001; 2006).

While the presence or absence of suitable nesting locations and the availability and abundance of prey are clearly important explanatory variables, seabirds often exhibit both linear and more complex non-linear relationships with their environment in time and space (Ballance et al., 2001). Prey abundance is typically highly heterogeneous at a range of spatial and temporal scales, making it difficult to develop accurate spatial characterizations that can then be aligned in an ecologically meaningful way with seabird data. Nevertheless, persistent patches of high prey abundance do occur and seabirds have evolved to find these areas, resulting in aggregation (Piatt, 1990; Schneider, 1990a; Fauchald and Erikstad, 2002; Yen et al., 2004b). These "hotspots" of activity are frequently associated with high prey density or with increased food availability due to human fishing activity and cetacean feeding (Garthe et al., 1996; Furness, 2003; Votier et al., 2004).

In the absence of appropriate prey abundance data (i.e. readily available data with high spatial, temporal and taxonomic resolution), identifying important areas often requires the use of surrogate variables that are proxies for prey abundance patterns. Surrogate variables have been successfully used to explain seabird distributions in the North-West Atlantic (Huettmann and Diamond, 2001). At-sea surveys have shown that many seabirds have distinct utilization patterns associated with specific ocean currents and water masses, and the boundaries between those features, as well as finer-scale oceanographic and bathymetric features that affect prey dispersion and availability (Schneider, 1990b; 1997; Balance et al. 2001, Daunt et al., 2003). In most regions, oceanographic (e.g. sea surface temperature and chlorophyll concentrations) and bathymetric variables show a strong across-shelf spatial gradient that is associated with patterns of seabird distribution and prey abundance. Seabird preference for shallow continental shelf waters versus deeper oceanic waters, proximity to shore, or to some distinct bathymetric feature (e.g. continental shelf edge) have been found to explain broad-scale patterns in abundance for a wide range of seabird species (Wynne-Edwards, 1935; Schneider, 1997; Yen et al., 2004a, b). For example, Yen et al. (2004a, b) found that seabirds target regions of complex and steep topographies where oceanographic conditions lead to elevated productivity (fronts and upwelling zones) and increased prey retention. As such, persistent geological ocean features, such as islands, banks, seamounts, submarine canyons and upwelling zones are increasingly being proposed and designated as components of an MPA network (Hooker et al., 1999).

The Challenge of Understanding Seabird Distribution and Abundance

Traditionally, sightings data have been represented as digital and non-digital distribution maps (atlases) using spatially aggregated observations (i.e. average number of birds per day in 10 degree squares (Jespersen, 1924; Moore, 1951); mean monthly density in 10 minute squares (Powers et al., 1980; Powers, 1983); or summarized data represented as contours of relative abundance (Powers and Brown, 1987). While the “atlas” approach has made a valuable contribution to the understanding of broad-scale spatial patterns in seabird distributions, few studies had attempted to link the spatial and temporal patterns of seabirds to the surrounding environment at each location. Furthermore, the spatial resolution of these types of maps is coarse, and predictions are usually discontinuous due to limited sampling effort.

The increased availability of environmental data at broad-spatial extents and relatively fine resolution, along with the development of sophisticated modeling techniques, it is now possible to link the distribution and abundance of seabirds quantitatively with the multi-dimensional environment at specific locations. Resource selection functions (RSFs) can be developed to relate the usage of seabird habitat to the availability of habitat (Manly et al., 2002), and the statistical relationship is then used to generate predictive maps of potential habitat use.

Historical seabird survey data, however, are often severely limited in time and space with some uncertainty associated with data collection methods. Linking these data to more continuous environmental data, therefore, requires algorithms that can accurately predict, even in the presence of outliers, missing data and unbalanced data sets (Hastie et al., 2001). Such algorithms are becoming increasingly more sophisticated and versatile, facilitating extrapolation beyond sampled areas to produce highly accurate continuous quantitative spatial predictions, which are based on mathematical formulas linking species to their environment (Guisan and Zimmerman, 2000; Huettmann and Diamond, 2001; Guisan and Thuiller, 2005; Elith et al., 2006). These modeling techniques are particularly useful for the marine environment, where studies span extremely broad areas and data gaps can be extensive (Hüttmann, 2000; Huettmann and Diamond, 2001; Leathwick et al., 2006; Pittman et al., in review). Although spatial predictive modeling of seabirds has rarely only been used (Huettmann and Diamond 2001; Yen et al., 2004a), similar approaches have already proven very successful for modeling the ecological niche of a wide range of terrestrial plants and animals (Hirzel et al., 2002; Elith et al., 2006). Uncertainty often exists with sampling design and where species detectability is highly variable. To minimize bias in abundance estimates and to avoid the uncertainty associated with ‘false absence”, “presence-only” data are more often used to represent species distributions instead of presence-absence or abundance data. Here we took a relatively conservative approach to data use by modeling species prevalence based on “presence only” data for those seabird species determined to be of special interest to the Stellwagen Bank National Marine Sanctuary.

Main Objectives

The main objective of this chapter is to provide spatially-explicit and quantitative information on the distribution and diversity of seabirds within Stellwagen Bank NMS and the wider Gulf of Maine. Seabirds are a conspicuous and ecologically important component of the marine ecosystem in the region. They exhibit high mobility and distinct temporal fluctuations in abundance requiring consideration of the distribution patterns at spatial scales far broader than the Sanctuary boundary itself. To achieve this, a statistical modeling approach was used to predict seabird distributions based on the relationship between patterns of occurrence and variability in the surrounding environment. The maps of species prevalence provided in this chapter can be used to identify potential hotspots and coldspots of occurrence both inside and outside the Sanctuary for both summer months and winter months. This information is intended to support of marine resource managers tasked with the development of ecosystem-based management approaches and site specific management plans for Stellwagen Bank NMS and the wider Gulf of Maine.

4.2 METHODS

Seabird data

Seabird sightings collected by the Cetacean and Seabird Assessment Program (CSAP) were extracted from the Manomet Bird Observatory's (MBO) (currently named Manomet Center for Conservation Sciences) database. The MBO database provides large sample sizes and exceptional spatial and temporal resolution for the Gulf of Maine region and the broader northeastern U.S. continental shelf. MBO data also provides a spatially extensive training data set to facilitate the development of accurate species distribution models. To date, relatively few individuals have analyzed this valuable historical data (Powers, 1983; Powers and Brown, 1987). A need for further analysis was defined almost two decades ago by Smith et al. (1988) who evaluated the utility of MBO data to meet the needs of the National Oceanic and Atmospheric Administration (NOAA), but prior to this study no prior quantitative modeling and digital mapping has yet been performed with these data.

NOAA's Northeast Fisheries Science Center, Woods Hole, provided the MBO database in ASCII format. In addition, a version of the original was also integrated within the PIROP (Intégré des Recherches sur les Oiseaux Pélagiques) database held by OBIS-SEAMAP (Read et al., 2006). Although a small spatial overlap exists, the PIROP data were collected primarily for Canadian seabird monitoring purposes and focused mainly on the Canadian Atlantic, while the Manomet data focused on the U.S. continental shelf extending from Nova Scotia, Canada, south to Cape Hatteras, North Carolina. The predictive modelling component of this study used the combined PIROP and MBO database. Records were extracted from a Microsoft Access database using Standard Query Language scripts (Appendix 1).

Seabird sampling techniques

Shipboard surveys were conducted by the Manomet Bird Observatory between April 1980 and October 1988 through contracts with the U.S. Department of Energy's Office of Health and Environmental Research and NOAA's Northeast Fisheries Science Center (MBO, 1980; 1981; 1982; 1986a; 1986b; 1987a; 1987b). These surveys were part of a long-term monitoring program designed to provide an assessment of the abundance and distribution of cetaceans, seabirds, and marine turtles in the shelf and shelf-edge waters (less than 100 fathoms) off the northeastern United States. The principle areas of interest were the waters on, and adjacent to, Georges Bank. MBO-dedicated observers were placed on research vessels undertaking a wide range of surveys including: NMFS bottom trawl or groundfish surveys; NMFS scallop survey; NMFS Marine Resources Monitoring Assessment and Prediction Program (MARMAP) plankton surveys; Environmental Protection Agency (EPA) surveys; and U.S. Coast Guard surveys. Seabird observer methods followed Powers (1982). Observations were recorded in 15 minute periods, where each period was considered an individual transect and the spatial coordinates were recorded using the ship's instruments. Seabirds were counted within a fixed strip width of 300 m at one side of the ship, traveling on a straight course, at a constant speed (approx. 8 - 12 knots). The duration of each sampling period was fixed, but transect length varied slightly depending on vessel speed. The spatial and temporal coverage of seabird observations were entirely dependent on the survey design used by the host vessel. The MBO data were originally intended for the estimation of seabird densities and relative abundance. However, the survey design does not provide data that can be used to estimate abun-

dance for spatial comparison. Instead, "presence only" data, that records when a species occurs at a given location along a transect can be extracted to provide robust species occurrence data in time and space.

Survey Effort

The survey effort extended across the Gulf of Maine and Georges Bank regions (Figure 4.2.1). Over 17,872 transects (approx. 4,400 hours) were conducted within the study area, of which 16,490 (1980-1988) and 1,392 (1965-1979) where conducted by MBO and PIROP, respectively. In the study region, sampling effort exhibited a bias towards mostly pelagic sampling, while shallow-water nearshore areas had comparatively little effort (Figure 4.2.2). In addition, sampling effort was relatively low over many of the deep water basins of the central Gulf of Maine. Survey effort was higher in summer (10,155 transects April 15th to October 15th) months than winter (7,716 transects October 16th to April 14th) (Table 4.2.1 and Figure 4.2.1). Effort was lowest for the months of February and March and highest in August and October.

Data selection

Species occurrence or "presence-only" data were selected for a suite of species identified by staff at NOAA's Stellwagen Bank NMS to include: Razorbill (*Alca torda*), Greater Shearwater (*Puffinus gravis*), Wilson's Storm-petrel (*Oceanites oceanicus*), Northern Gannet (*Morus bassanus*), and all auks (Alcidae). These species are considered to be good indicators, representing a wide range of the pelagic birds present in the region, and included seasonal non-breeding birds (Wilson's Storm-petrel and Greater Shearwater), breeding birds (some auks), and birds with different feeding strategies and diet preferences (i.e. Northern Gannet are fish eating plunge divers and Wilson's Storm-petrel are plankton eating surface feeders).

The "presence-only" approach used allowed inclusion of most MBO data without any major data quality filtering (i.e. uncertainties regarding transect length, width, duration, wind speed, species absences). This analysis assumed species detectability was constant across the study area. The survey effort and sightings were grouped into 5 km^2 spatial units or "bins" (Huettmann and Diamond, 2006) using ArcGIS 9.1. The number of occurrences for each species, independent of flock size, was then divided by the survey effort (number of transects) to create an "Index of Relative Prevalence" (IRP), with values ranging from 0 – 1. These values were mapped and used as the response variable for predictive modeling, similar to an index of presence corrected for effort. This binning approach obviates much of the need to correct for low or variable precision in the geolocations of transects. Furthermore, the data did not provide information to allow separate analyses for juveniles and adults.

Table 4.2.1. Allocation of seabird survey effort by month for the Gulf of Maine study area based on MBO and PIROP combined (1965-1988).

Month	Proportion of total (%)
January	5.1
February	4.3
March	3.8
April	10.1
May	9.9
June	7.7
July	6.2
August	13.9
September	8.9
October	12.5
November	7.3
December	10.2

Table 4.2.2. Attributes and source of environmental variables used to predict habitat preferences based on seabird occurrence in the Gulf of Maine. NOAA/CCMA= Data processed by Center for Coastal Monitoring and Assessment; NOAA/NGDC= Data processed by National Geophysical Data Center.

Variable	Time Scale	Spatial Scale	Provider
Mean Chlorophyll *a*	July & Dec. (1997-2005)	1.1 km.	NOAA/CCMA
Mean Turbidity	July & Dec. (1997-2005)	1.1 km	NOAA/CCMA
Mean SST	July & Dec. (1985-2004)	1.1 km	NOAA/CCMA
Bathymetry	N/A	2 minute	NOAA/NGDC
Slope	N/A	2 minute	NOAA/NGDC
Coastline	N/A	1:70,000	NOAA/NGDC
Shelf Edge	N/A	N/A	NOAA/NGDC

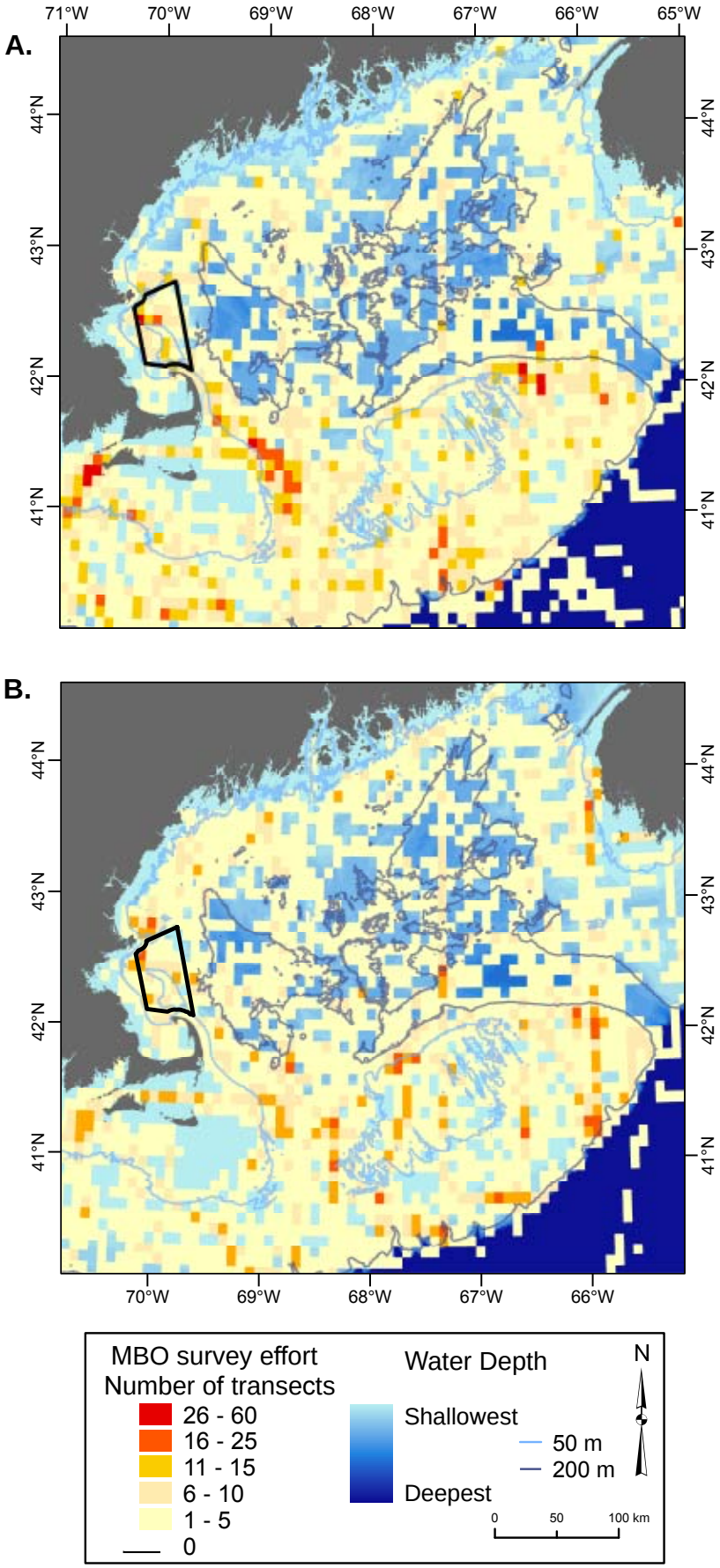

Figure 4.2.1. Sampling effort for the Gulf of Maine study area calculated in 5 minute bins for (a) summer (Apr 15 – Oct 15) and (b) winter (Oct 16 – Apr 14) seasons.

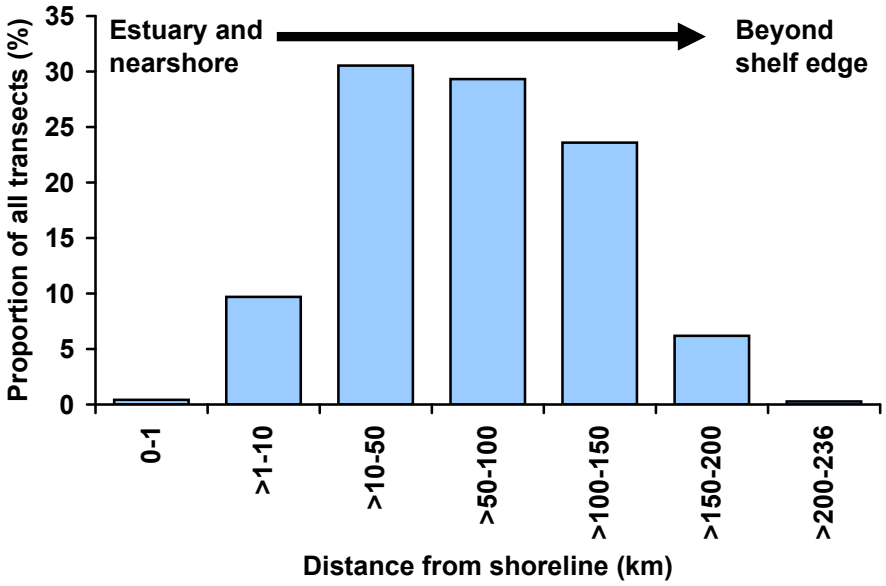

Figure 4.2.2. Distance from MBO transect point to the nearest coastline (both mainland and islands).

Environmental data

Accurate and broad-scale environmental data including prey abundance that are both suitable for alignment with seabird survey data and appropriate for predictive modeling are still largely unavailable for most marine regions. Recent studies, however, have shown that environmental data that represent indirect species-environment relationships can also be used to develop accurate spatial predictions of species distributions (Hüttmann, 2000; Guisan and Zimmermann, 2000; Elith et al., 2006). Environmental layers used for this study consisted of bathymetry, monthly means for sea surface temperature (SST), chlorophyll *a* concentration, and turbidity (Table 4.2.2). For satellite-derived oceanographic data (SST, chlorophyll *a* and turbidity), values among months within a single season were highly correlated. Therefore, to avoid collinearity of predictor variables and aid interpretation of results, a single month that best represented an entire season (winter or summer) was selected. For SST, chlorophyll *a*, and turbidity, long-term means for the month of July were used for the summer model and December for the winter model (Figure 4.2.3). In addition, GIS tools were used to calculate slope (derived from bathymetry), proximity to the coastline and proximity to the approximate location of the shelf edge (200-300 m isobath). Slope identifies the maximum rate of change in value from each cell to its neighbors.

Modeling technique

Stochastic Gradient Boosting using TreeNet™ (Salford Systems Inc.) was used to determine the relative importance of each environmental layer and to predict species distributions for every 5 km^2 bin across the Gulf of Maine study area. Stochastic Gradient Boosting is a nonparametric regression modeling method, known to be robust to errors in the data, outliers, missing values, and overfitting. In TreeNet™, regression tree models are built up gradually through a large collection of small trees, each of which improves on its predecessors through an error-correcting strategy based on reducing the residual variance (Friedman, 2001). Furthermore, it is not adversely influenced by irrelevant predictors and therefore, does not require prior variable selection or data reduction. Corrected data for most bird species consisted of a gradient of prevalence values ranging from 0.0001 (virtually absent and non-preferred habitat) to almost 1 (high presence and preferred habitat). However, only bins with a value of more than 0.001 were used in model development. The application of the TreeNet™ algorithm to a prevalence gradient (similar to a Poisson distribution) facilitates the development of accurate models (Elith et al., 2006). Using ArcGIS 9.1, seabird prevalence data and environmental data were extracted for each 5 km^2 bin and then imported into TreeNet™ in ASCII format and modeled using default options to derive predictions. The final predictions for the response variable within each bin were then imported into ArcGIS 9.1 and mapped.

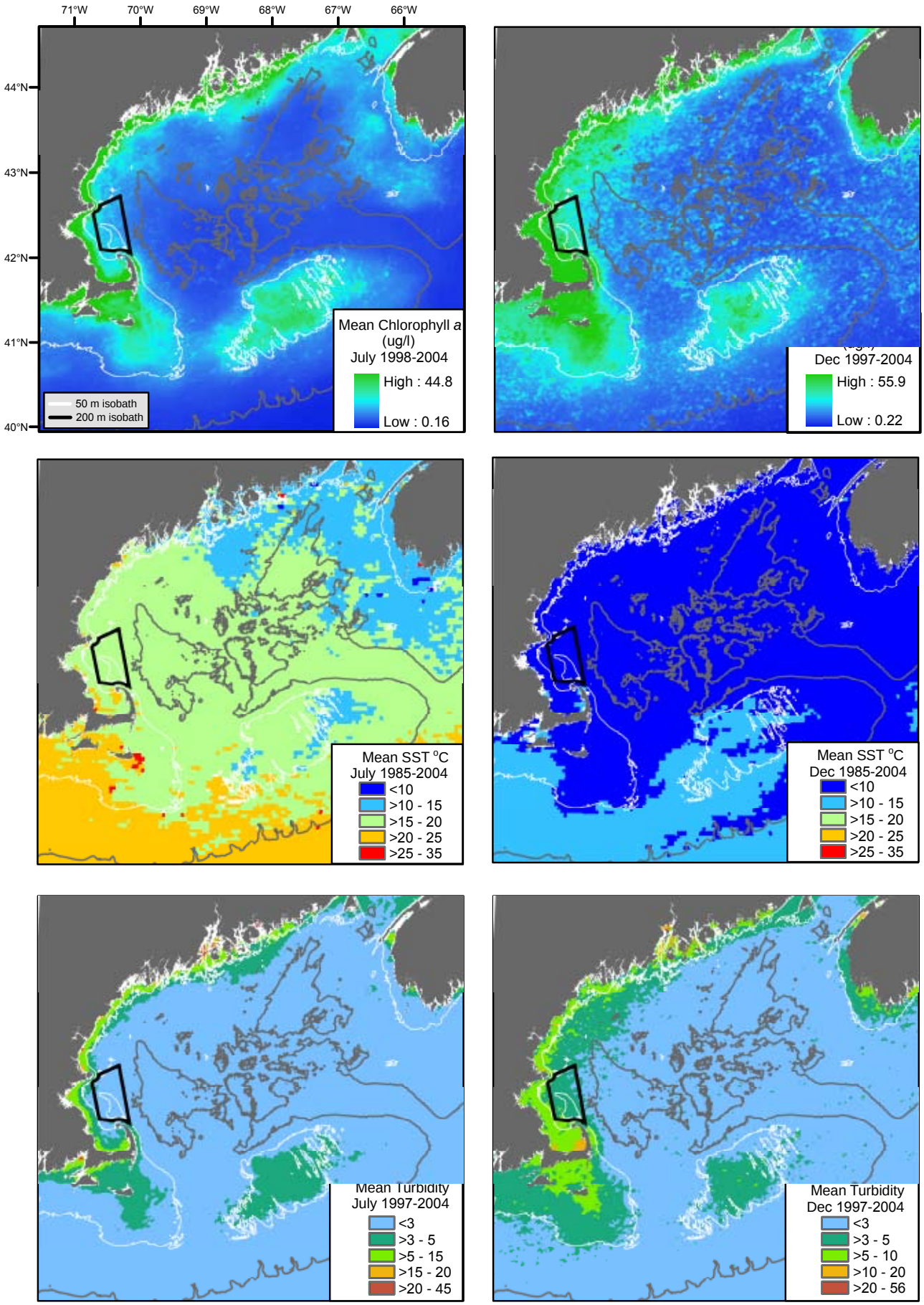

Figure 4.2.3. Mean chlorophyll *a* concentration, mean SST and mean turbidity for July (summer) (Maps A, B and C, respectively) and December (winter) (Maps D, E and F, respectively).

The relative contribution of the predictor variables to the overall patterns of seabird presence was determined using the variable importance score generated by TreeNet™. The variable importance score is based on the improvements of all splits associated with a given variable across all trees in the model, which is then rescaled across all trees so that the most important variable always gets a score of 100. Other variables receive scores that are relative to their contribution to the model's predictive power.

4.3 RESULTS

Summary information

An estimated 60 species of seabird were recorded within the Gulf of Maine, based on sightings from the Manomet Bird Observatory surveys (1980-1988). The most commonly encountered species, and in some cases, the most numerically abundant were the Herring Gull (47.6% occurrence, 12.8% of all positively identified species), Great Black-backed Gull (45.2% occurrence, 12.4% of all), Greater Shearwater (34.3% occurrence, 6.37% of all), Black-legged Kittiwake (29.9% occurrence, 15.8% of all), Northern Gannet (23.6% occurrence, 6.8% of all), Wilson's Storm-petrel (22.7% occurrence, 3.18% of all) and Northern Fulmar (22.7% occurrence, 1.9% of all) (Figure 4.3.1). An estimated 32 species were identified for Stellwagen Bank NMS with Herring Gulls and Great Black-backed Gulls most frequently seen (Figure 4.3.2). The species rank based on frequency of occurrence was very similar between Stellwagen Bank NMS and the broader Gulf of Maine, with the exception of gulls that were more frequently sighted and shearwaters less frequently sighted within Stellwagen Bank NMS. In addition, there were five separate sightings of the Federally endangered Roseate Tern in the Gulf of Maine, one of which was recorded within Stellwagen Bank NMS. Roseate Tern flock sizes were relatively large with 32 individuals sighted on a transect approximately 30 km east of Cape Cod and 22 individuals sighted on a transect approximately 10 km west of Martha's Vineyard.

Temporal patterns of total abundance

Monthly total abundance data for eight seabird species, corrected for effort, were compared to examine temporal patterns of abundance (Figure 4.3.3). Although these data present a simplified estimate of monthly changes in seabird abundance, the temporal patterns of presence and absence for the Gulf of Maine are clearly shown. Razorbill were almost absent for most of the summer months in offshore waters of the Gulf of Maine, with highest abundance in mid-winter (January). Similar patterns were found for Common Murre and Black Guillemot with a peak in December. Thick-billed Murre, Dovekie, and Northern Gannet were also largely absent in the mid-summer months. In contrast, Wilson's Storm-petrel was present exclusively in the summer months, and Greater Shearwater was most abundant from mid-summer months to early winter. However, these simplified estimates of total abundance should be interpreted with caution given limitations in the sampling protocol, including: (1) unknown species detectability, (2) opportunistic survey locations, and (3) non-comparable abundance estimates. Consequently, instead of an in-situ focus, we emphasize the more reliable inference from the predicted data presented below.

Seabird distributions

Auks (*Alcidae*)

Summer: A total of 52 sightings (presence only) were recorded offshore for all auks, except Razorbill, in the study area. The spatial patterns in IRP (Index of Relative Prevalence) for all Alcids (Common Murre, Thick-billed Murre, Black Guillemot and Dovekie) indicated a coastal distribution of birds on the northern section of the Gulf of Maine (Figure 4.3.4). Other clusters of sightings occurred over the deeper waters above the eastern slope of Georges Bank, and also over the Northeast Channel and the Great South Channel. However, auks were almost absent from Cape Cod and much of the central Gulf of Maine.

Bathymetric slope was determined to be the most powerful predictor followed by SST for the predictive model (Table 4.3.1), resulting in highest prevalence for nearshore coastal areas, especially along the island-rich coast of Maine in the northern section of the Gulf of Maine (Figure 4.3.5). High prevalence was also predicted for the southern tip of Nova Scotia, the shoals of Georges Bank, Nantucket and Stellwagen Bank. Lowest predicted IRP was Cape Cod Bay, the slopes of Georges Bank (60 – 100 m depth) and the slopes (>60 m depth) south of Martha's Vineyard.

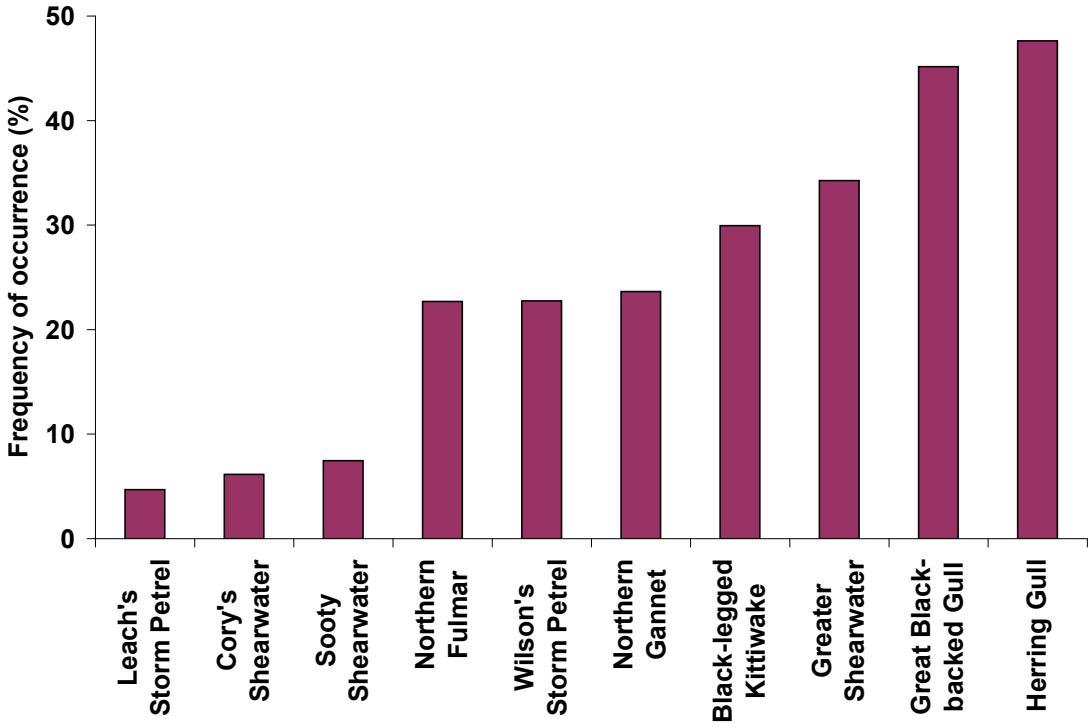

Figure 4.3.1. Percent frequency of occurrence for the most widely sighted species in the Gulf of Maine using Manomet Bird Observatory survey data for all seasons combined (1980-88). Only species with greater than 5% occurrence are shown.

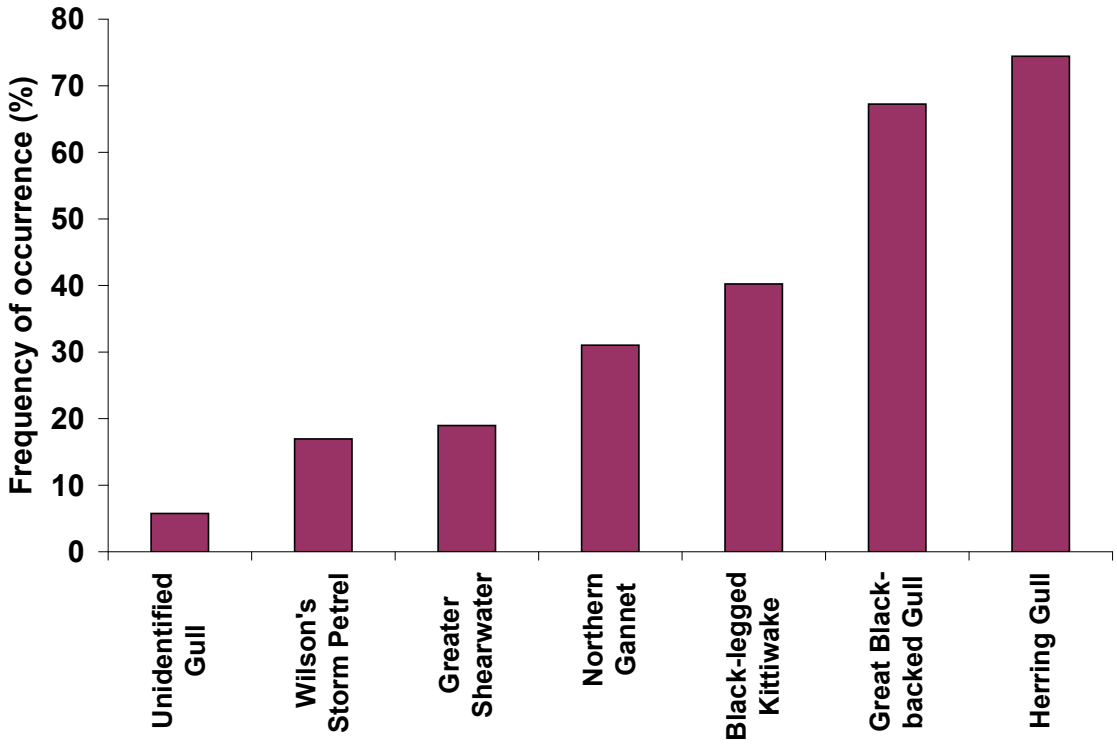

Figure 4.3.2. Percent frequency of occurrence for the most widely sighted species in Stellwagen Bank National Marine Sanctuary using Manomet Bird Observatory survey data for all seasons combined (1980-88). Only species >5% occurrence are shown.

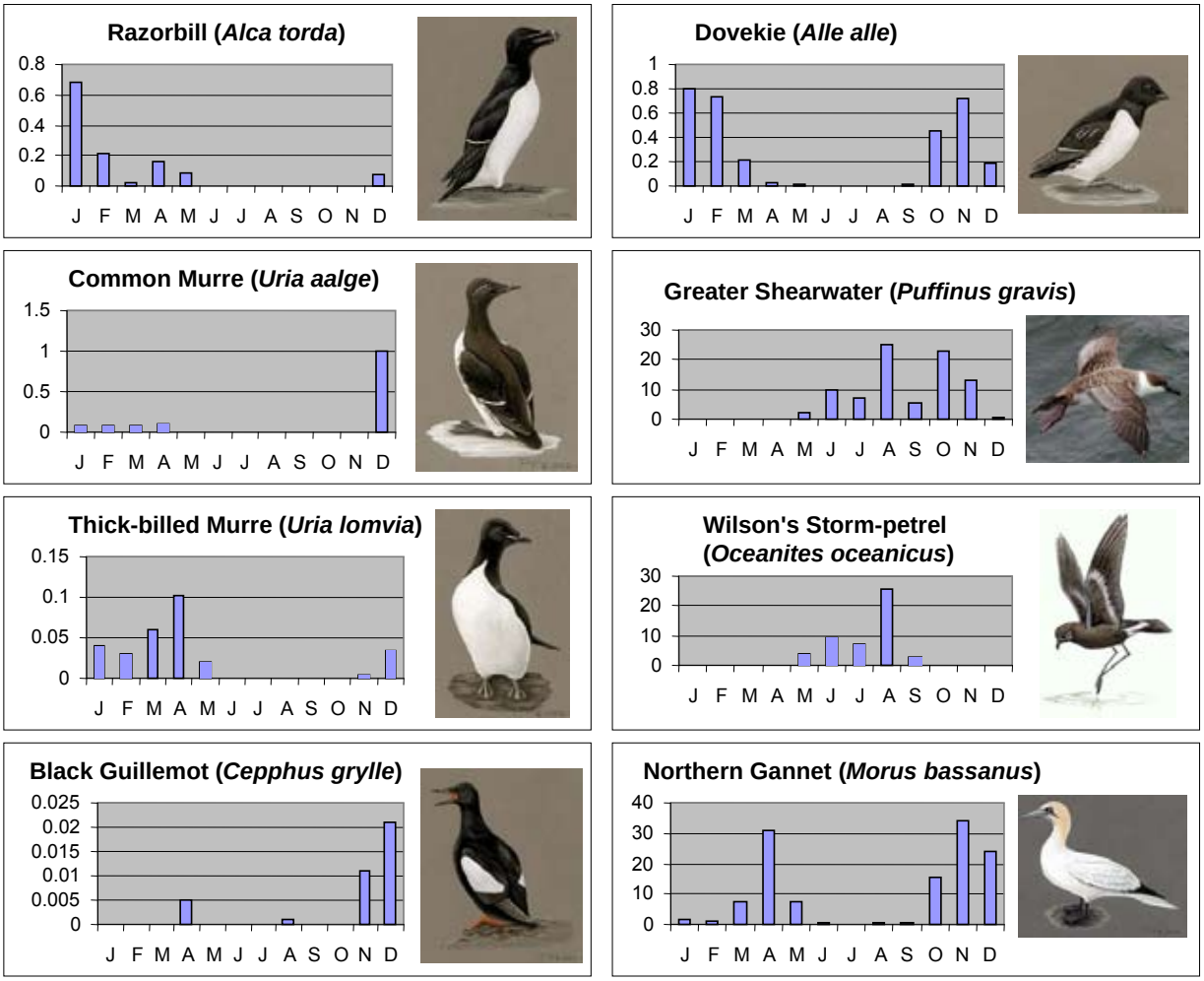

Figure 4.3.3. Monthly seabird abundance corrected for effort using Manomet Bird Observatory data (1980-1988). Pictures from P. Myers et al. 2006. The Animal Diversity Web (online). Accessed at http://animaldiversity.org. University of Michigan Museum of Zoology.

Table 4.3.1. Predictors and their relative contribution (%) to the explained variation in the response variable as computed by TreeNet™. The most relevant variables are shown in bold.

	Mean depth	Mean slope	Distance to shelf	Distance to shore	Mean chlorophyll *a*	Mean turbidity	Mean SST
Auks (Summer)	16	**100**			36	34	51
Auks (Winter)	**90**	44	25	50	42	**100**	48
Razorbill (Winter)	100						
Greater Shearwater (summer)	82	81	28	49	**88**	82	**100**
Greater Shearwater (winter)	56			**100**	**99**	56	
Northern Gannet (summer)	82	55	12	22	58	73	**100**
Northern Gannet (winter)	79	77	25	30	65	**89**	**100**
Wilson's Storm Petrel (summer)	**100**	74	42	29	95	85	**92**
Wilson's Storm Petrel (winter)		**100**		**91**	86		74

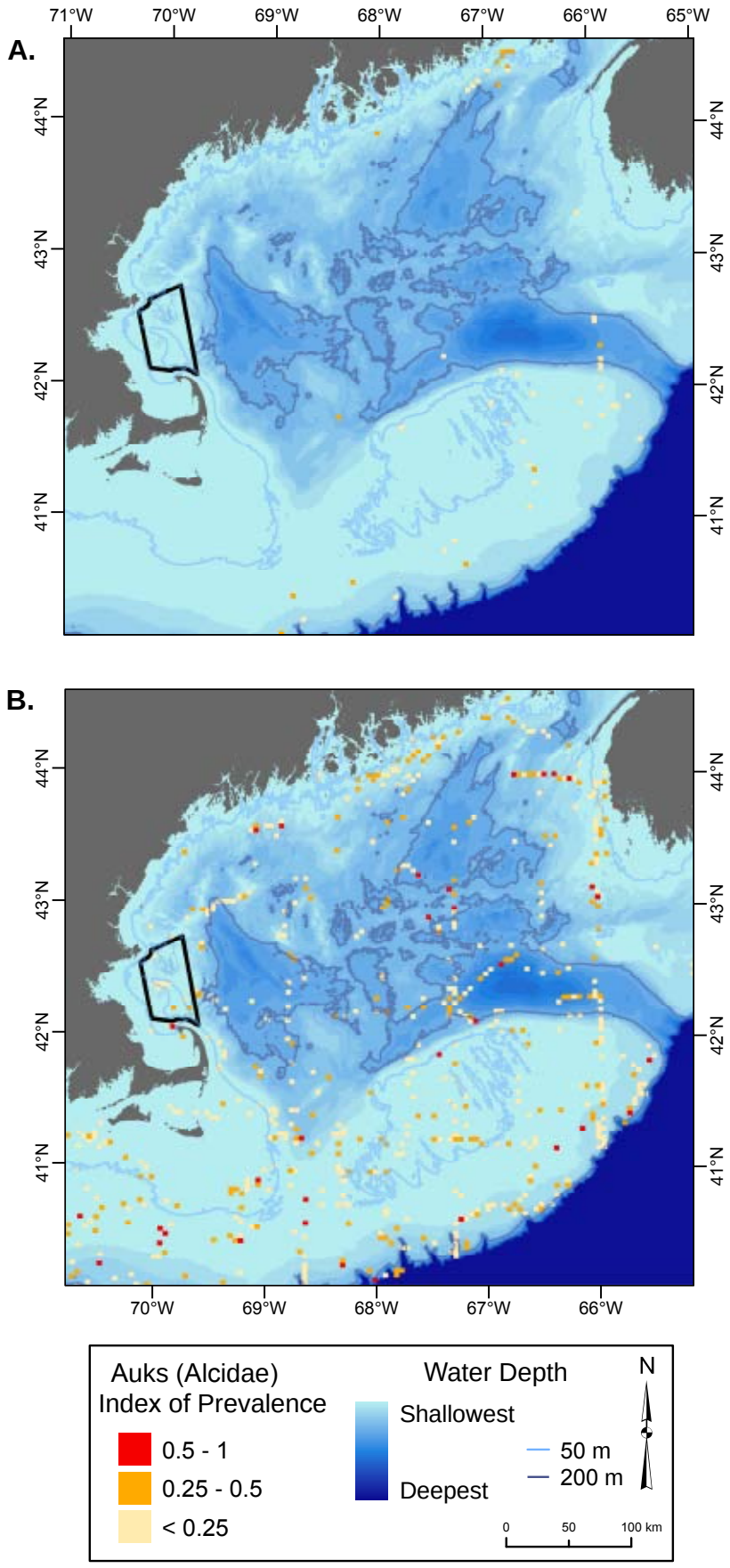

Figure 4.3.4. Seasonal auk (Alcidae) distribution patterns in the Gulf of Maine based on effort corrected presence data (Index of Relative Prevalence) for (a) summer, and (b) winter seasons.

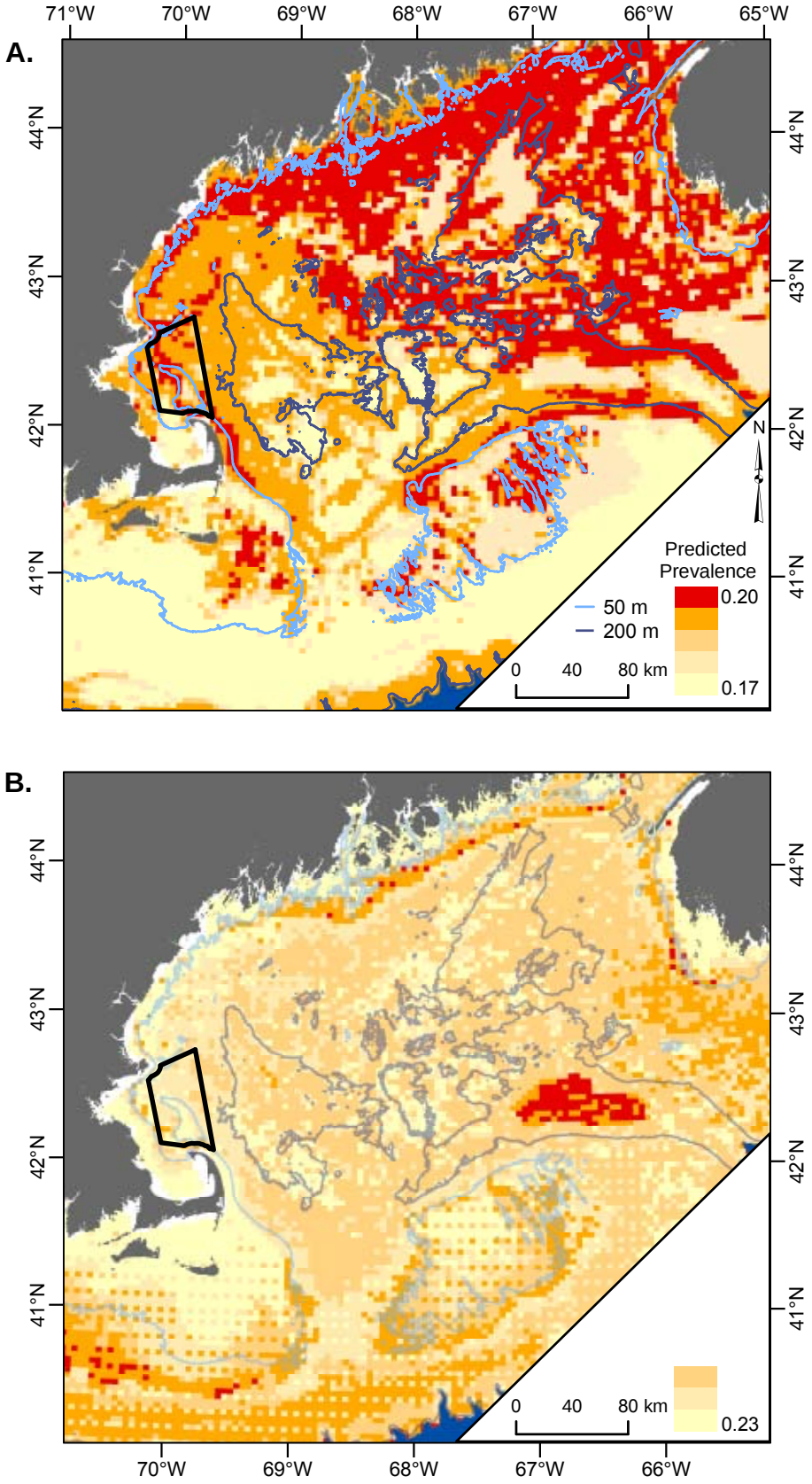

Figure 4.3.5. Seasonal auk (Alcidae) predictions of relative prevalence in the Gulf of Maine for (a) summer and (b) winter. TreeNet predictions were based on the statistical relationship between effort corrected presence and a set of environmental variables. Note that the range of predicted values varies between summer and winter models.

Winter: A total of 543 sightings (presence only) were recorded in the study area. The winter IRP revealed highest prevalence close to the islands of Maine and the southern tip of Nova Scotia, near Yarmouth and the mouth of the Bay of Fundy, as well as across Georges Bank, the Great South Channel, and the deeper waters sloping toward the shelf edge south of Nantucket Shoals (Figure 4.3.4).

Turbidity and depth were the strongest predictors of the observed distributions for the predictive model (Table 4.3.1). Highest prevalence was predicted over Georges Basin (200-300 m depth) north of Georges Bank, the relatively narrow strip of coastal slope (60-100 m depth) along the Maine coast continuing north to the Bay of Fundy, and along a similar depth contour across the southern tip of Nova Scotia (Figure 4.3.5). Lowest prevalence was predicted for the shallowest waters within Cape Cod Bay (<40 m depth), along most of the shallowest nearshore waters of the mainland coast, for Nantucket Shoals (<40 m depth), and parts of the shallowest (<40 m depth) shoals on Georges Bank (Georges & Cultivator Shoals).

Razorbill (*Alca torda*)

Summer: Very few sightings (n=15) were recorded for Razorbill during the summer season. Birds were recorded primarily along the deeper water (>100 m depth) edges of Georges Bank (Figure 4.3.6). However, survey effort was lower for nearshore areas, and therefore the patterns of occurrence for Razorbill may not have been adequately represented in the MBO data. Few sightings prevented prediction of Razorbill summer pattern (no map is shown). Razorbills nest at seven sites in the Gulf of Maine. The largest nesting colonies are at Matinicus Rock, Machias Seal island, and Yellow Murre Ledge. Populations have been increasing in recent decades.

Winter: Few sightings (n=75) were recorded for Razorbill in winter, and distributions appeared to be very localized, with clusters of sightings within Stellwagen Bank NMS; along the slope edges of Georges Bank, and the deeper sections (>70 m depth) of the Great South Channel (Figure 4.3.6). Birds were also prevalent along the Maine coastline and the southern tip of Nova Scotia, extending towards the mouth of the Bay of Fundy. The predicted patterns for Razorbill (no map is shown) were driven by depth (Table 4.3.1). Overall, slightly higher prevalence was predicted for waters over sloping bathymetry and for basins near the edges of shallow water features.

Greater Shearwater (*Puffinus gravis*)

Summer: Sightings data indicated that Greater Shearwater were extremely widespread and highly prevalent across the entire Gulf of Maine (present in 2,800 transects), but with distinctive patterns of high IRP associated with Georges Bank and the edges of the Nantucket shoals region (Figure 4.3.7). Far fewer sightings were recorded along the mainland coast, although waters within Stellwagen Bank NMS exhibited several cells with high prevalence.

Spatial pattern predictions were best explained by SST and chlorophyll *a* concentration, along with depth, slope and turbidity contributing substantially to the explained variation (Table 4.3.1). Highest IRP was predicted for the shoals of Georges Bank and Nantucket, and the sloping coastal shelf (<100 m isobath) in the northern Gulf, and south of Nova Scotia extending to Browns Bank and throughout the Bay of Fundy (Figure 4.3.8). High IRP was also predicted for the mouth of Buzzards Bay and Rhode Island Sound. Southeast sections of the Gulf of Maine (Cape Cod Bay and deeper waters immediately southeast of the Cape) had very low predicted values.

Winter: Similar widespread distribution patterns were evident for Greater Shearwaters in winter, although markedly fewer occurrences (n = 1321) were recorded when compared with summer (Figure 4.3.7). Most sightings occurred over Georges Bank and the Great South Channel, with birds less frequently sighted using nearshore waters.

The predicted winter distribution of Greater Shearwater (Figure 4.3.8) was driven by distance to shore and chlorophyll *a* concentration (Table 4.3.1). Spatial patterns were less complex than the summer model, but similarly, the prediction indicated a slight preference for the central waters of the Gulf of Maine, rather than coastal regions. Deeper waters (>180 m depth) over Wilkinson Basin, the sloping shelf (50 – 100 m depth) south of Nantucket Island, and the shallow (<50 m depth) waters of Georges Bank received marginally higher IRP. Low IRP was predicted for the shallowest waters (< 80 m depth) along the entire nearshore zone of the Gulf of Maine.

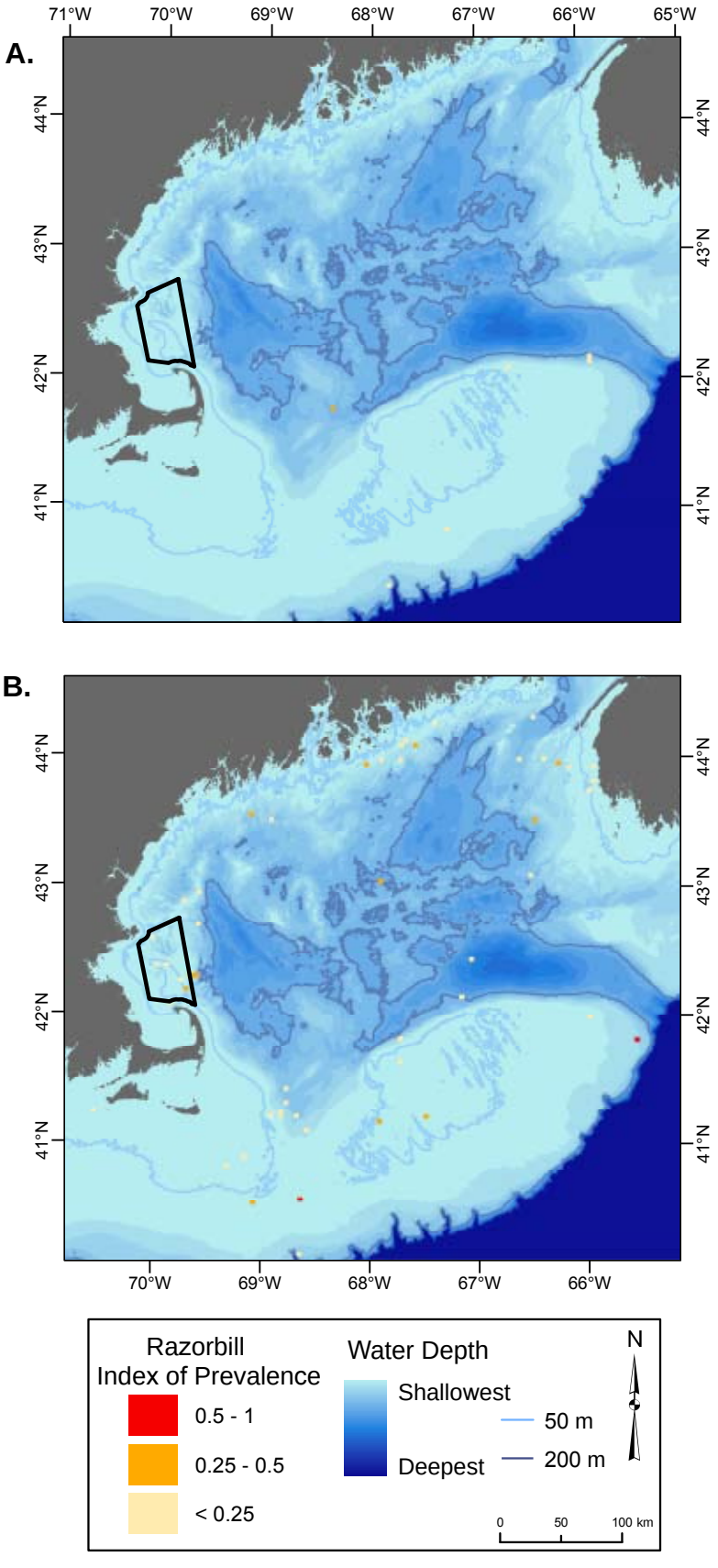

Figure 4.3.6. Seasonal Razorbill distribution patterns in the Gulf of Maine based on effort corrected presence data for (a) summer, and (b) winter seasons. Predictions are not shown for this species due to an insufficient number of sightings.

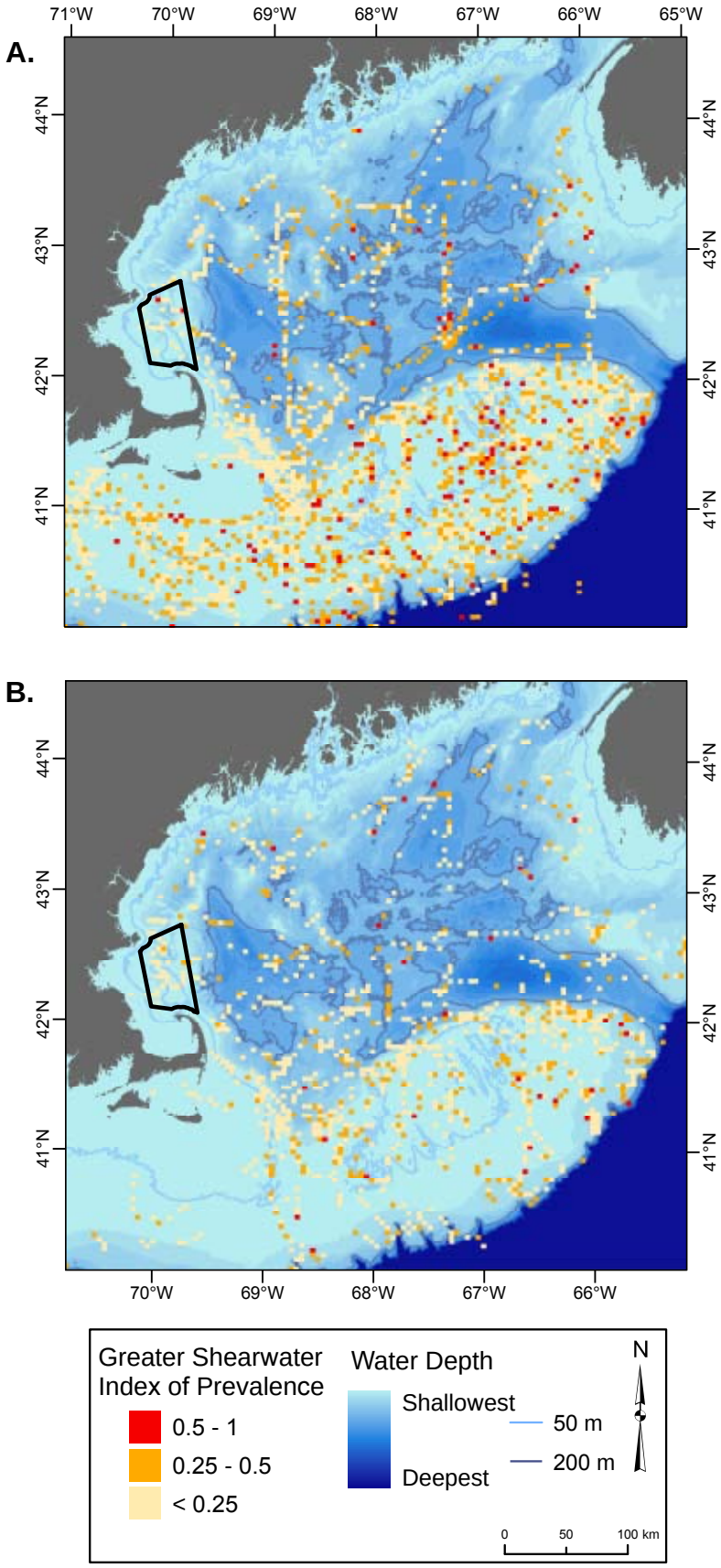

Figure 4.3.7. Seasonal Greater Shearwater distribution patterns in the Gulf of Maine based on effort corrected presence data (Index of Relative Prevalence) for (a) summer, and (b) winter seasons.

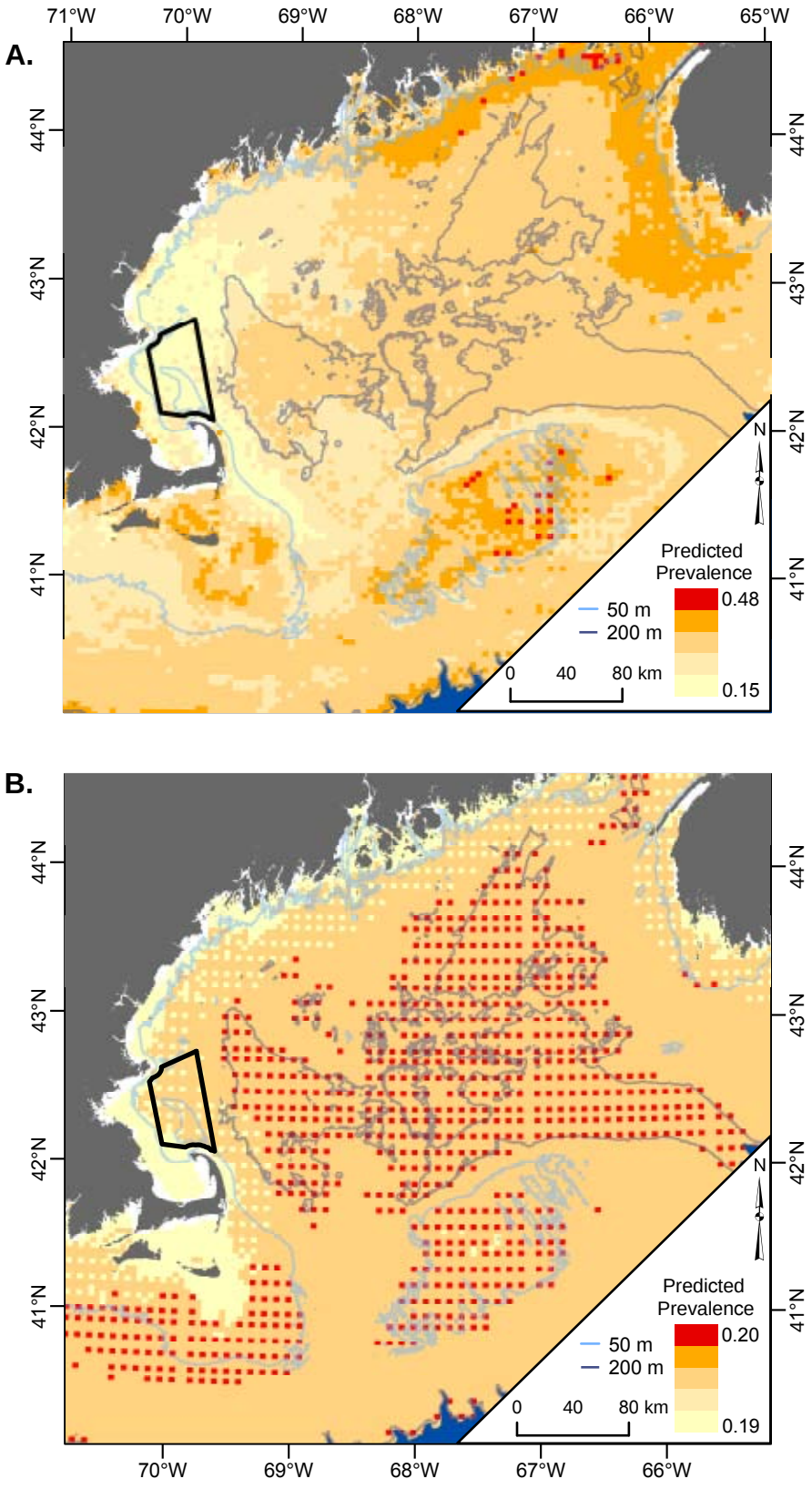

Figure 4.3.8. Seasonal Greater Shearwater predictions of relative prevalence in the Gulf of Maine for (a) summer and (b) winter. TreeNet predictions were based on the statistical relationship between effort corrected presence and a set of environmental variables. Note that the range of predicted values varies between summer and winter models.

Northern Gannet (*Morus bassanus*)
Summer: Sightings were recorded on a total of 748 transects. Northern Gannet were sighted more frequently in the southern Gulf of Maine and over Georges Bank, and the Great South Channel, although prevalence was relatively low (Figure 4.3.9). Hotspots of prevalence were recorded for a few areas off Nova Scotia, Jordan Basin, Northeast Channel and Georges Bank.

The spatial predictions (Figure 4.3.10) showed distinct hotspots for Northern Gannets, with patterns of prevalence determined mostly by SST and depth (Table 4.3.1). Highest IRP was predicted for the nearshore waters around southern Nova Scotia and the central Bay of Fundy. High values also were predicted over deeper water basins such as Georges Basin, Wilkinson Basin, and Sharrer Basin (immediately east of Stellwagen Bank NMS), as well as Rodgers Basin and Jordan Basin (north central Gulf of Maine). Other features with high prevalence included Browns Bank, Grand Manan Banks, Davis Bank (south of Cape Cod) and the slopes (50-70 m depth) of Georges Bank. In contrast, relatively few birds were predicted for most of the very nearshore zones. Areas with lowest IRP included Stellwagen Bank NMS, the Cape Cod region, the deeper (>30 m depth) edges of Davis Bank, the steeply sloping (> 70 m depth) northern edges of Georges Bank and the waters between Georges Bank, and the continental shelf edge.

Winter: Northern Gannet were more frequently sighted in winter (n= 2096 transects). The largest cluster of high IRP prevalence values was recorded for the area of shelf slope south of Nantucket. Less aggregated patterns of high values were also found across Georges Bank and the deeper waters west of southern Nova Scotia, between Lurcher Shoal and German Bank (Figure 4.3.9). Birds were widespread, albeit at relatively low prevalence, from the Great South Channel northwards through Stellwagen Bank NMS and along the coast of Maine.

SST and turbidity variables determined the predicted pattern during winter (Table 4.3.1). High prevalence was predicted for the southern edges of Nantucket Shoals and the slope (between 40 and 70 meter isobaths) south of Martha's Vineyard (Figure 4.3.10). Relatively high prevalence was also predicted for the very nearshore waters along the Maine coastline and the shoals of Georges Bank. Overall, low prevalence was predicted throughout much of the Gulf of Maine, with lowest values (almost absent) for the very shallow (<30 m depth) waters of Nantucket Sound.

Wilson's Storm-petrel (*Oceanites oceanicus*)
Summer: Sightings were recorded at a total of 2,713 transects. Birds were widely distributed throughout the Gulf of Maine in summer, but with few birds sighted nearshore (Figure 4.3.11). Highest prevalence was recorded for the slopes at greater depth leading to the continental shelf edge. Clusters of high IRP were found for the Outer Schoodic Ridge and Jordan Basin (north western Gulf of Maine), and an area south east of Seguin Island, Maine.

The predicted distribution pattern for Wilson's Storm-petrel (Figure 4.3.12) was driven by depth, chlorophyll *a* concentration and SST (Table 4.3.1). Highest IRP was predicted for Georges Basin (north of Georges Bank), the entrance to the Northeast Channel, and the waters around the basins and ledges in the south central Gulf of Maine to the east of Stellwagen Bank NMS. Very low IRP was predicted for shallow coastal regions, the Nantucket region, and much of Georges Bank, particularly the shoals.

Winter: Very few (n = 23 transects) Wilson's Storm-petrel were sighted within the Gulf of Maine in winter (Figure 4.3.11). These sightings were almost entirely confined to Georges Bank and the Great South Channel. The prediction was driven by slope and distance to shore (Table 4.3.1). Insufficient numbers of sightings were recorded to develop predictive maps during winter.

Patterns of Multi-Species Occurrence
The average value of effort corrected number of species based on all eight seabird species selected for this study combined (Razorbill, Common Murre, Thick-billed Murre, Black Guillemot, Dovekie, Greater Shearwater, Northern Gannet and Wilson's Storm-petrel) was used to represent species richness patterns for the selected species.

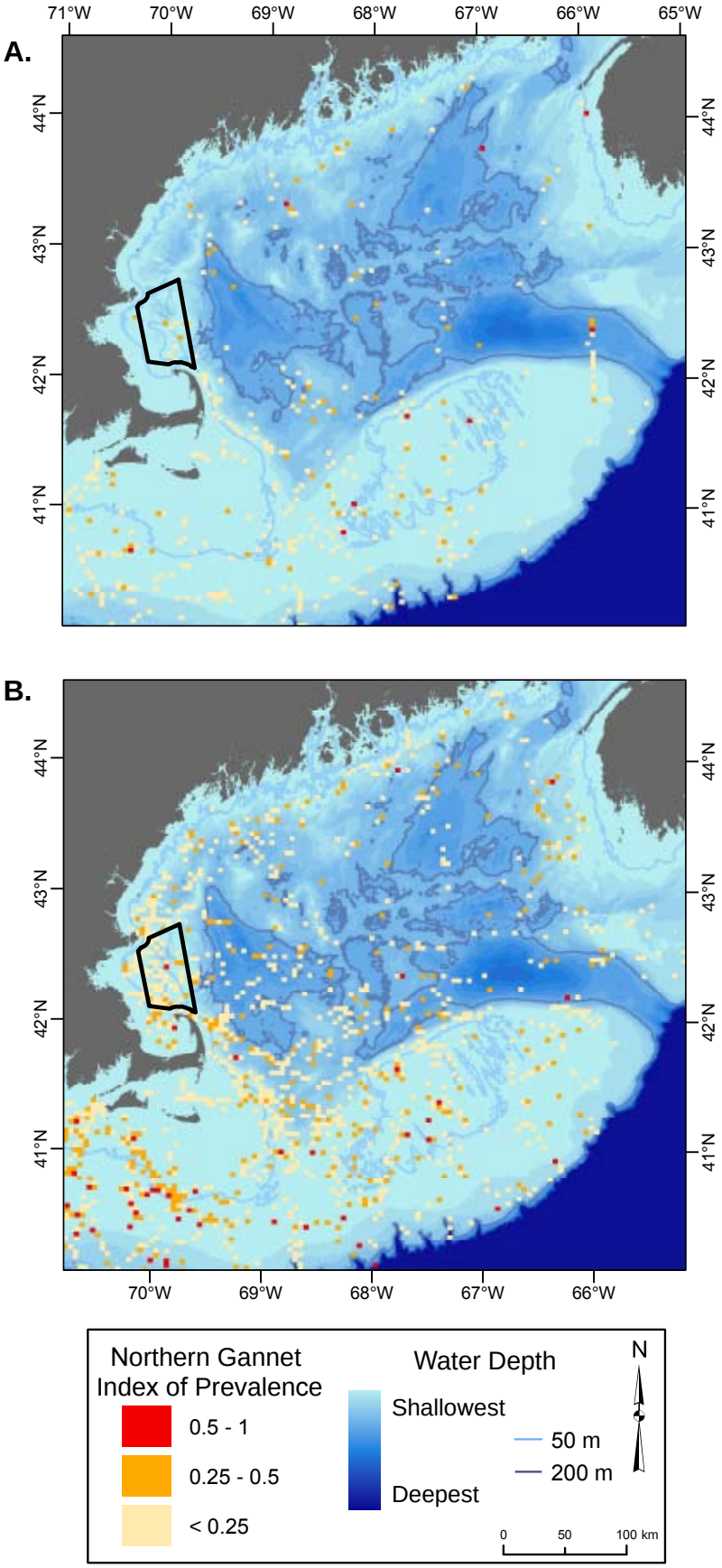

Figure 4.3.9. Seasonal Northern Gannet distribution patterns in the Gulf of Maine based on effort corrected presence data (Index of Relative Prevalence) for (A) summer, and (B) winter seasons.

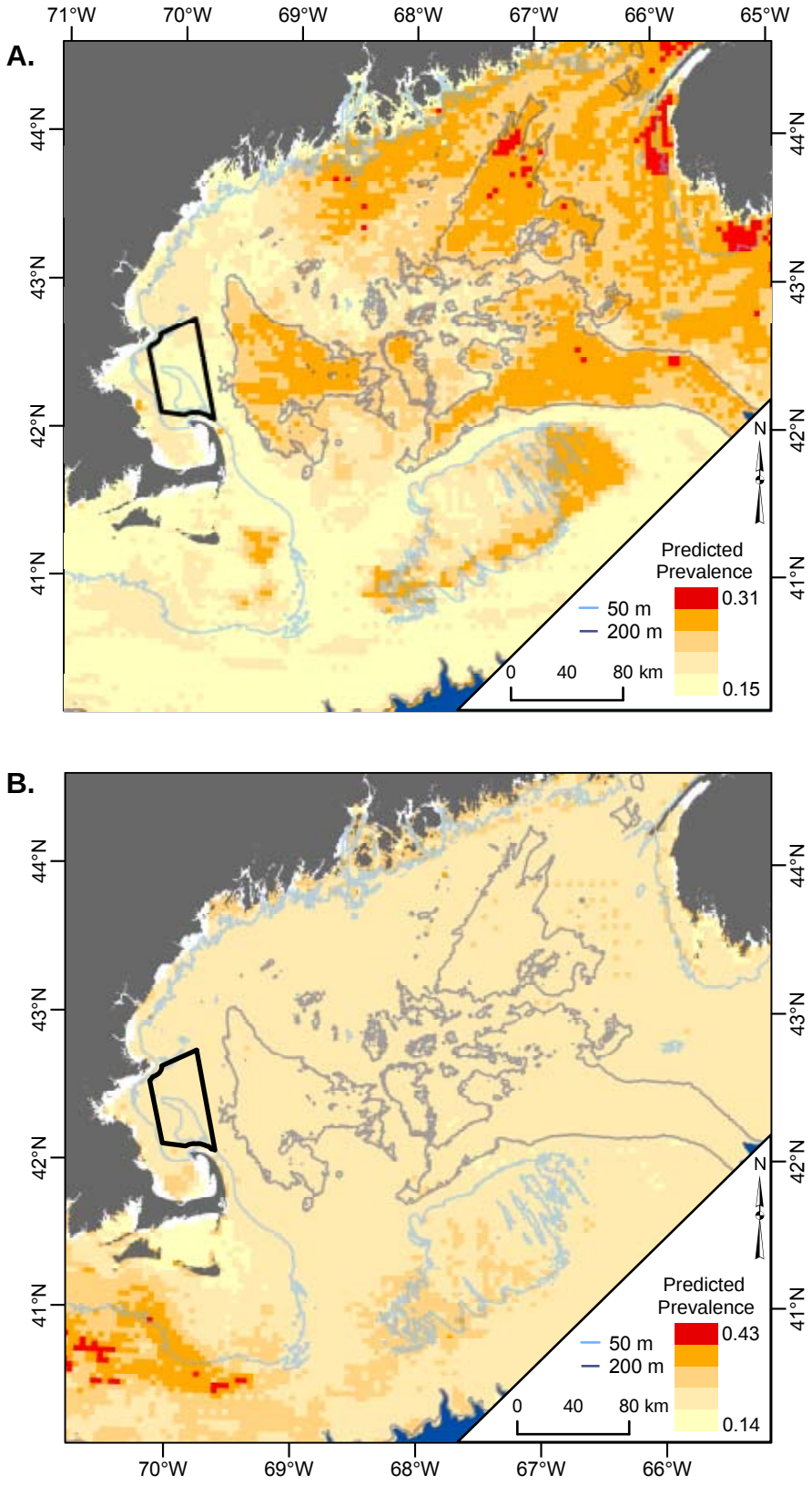

Figure 4.3.10. Seasonal Northern Gannet predictions of relative prevalence in the Gulf of Maine for (a) summer and (b) winter. TreeNet predictions were based on the statistical relationship between effort corrected presence and a set of environmental variables. Note that the range of predicted values varies between summer and winter models.

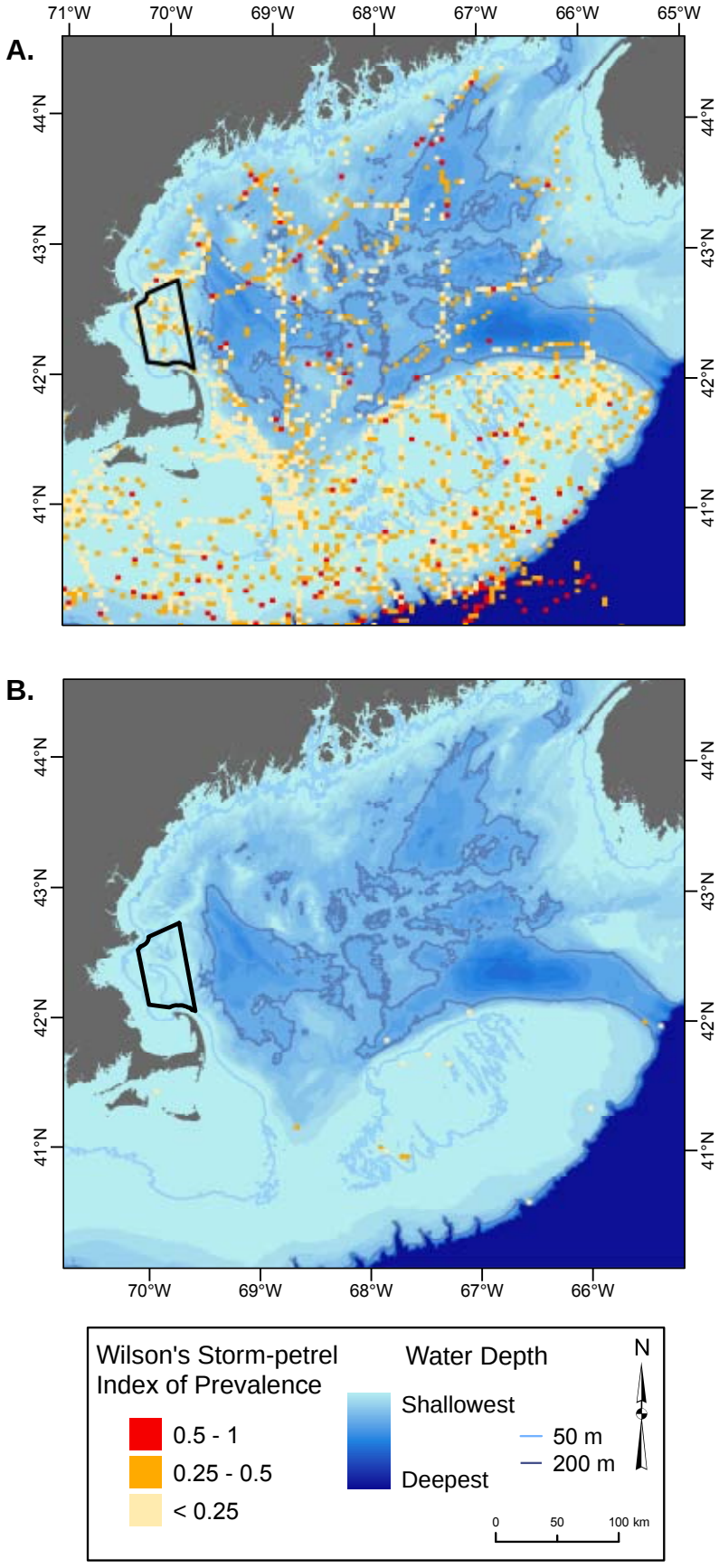

Figure 4.3.11. Seasonal Wilson's Storm Petrel distribution patterns in the Gulf of Maine based on ef fort corrected presence (Index of Relative Prevalence) data for (a) summer, and (b) winter seasons.

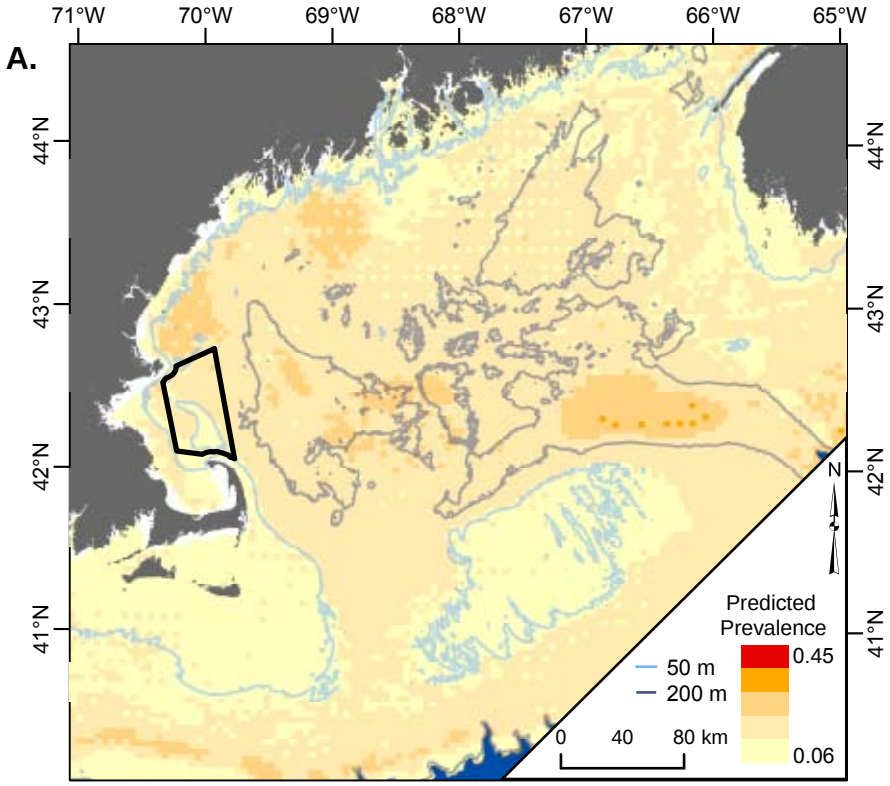

Figure 4.3.12. Seasonal Wilson's Storm Petrel predictions of relative prevalence in the Gulf of Maine for (a) summer. TreeNet predictions were based on the statistical relationship between effort corrected presence and a set of environmental variables. Insufficient sightings were available to develop a predictive model for winter distributions.

Summer: The mapped values showed that species co-occurrence was relatively high across the region, with species richness hotspots occurring along the sloping edges of Georges Bank, the edge of the continental shelf, the shoals of Georges Bank, the edge of the North East Channel, the Great South Channel, and several of the central Gulf basins and ledges (Figure 4.3.13). Species co-occurrence within Stellwagen Bank NMS was also relatively high. In contrast, several cold spots were identified along the shoal waters southwest of Martha's Vineyard, the steeply sloping edge of Davis Bank, and northward along the Boston Harbor Traffic Lane past Cod Cape.

Winter: No obvious spatial trends emerge from the average effort corrected number of species for winter (Figure 4.3.13). Isolated hotspots appear on Georges Bank and the edge of the Great South Channel and Northeast Channel, as well as the Stellwagen Bank region and the waters between southern Nova Scotia and the Grand Manan Banks.

Patterns of mean number of species

An alternative representation of seabird diversity was produced using all 60 species (excluding all unknown species) by calculating a mean value from all transects within a grid of 5 x 5 minute cells for summer and winter. The influence of amount of effort in determining species richness was considered minimal across the region as a whole. Mean number of species was not highly correlated with survey effort for summer or winter (r^2 = 0.3 and 0.37, respectively). In fact, the locations with highest mean number of species received only low to intermediate levels of effort. Note that due to variance in detectability, the number of species identified during these surveys (1980-1988) is almost certainly an underestimate of the total number of species that use the region. This is compounded by the fact that some rare or infrequently-seen species are likely to have been recorded as unidentified species (i.e. unidentified gulls, terns, auks, ducks, cormorants etc.).

Summer: The maximum mean number of species during winter was nine seabirds. High mean number of species are clustered around a few hot spots mainly in the southern Gulf of Maine and slope waters south of Nan-

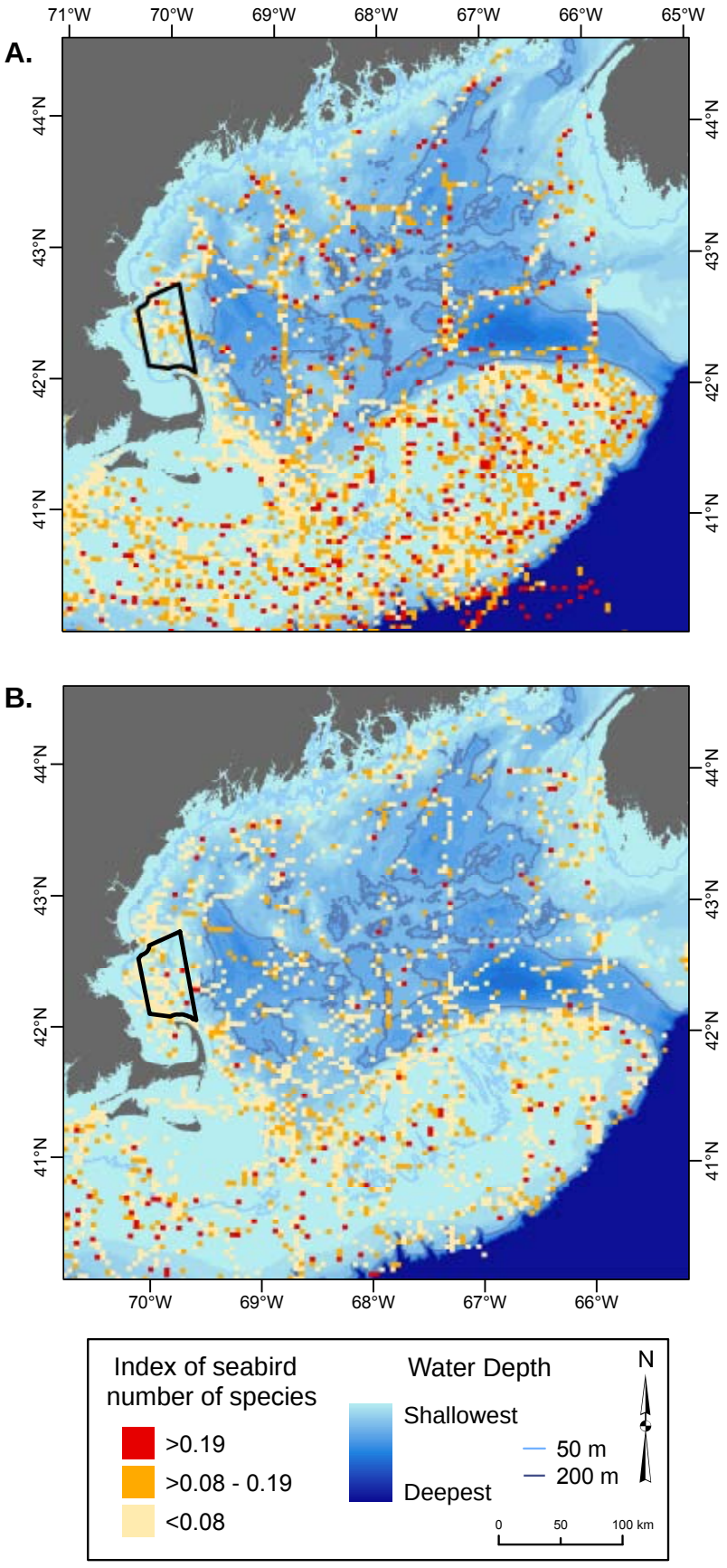

Figure 4.3.13. Seasonal effort corrected number of seabird species using the eight focal seabirds for (a) summer, and (b) winter seasons.

tucket Shoals (Figure 4.3.14). Areas of relatively high species richness were also found along the northern coast of Maine and along the Great South Channel northward to Cape Cod.

Winter: The maximum mean value for winter was 12.3 seabirds. Winter hotspots for mean number of species included Stellwagen Bank, Nantucket Sound and nearby waters on the slopes of Davis Bank, the Northeast Channel and Browns Bank, and the waters near Franklin Swell and Powell Swell north of Georges Bank (Figure 4.3.14). Further north, high mean number of species occur near the mouth of the Bay of Fundy around Grand Manan Banks.

Seabird utilization of Stellwagen Bank National Marine Sanctuary

The Stellwagen Bank NMS region supported all focal species in either one or both seasons. Non-breeding summer migrants (Greater Shearwater and Wilson's Storm-petrel) were particularly prevalent within Sanctuary waters. Analysis of MBO data for 1980 to 1988 revealed that Stellwagen Bank NMS supported a higher number of species during winter months than summer months, with a maximum mean value of eight seabird species per 5 x 5 minute cell in winter. In winter, the majority of cells supported a mean greater than four species. Highest seabird diversity was recorded over the northern tip of Stellwagen Bank and southern Tillies Basin. In summer months, the maximum mean number of species using Stellwagen Bank NMS was four, with highest mean number of species occurring over the central Stellwagen Bank area and Tillies Basin.

Patterns of prevalence indicated that auks used Stellwagen Bank NMS more in winter than summer. Highest auk prevalence (0.5) was recorded in winter at the southern end of the Stellwagen Bank and northern tip of Cape Cod (0.75). Highest prevalence for auks in winter over the southern tip of Stellwagen Basin was also predicted in the model. Similar seasonal use patterns were found for Razorbill, with absence in summer and intermediate level prevalence in the southern Stellwagen Bank NMS in winter. Greater Shearwater were more prevalent than auks in both winter and summer seasons, with sightings recorded from most cells within the Stellwagen Bank NMS region. Tillies Basin supported highest prevalence, particularly in the summer months. Northern Gannet were widespread throughout the Stellwagen Bank NMS in winter with highest prevalence in the south and central portions of the Sanctuary. Northern Gannets were also recorded in summer, although they were both less widespread and less prevalent than in winter. Wilson's Storm-petrel was also distributed throughout the Stellwagen Bank NMS in summer with highest prevalence over shallow waters on central Stellwagen Bank and over deeper waters of Tillies Basin. Wilson's Storm-petrel was not recorded within the sanctuary during winter months.

4.4 DISCUSSION

Despite extensive survey work across multiple disciplines, the offshore distribution of seabirds in the Gulf of Maine has not been well studied. This project is the first attempt to develop quantitative predictive models to map seabird species distributions for the Gulf of Maine region. The effort corrected relative occurrence maps and spatial prediction maps presented here link multiple species of pelagic seabirds to their environment across the entire Gulf of Maine. Previous ecological analyses in the region have been limited to nesting sites alone, single species, at much finer spatial scales. Both relative abundance maps and predictive modeling reveal that several species exhibit distinct distribution patterns including some localized hotspots of occurrence. Bathymetric features such as the coastline, the nearshore slopes along the northern sections of the Gulf of Maine, as well as bathymetric features such as Georges Bank, the Great South Channel and the Northeast Channel, and the waters offshore from the southern tip of Nova Scotia appear to represent distinct features within the Gulf of Maine ecosystem supporting a high diversity and abundance of seabirds. Further studies are required to determine their ecological significance and to further elucidate on the spatial and temporal dynamics of seabird species utilization patterns and ecological interactions for these areas.

Predictive modeling determined that these patterns were influenced by a species-specific (or group-specific) suite of environmental variables. Overall, depth and sea surface temperature were the most important predictors and further studies are required to examine the significance of these variables for the selected species and in characterizing habitat types for seabirds, as well as explaining offshore distribution patterns in the Gulf of Maine region.

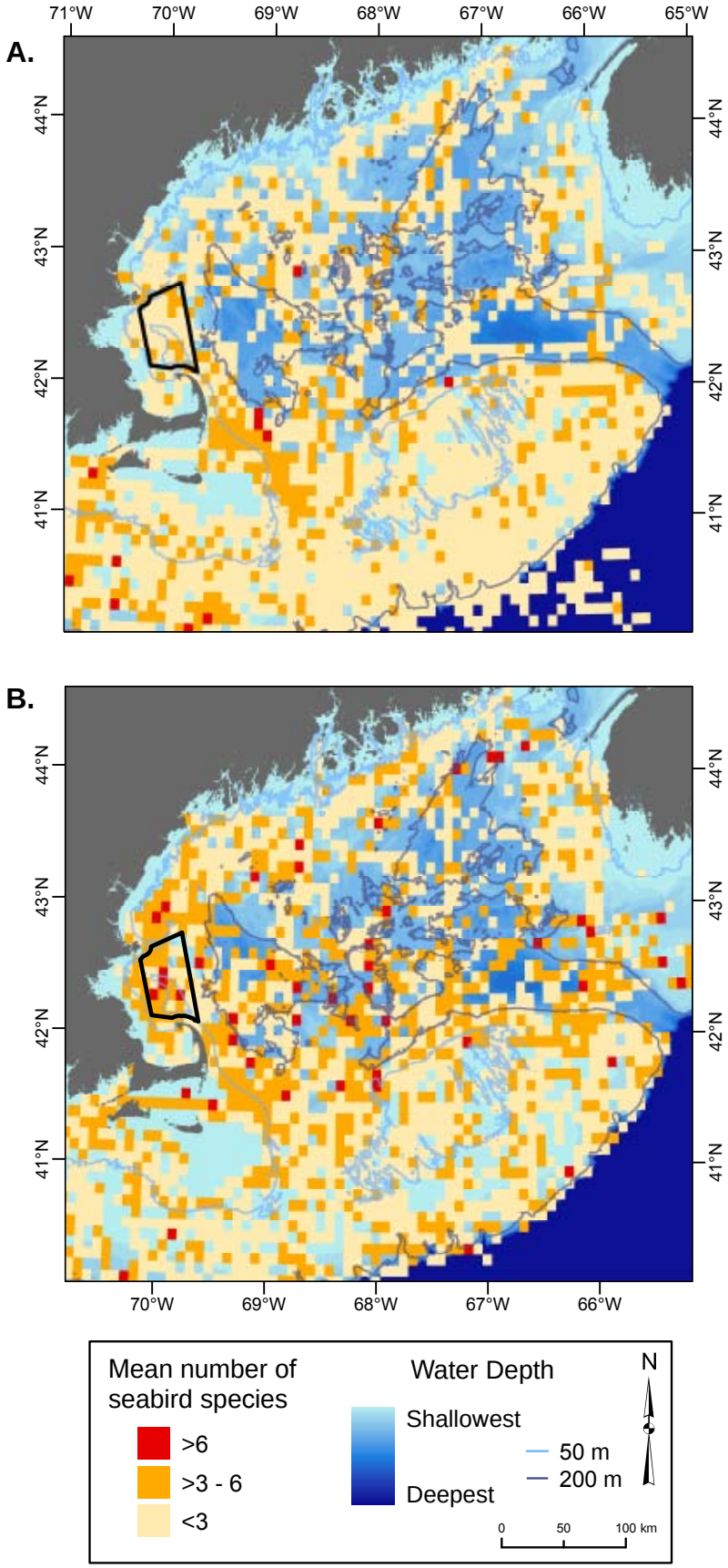

Figure 4.3.14. Mean number of seabird species using all 60 species calculated in 5 minute bins for (a) summer, and (b) winter seasons.

Northern Gannet responded similarly to variability in environmental variables in both summer and winter, with the center of high prevalence shifting southward in winter. For all other species, the relative influence of key environmental predictors varied between seasons. Sea surface temperature was an important predictor for three species (Wilson's Storm-petrel, Northern Gannet and Greater Shearwater) in both summer and winter seasons. Chlorophyll *a* concentrations also were important for Wilson's Storm-petrel and Greater Shearwaters in both seasons. Depth was important for Wilson's Storm-petrel and Razorbill in summer and for all auks in winter. Slope was important for Wilson's Storm-petrel in winter, but for auks only in summer. In contrast, distance to the shelf edge appeared to be of lower importance for these species, while distance to shore was more relevant to the pelagic non-breeding migrants such as Greater Shearwaters and Wilson's Storm-petrel, than for local breeders (such as Gannets and auks), which tend to be distributed closer to shore.

Model Interpretation, Limitations and Research and Management Implications

Both the effort-corrected presence maps and the prediction maps can be used to rank regions of seabird occurrence, which in turn may indicate areas of relative habitat preference, or even relative habitat quality. Table 4.4.1 lists the summer and winter prevalence hotspots and coldspots for all auks, Greater Shearwater, Northern Gannet and Wilson's Storm-petrel in the Gulf of Maine study area. This can be used to prioritize future ecological studies of seabirds. Although only a part of the complex picture, distribution models have frequently been put to good use for a variety of management purposes, such as locating areas of high prevalence or low prevalence to support designation and re-evaluation of MPA's, or the development of sensitivity maps related to current or future human activity (Huettmann, 2000; Wiese et al., 2001; Wiese, 2002; Yen et al., 2004a). For instance, hotspots of prevalence may coincide with proposed wind farm developments, offshore oil and gas installations, fishing activity patterns or pollution events, such as chronic oil spills or effluent outflow sites. Although information on seasonal spatial patterns is valuable baseline information, it may not be sufficient on its own for purposes of impact assessment, where other factors such as animal health, reproduction and survival should be taken into account (Morris and Doak, 2002).

The resultant models have great value at estimating broad-scale spatial patterns of seabird prevalence across the study region and should be interpreted in a relative sense. These gradients of prevalence allow us to view specific sub-regions in a broader spatial context. Furthermore, a quantitative linking to the environment provides some insight into potential direct and indirect ecological mechanisms that could provide valuable information for predicting the influence of environmental change. Predicting the distribution of highly mobile birds, however, is problematic, particularly when insufficient information is available to guide scale selection (Guisan et al., in press). Consequently, it is important to consider that values presented here may not represent 'true presence' or 'true absence'. Nor can sound inferences be made to actual population sizes (Boyce and McDonald, 1999; Huettman, 2001). Further research is required to substantiate the analytical results (e.g. model validation), particularly since model selection is known to be influenced by scale, data quality and even the algorithm used for developing the prediction. We recommend that future efforts be used to validate the major findings from this study. For instance, the accuracy of predicted hot- and coldspots should be assessed using high quality alternative data and then updating the models incrementally. Currently, such data do not exist with sufficient spatial coverage, but nevertheless are urgently needed for the region. Instead, we propose using both peer-review and local expert knowledge to generate a level of consensus on the accuracy and interpretation of the model.

Finally, it is also unclear what our predictions mean in relation to the entire flyway for each species and for populations or even life stages (i.e. juveniles and adults). Few studies have tracked movement patterns, therefore little is known about even the daily movement activities of individual seabirds in the Gulf of Maine. Consequently, further studies are required to investigate movement patterns in relation to the multi-scale ecological processes underlying the spatial and temporal patterns presented here. Furthermore, analytical techniques similar to those applied here could be used to develop predictive models for several other numerically abundant species (i.e. Herring Gull, Great Black-backed Gull, terns, kittiwake etc.) across time and space.

Table 4.4.1. Hotspots and coldspots of prevalence for selected seabird species/group for the Gulf of Maine study area based on effort corrected presence data for both summer and winter seasons.

All auks	
Summer Hotspots	***Winter Hotspots***
Nearshore Maine	Georges Basin
Southern Nova Scotia	Nearshore Slope (60-100 m) Maine
Shoals of Georges Bank	Southern Nova Scotia
Nantucket Shoals	
Stellwagen Bank	
Summer Coldspots	***Winter Coldspots***
Cape Cod Bay	Cape Cod Bay (<40 m)
Slopes of Georges Bank (60-100m)	Shallow inshore/nearshore Maine
Slopes (>60 m) south of Martha's Vineyard	Nantucket Shoals (<40 m)
	Georges & Cultivator Shoals (<40 m)

Northern Gannet	
Summer Hotspots	***Winter Hotspots***
Southern Nova Scotia	Slope South of Martha's Vineyard
Bay of Fundy	Georges Shoals
Georges Basin	Shallow Nearshore Maine
Wilkinson Basin	Shallow Nearshore Nova Scotia
Rogers & Jordon Basin	
Grand Manan Banks	***Winter Coldspots***
Browns Bnak	Nantucket Sound (<30 m)
Davis Bank	
Slopes of Georges Bank (50-70 m)	
Summer Coldspots	
Stellwagen Bank NMS	
Slope waters of Georges Bank (>70 m)	
Great South Channel	
Nantucket Sound	

Greater Shearwater	
Summer Hotspots	***Winter Hotspots***
Shoals on Georges Bank	Central Gulf of Maine
Nantucket shoals	Wilkinson Basin
Northern Maine nearshore slope	Shelf south of Nantucket (>60 m)
Southern Nova Scotia	Georges Shoals (<50 m)
Bay of Fundy	
Browns Bank	
Summer Coldspots	***Winter Coldspots***
Cape Cod Bay	Shallow nearshore (<80 m)
Stellwagen NMS	Cape Cod Bay
Slope of Davis Bank	Nantucket Shoals
New Hampshire Coast	

Wilson's Storm-petrel	
Summer Hotspots	
Georges Basin	
Entrance Northeast Channel	
Basins and ledges south central Gulf of Maine	
Seaward of continental Shelf edge	
Summer Coldspots	
Shallow Nantucket region	
Shallow Georges Shoals	
Shallow nearshore Maine and Nova Scotia	

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CHAPTER 5 - CETACEAN DISTRIBUTION AND DIVERSITY

Simon Pittman, Bryan Costa, Connie Kot, David Wiley, and Robert D. Kenney

5.0 OBJECTIVES

The effective management and conservation of cetaceans within SBNMS and the wider Gulf of Maine requires baseline information in the form of accurate and spatially explicit maps of cetacean abundance, as well as characterizations of cetacean-environment relationships. Information on the spatial and temporal distribution of cetaceans can be a valuable tool in the analysis and mitigation of threats from human activity. In addition, investigating cetacean-environment relationships can be extremely useful for: (1) identification and characterization of high-use areas; (2) prediction of spatial and temporal shifts associated with environmental change (Hamazaki, 2002; Redfern *et al.,* 2006); (3) interpretation of historical population trends estimated from sightings data; and (4) optimization of cetacean survey designs (Forney, 2000).

To examine cetacean-environment relationships and the spatial and temporal patterns of relative abundance in the southern Gulf of Maine, cetacean abundance across the region was mapped and seasonal species patterns were interpreted. A wide range of environmental variables that include key ambient water parameters, bathymetric structure, and prey densities were also mapped for each season. The spatial extent of the study area included known feeding grounds and other high-use areas, such as corridors of cetacean movement within the SBNMS and the surrounding southern Gulf of Maine.

5.1 INTRODUCTION

Whales, dolphins, and porpoises are long-lived marine mammals known collectively as cetaceans within the superorder Cetartiodactyla. Cetacea is divided into two suborders: (1) Mysticeti (baleen whales) and (2) Odontoceti (toothed whales). The baleen whales are characterized by having baleen plates for filtering food from water and are comprised of four families: Balaenidae (bowhead and right whales); Balaenopteridae, or Rorquals, (minke, sei, blue, fin, Bryde's and humpback whales); Eschrichtiidae (gray whale) and Neobalaenidae (pygmy right whale) (Rice, 1998). Toothed whales are generally smaller-bodied than baleen whales, with the exception of the sperm whale and a few of the larger beaked whales. They are comprised of 10 families, with the Delphinidae (marine dolphins), Phocoenidae (porpoises) and Ziphiidae (beaked whales) being the most speciose families (Rice, 1998). Cetaceans are widely distributed throughout the world's oceans and are capable of travelling large distances relatively rapidly, but also show site fidelity to specific feeding grounds and calving areas. In many regions, they are considered key predators of small fish, zooplankton and squid. Relative to many other marine animals, they exhibit low fecundity. These biological characteristics, coupled with their dependence on specific prey types, mean that cetaceans also function as important bioindicators of the health and productivity of marine ecosystems (Reijnders *et al.,* 1999; Greene *et al.,* 2003).

Cetaceans in the Gulf of Maine

The territorial waters of the United States (U.S.) support a wide diversity of cetaceans (approximately 60 species), with many areas recognized as critical habitat for endangered cetaceans (Read and Wade, 2000). The Gulf of Maine region, which includes Georges Bank, is regularly utilized by at least 13 species of cetacean (Hain and Waring, 1994), primarily for feeding although they have also been observed mating and nursing their young in the area. The spring-fall distribution of North Atlantic right whales is centered in the Gulf of Maine and adjacent waters (Winn *et al.,* 1986), with five of the six known major congregation areas either within or bordering the Gulf of Maine (NOAA, 2005a). To help protect these animals, critical habitats for North Atlantic right whale were designated by the U.S. and Canada in July 1994 for the Great South Channel, Cape Cod Bay, Bay of Fundy, and the Scotian Shelf (Figure 5.1.1 for U.S. designations). The Gulf of Maine is also recognized as an area that provides resources for one of four geographically and possibly genetically discrete subpopulations of the endangered humpback whales (*Megaptera novaengliae*) in the western North Atlantic (Katona and Beard, 1990; NOAA, 2005b). Two other aggregations on feeding grounds have been identified off Iceland and northern Norway. Cetaceans are consumers of fish, zooplankton, and squid in the region, with a significant trophic overlap with commercial fisheries (Kaschner *et al.,* 2001). Kenney *et al.* (1997) calculated that cetaceans consumed a total of 638,000 tons of prey annually in the Gulf of Maine: 86% were fish, 12.7% zooplankton, and less than 1.5% were squid. Atlantic herring (*Clupea harengus*) are an important prey item for many of the cetaceans in

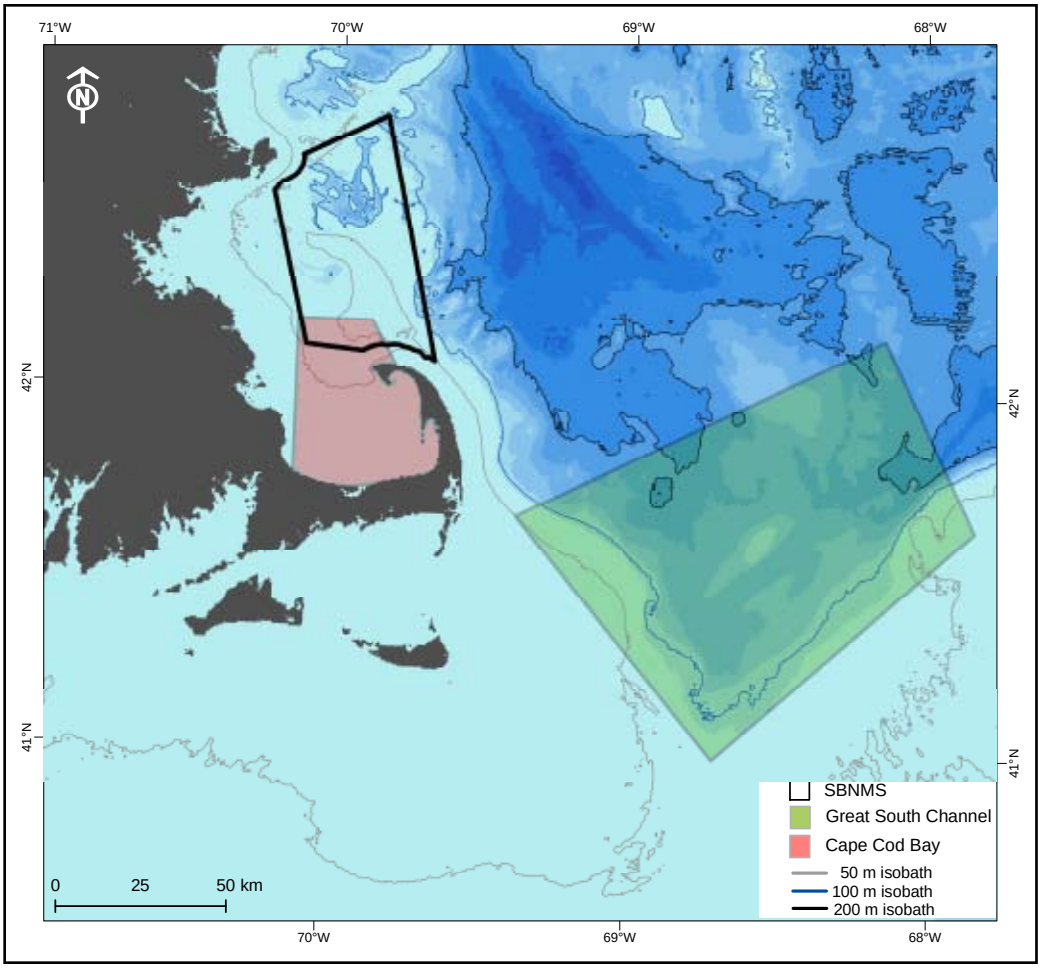


Figure 5.1.1. Critical habitat designations for North Atlantic right whale established in 1994 in the southern Gulf of Maine. These areas are designated as part of the Atlantic Large Whale Take Reduction Plan legislated under the Marine Mammal Protection Act with temporal closures for the gillnet fishery and lobster fishery.

the region, comprising approximately half of the prey items for harbor porpoise and white-sided dolphin, 34% of the prey for minke whale, and 17% of the prey for both humpback and fin whales (Read and Brownstein, 2003). Two of the large whales (sei and North Atlantic right whale) that use the Gulf of Maine are planktivorous, feeding almost entirely on zooplankton such as calanoid copepods and krill.

The southern Gulf of Maine, particularly the region from the Great South Channel to Stellwagen Bank and Jeffreys Ledge, is considered to support the highest densities of cetaceans on the northeast U.S. continental shelf (Kenney and Winn, 1986). Consistent aggregations of baleen whales occur in Cape Cod Bay and Massachusetts Bay in late winter and early spring, the Great South Channel in late spring and the lower Bay of Fundy, Scotian Shelf and Jeffreys Ledge in the summer and fall (Reeves and Kenney, 2003). Humpback, fin and right whales exhibit strong maternal fidelity to specific feeding grounds in the southern Gulf of Maine. Clapham and Seipt (1991) and Weinrich (1998) found that individuals who visited Stellwagen Bank and Jeffreys Ledge as calves were more likely to return in subsequent years. High return rates have also been reported for humpbacks using Massachusetts Bay, with as many as 85% of individuals observed in one year returning the next (Mayo *et al.,* 1988). Although cetaceans appear frequently at specific locations, tracking of individual movements elsewhere in the Gulf of Maine suggests that some individuals may carry out extensive broad ranging movements (Mate *et al.,* 1997; Read and Westgate, 1997; Baumgartner and Mate, 2005) with some travelling large distances (> 2,000 km) in a matter of days before returning to the tagging area (Baumgartner and Mate, 2005). Regardless of the apparent variability of space use patterns, certain areas have distinct environmental characteristics that result in persistent aggregations of individuals of several species from year to year.

Threats to cetaceans

Vessel impact

Increases in the size and speed of vessels have resulted in a corresponding increase in vessel impacts (Laist *et al.,* 2001). Moore *et al.* (2005) found that as many as 14 out of 30 right whales that received post-mortem examinations between 1970 and 2002 died because of vessel collision. Wiley *et al.* (1995) reported that 30% of humpback whales stranded along the U.S. Atlantic coast between 1985 and 1992 had injuries caused by ships. Using data on vessel traffic and right whale density, Nichols and Kite-Powell (2005) predicted 1.9 potential ship strikes of right whales per year for Cape Cod Bay.

All cetacean species in the current study exhibited space-use patterns that coincided with areas intensively utilized by boat traffic for fishing, commercial shipping, military operations and recreational activity. In the southern Gulf of Maine region five major corridors of vessel traffic pass directly through the Stellwagen Bank National Marine Sanctuary (SBNMS) and two major corridors transect the Great South Channel right whale critical habitat area (Ward-Geiger *et al.,* 2005). The main Boston shipping channel transects cetacean high-use areas across southern Stellwagen Bank and southward along the 100 m isobath and Great South Channel (Figure 5.1.2). This still presents an unresolved conflict of interests since vessel strikes and entanglement in fishing gear are considered severe threats to large whales in the southern Gulf of Maine. Approximately one-third of all right whale mortality is caused by human activities of which 20-30% is attributed to ship strikes (Kraus, 1990).

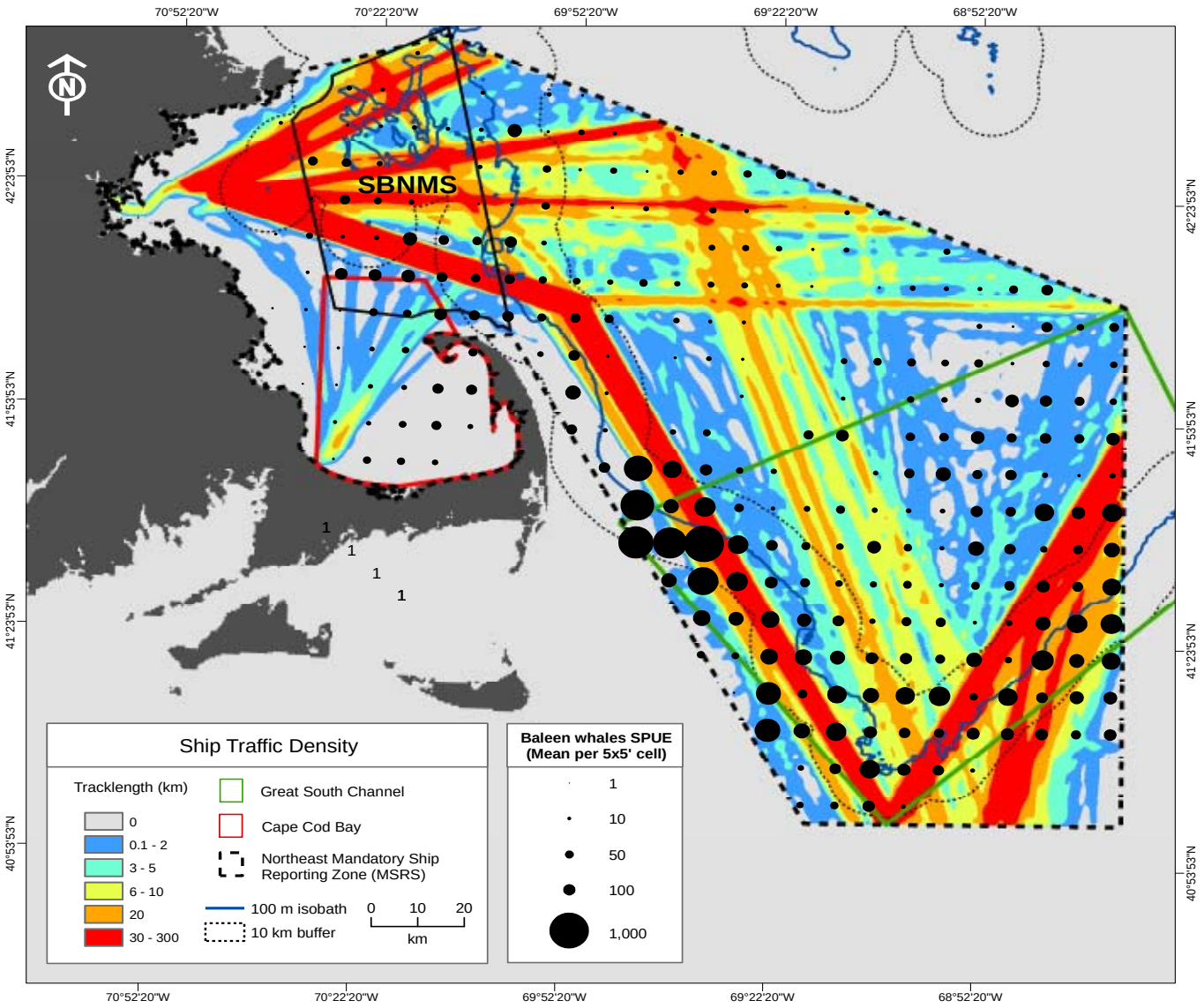
In an attempt to reduce this threat a vessel reporting system has been active since July 1999. The reporting system, known as the Mandatory Ship Reporting System (MSRS) requires all commercial ships greater than 300 tons to report their positions when entering areas close to right whale critical habitat, so that they can then be notified of whale distributions and avoid impacts.

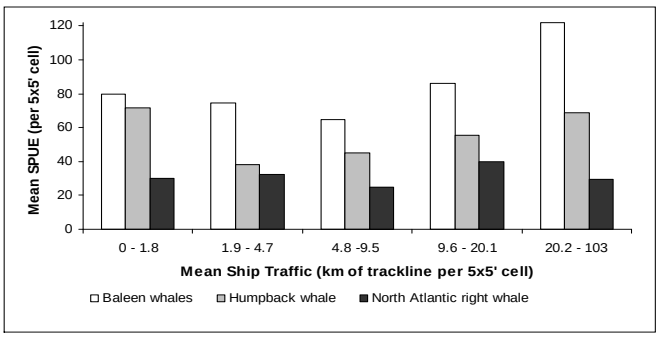
Fishery interactions

High densities of cetaceans, particularly piscivorous species, are typically found in areas of high fishing intensity (Kaschner *et al.,* 2001). This co-occurence increases the likelihood of entanglement in fishing gear, a significant cause of cetacean injury and mortality in many regions of the world (Reeves et al. 2003). Analysis of scars on humpbacks and right whales in the Gulf of Maine region indicate that between 50% and 70% of animals in some populations have been entangled at least once in their lives and between 10% and 30% are regularly entangled (Robbins and Mattila, 2004). Marks or scars from entanglement with fishing gear were reported from 75.6% of all right whales (Knowlton et al. 2003). Entanglement of cetaceans has been identified as a concern in the SBNMS, with several incidences of entangled humpback whales reported (Weinrich, 1999). Wiley *et al.* (2004) calculated a relative interaction potential (RIP) index identifying hotspots of potential whale entanglement in SBNMS. The highest probability of entanglement occurred around Stellwagen Bank's southwest and northwest corners and Jeffreys Ledge (Wiley *et al.,* 2004).

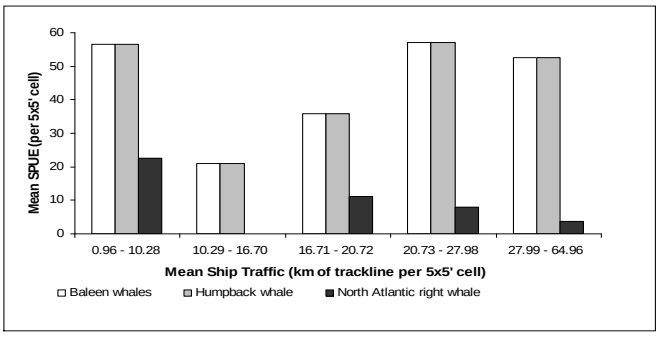
Fishing activity also poses a significant threat to smaller cetaceans since they are also very susceptible to entanglement in fishing gear. In the Gulf of Maine, most cetacean bycatch is associated with the sink gillnet fishery, although entanglements have also been documented in lobster pots, weir, purse seine, tub trawl, and bottom trawl gear (Smith *et al.,* 1993; NOAA, 2005ab). The incidental take of harbor porpoise and Atlantic white sided dolphins has been well documented for gillnet fisheries in the Gulf of Maine (Gilbert & Wynne 1987, Waring *et al.,* 1990; Smith *et al.,* 1993). In fact, harbor porpoises in the region were subject to the largest known bycatch of any marine mammal in U.S. waters (2,900 individuals equivalent to 57% of all cetacean bycatch in 1990). However by 1999, bycatch of these cetaceans had declined to 332 individuals (19% of bycatch) after the implementation of bycatch reduction measures (i.e., time-area closures, gear modifications NOAA, 2002) and decreasing fishing effort due to declining fish stocks (Read and Wade, 2000; Read, 2006).

In addition, greater availability of prey through discarding of fish bycatch and from the action of trawling may also influence the distribution of cetaceans. For example, DeAlteris *et al.* (2000) reported that whales followed shrimp trawls in the Gulf of Maine in order to catch fish as they escaped from the trawls. In contrast, commercial exploitation of fish populations leading to prey depletion and changes in the structure of fish communities is thought to have a major influence on the distribution and abundance of cetaceans, yet few studies have focused on this potential impact (Reeves et al. 2003).





Within MSRS



Within SBNMS

Figure 5.1.2. Relative ship traffic density (kilometers of ship track per square kilometer) representing data from the first three years (1999–2002) of the northeast Mandatory Ship Reporting System. The letters indicate five high-use corridors that were defined as the top two decile classes. Managed areas include the Federally designated Cape Cod Bay and Great South Channel right whale critical habitats, Stellwagen Bank National Marine Sanctuary, and the northeast mandatory ship reporting boundary are shown (map adapted from Ward-Geiger *et al.,* 2005). Bar charts show the relative abundance (SPUE) of baleen, humpback, and North Atlantic right whales (July 1999 - July 2002) grouped by mean ship traffic density.

Other potential threats

Contaminants: Cetaceans from many regions worldwide, particularly odontocetes from the northern hemisphere, have been reported with high concentrations of organochlorines, organotins and heavy metals in their tissues (O'Shea, 1999; Reijnders *et al.,* 1999). Weisbrod *et al.* (2001) found elevated levels of organochlorine in pilot whales and Atlantic white-sided dolphins from the southern Gulf of Maine, with the latter considered to have bioaccumulated potentially hazardous concentrations of polychlorinated biphenyls (PCBs) and chlorinated pesticides. In addition, a wide range of PCBs and pesticides have been detected in baleen whale species, including the endangered right whale, although concentrations were not been considered hazardous (Weisbrod *et al.,* 2000).

Biotoxins: Cetacean exposure to marine biotoxins associated with harmful algal blooms (HABs) has been documented in the Gulf of Maine (Doucette *et al.,* 2006). In winter 1987/88, 14 humpback whales in the southern Gulf of Maine died after consuming Atlantic mackerel contaminated by dinoflagellate saxitoxin (Garcia *et al*., 1989). The dinoflagellate genus *Alexandrium*, which produces the paralytic shellfish poisoning (PSP) saxitoxin, blooms at the time of high right whale abundance. During spring and summer blooms, toxicity levels generally increase from southern New England northwards to the Bay of Fundy. Doucette *et al.* (2006) found that samples of the dominant right whale prey, the calanoid copepod *Calanus finmarchicus*, and feces from at least 11 different right whales in the northern Gulf of Maine, tested positive for toxins. It has been hypothesized that trophic transfer of marine toxins may be a contributing factor to the poor recovery of the right whale, although neither chronic nor sublethal health effects are known for cetaceans (Durbin *et al.,* 2002).

Climate change: Complex and often nonlinear interactions between major components of the ecosystem need to be understood in order to predict the influence of climate change on the spatial and temporal distribution of cetaceans. The most significant effects of climate change on cetacean distribution and abundance are likely to occur through the interaction between the variability in sea-surface temperature, prey abundance and cetacean breeding success (Kenney *et al.,* 2001; Greene *et al.,* 2003; Greene and Pershing, 2004). Predictive models based on the empirical relationship between species and their environment will provide a useful tool for projecting potential population shifts under various climate change scenarios. More studies are required to identify meaningful predictors for individual cetacean species and to better understand how cetacean ecology in the Gulf of Maine region will be affected as these predictors change.

Habitat change: Habitat loss, habitat degradation and competition for prey are recognized as key threats to cetaceans worldwide (Reeves *et al.,* 2003). The impacts of benthic trawling, dredging and coastal land-use developments on cetacean health and habitat utilization have not been examined adequately for the implications of these activities in the Gulf of Maine region to be determined.

Cetacean-prey linkages

Several species of cetaceans in the Gulf of Maine have been studied extensively, revealing distribution patterns that are strongly linked to spatio-temporal patterns of prey abundance. For instance, persistent right whale aggregations are well-known for Cape Cod Bay and the Great South Channel, particularly in spring when zooplankton densities in these locations are high. The distribution of plankton patches is linked to a complex interaction between oceanic conditions, such as temperature, stratification, bottom topography, and currents (reviewed by Reeves and Kenney, 2003). Humpback whales in the southern Gulf of Maine appear to track densities of their preferred fish prey, feeding mainly on Atlantic herring (*Clupea harengus*), northern sand lance (*Ammodytes dubius*), Atlantic mackerel (*Scomber scombrus*) and other small-bodied and abundant schooling fish. These fish are predominantly planktivorous and are therefore also linked to the spatio-temporal patterns of phytoplankton and zooplankton. Payne *et al.* (1990) and Weinrich *et al.* (1997) described shifts in the distribution of humpback whales in the southern Gulf of Maine in response to the declining abundance of herring in the 1970s. As herring declined, populations of sand lance (a competitor, predator and prey of herring), increased dramatically and humpbacks moved to areas with a greater abundance of sand lance (Payne *et al.,* 1990; Weinrich *et al.,* 1997). The complex and cyclical relationship between zooplankton, planktivorous fish, and baleen whales led Payne *et al.* (1990) to hypothesize that the abundance and distribution of planktivorous fishes have played a significant role in structuring baleen whale populations in the southern Gulf of Maine. Further analysis showed that similar shifts in response to trends in fish abundance also occurred in white-sided dolphins and harbor porpoise (Kenney *et al*. 1996)

Many environmental variables interact to determine hotspots for prey abundance. For instance, changes in depth and the presence of bathymetric features with high relief are known to influence water movements, enhance mixing and upwelling, and concentrate prey (Hyrenbach *et al.,* 2000). Several studies have found that the distribution and abundance of cetaceans can be sufficiently explained by bathymetric attributes (Hooker *et al.,* 1999; Yen *et al.,* 2004). Identifying areas where prey are concentrated is important to predict species relative abundance.

5.2 METHODS

Cetacean sightings data

Data on cetacean sightings were acquired from two sources: (1) the North Atlantic Right Whale Consortium (NARWC) sightings database held at the University of Rhode Island (Kenney, 2001); and (2) the Manomet Bird Observatory (MBO) database, held at the National Oceanic and Atmospheric Administration's (NOAA) Northeast Fisheries Science Center (NEFSC).

NARWC data

The data contained survey effort and sightings data from ship and aerial surveys and opportunistic sources between 1970 and 2005. The main data contributors included: Cetacean and Turtles Assessment Program (CETAP); Canadian Department of Fisheries & Oceans; Provincetown Center for Coastal Studies; International Fund for Animal Welfare; NOAA's Northeast Fisheries Science Center (NEFSC), New England Aquarium (NEA), Woods Hole Oceanographic Institution (WHOI), and the University of Rhode Island. Three classes of survey data are defined for NARWC (Kenney and Winn, 1986; Shoop and Kenney, 1992) as follows:

1) Dedicated aerial surveys. These are the most rigorously designed and conducted surveys, used to estimate population densities via line-transect methods (i.e. DISTANCE; Buckland *et al.,* 2001). Samples must be unbiased samples of available habitat with an equal likelihood of sampling any location. Cross-legs, transits, and circling are eliminated from the density estimates.

2) Platforms-of-opportunity (POP) surveys. These aerial and shipboard surveys use trained observers placed on host ships and aircraft including Coast Guard cutters, U.S. and foreign research vessels, ferries, tugs, Coast Guard fisheries enforcement aircraft, Coast Guard radio-thermography aircraft and private vessels. Locations of sightings, survey tracks and environmental data are recorded. Data from systematic surveys not designated for line-transect density estimation (e.g., right whale population monitoring survey) are collected and archived using the same formats as POP surveys. Dedicated line-transect survey data can be treated like POP survey data by including all transits, cross-legs and circling.

3) Opportunistic sightings. These are data records with only sightings information and no associated survey effort, including reports from whale-watching boats, swordfish spotter pilots or commercial fishermen. Also included are sightings from systematic surveys where the effort data were not appropriately collected or were not provided.

Calculating Sightings-Per-Unit-Effort (SPUE):

Only records from dedicated aerial and platforms-of-opportunity surveys, which met the data selection criteria, were used to calculate SPUE:

Data selection criteria

1. Sufficient information to reconstruct survey tracks
2. On effort (i.e. they were recorded on a survey line)
3. There was at least one observer on watch
4. Visibility ≥ 2 nautical miles
5. Altitude ≤ 366 meters above sea level (only for aerial surveys)
6. Beaufort Sea State ≤ 3 (for small marine mammals)
7. Beaufort Sea State ≤ 4 (for medium and large marine mammals)

A total of 653,725 km of survey track and 34,589 cetacean observations were provisionally selected for analysis.

In order to minimize bias from uneven allocation of survey effort in both time and space, we calculated the sightings-per-unit-effort (SPUE) (Equation 1; Kenney and Winn, 1986; Shoop and Kenney, 1992) for all cetacean species by month for a grid of 5 x 5 minute cells (n = 1,378) covering the southern Gulf of Maine study area (Figure 5.2.1). SPUE allows comparisons between discrete spatial units and temporal subsets within the study area (Shoop and Kenney, 1992).

$$SPUE = 1{,}000 \times \frac{n}{e} \qquad \text{(Eq. 1)}$$

Where:
n = number of individual cetaceans
e = km of surveyed trackline
The factor of 1,000 was included to avoid very small decimal SPUE values

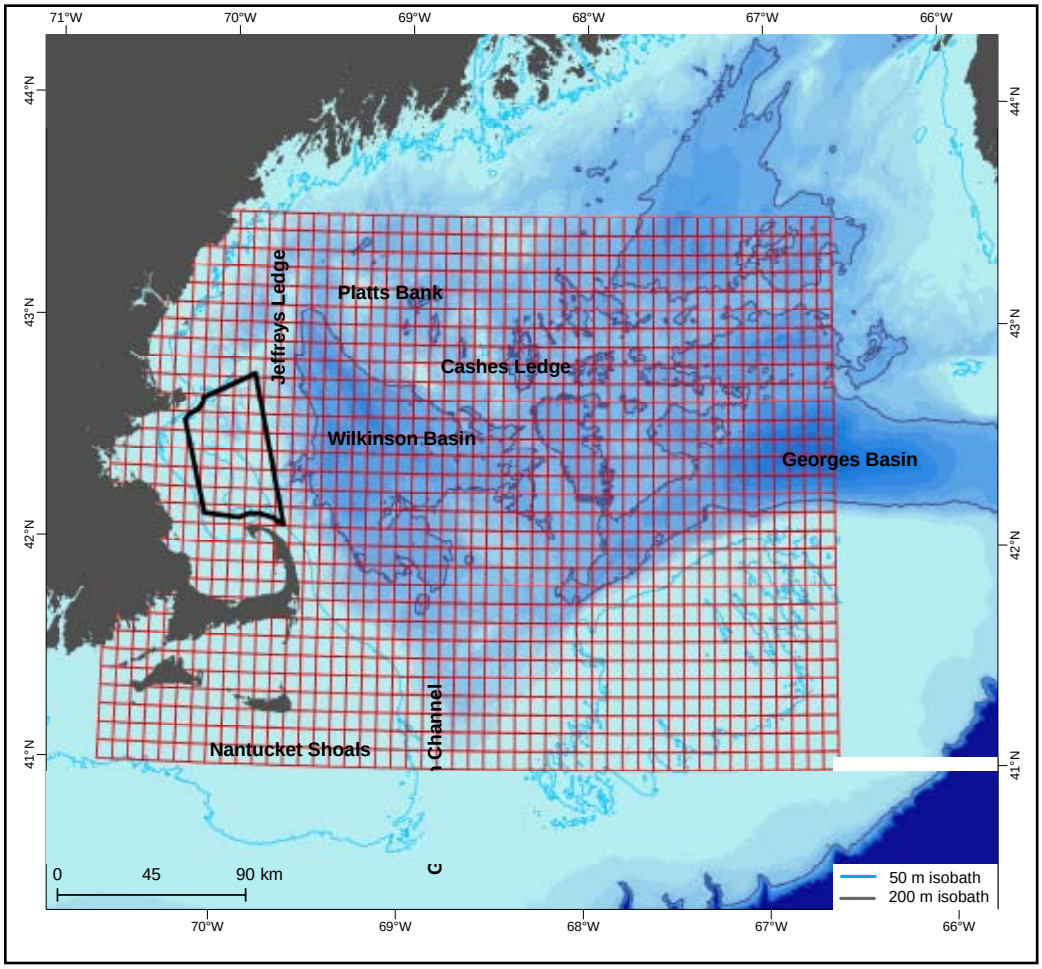


Figure 5.2.1. Southern Gulf of Maine study area showing the spatial extent of the sightings-per-unit-effort data (SPUE). Grid contains 1,378 cells.

Few surveys provided enough information to calculate probability of detection functions for individual species. We therefore assumed equal detectability for each species across platforms within Beaufort sea state 3 and 4. Attributes of the SPUE dataset included: 1) EFFORT - calculated as km of valid track surveyed; 2) ANIMALS - calculated as the number of individual cetaceans sighted; and 3) SPUE - calculated as the number of cetaceans per 1000 km of trackline surveyed.

Manomet Bird Observatory (MBO) data

MBO's Cetacean and Seabird Assessment Program (CSAP) was contracted from 1980 to 1988 by the National Marine Fisheries Service (NMFS) Northeast Fisheries Science Center (NEFSC) to provide an assessment of the

relative abundance and distribution of cetaceans, seabirds and marine turtles in the shelf waters of the north-eastern United States (MBO 1980, 1981, 1982, 1986a, 1986b, 1987a, 1987b). Trained observers were placed on ships of opportunity and used the same strip-transect survey protocol as described for seabirds in Chapter 4. The CSAP program was designed to be completely compatible with NMFS/NEFSC databases so that marine mammal data could be compared directly with fisheries data throughout the time series during which both types of information were gathered.

In order to prepare the MBO dataset for integration with NARWC's SPUE data, a series of data selection and geoprocessing steps was required (Figure 5.2.2). This process included extracting cetacean sighting records; updating database field names to match the NARWC database; creating geometry to represent survey tracklines and applying a set of data selection criteria designed to minimize uncertainty and bias in the data used. The NARWC selection criteria were applied to MBO data. Specifically, cetacean sightings from the MBO data were included in the biogeographic assessment if they were:

1. On effort - i.e. they were recorded on a survey line
2. At least one observer was on watch ('on effort')
3. Beaufort Sea State ≤ 3 (for small cetaceans)
4. Beaufort Sea State ≤ 4 (for large cetaceans)

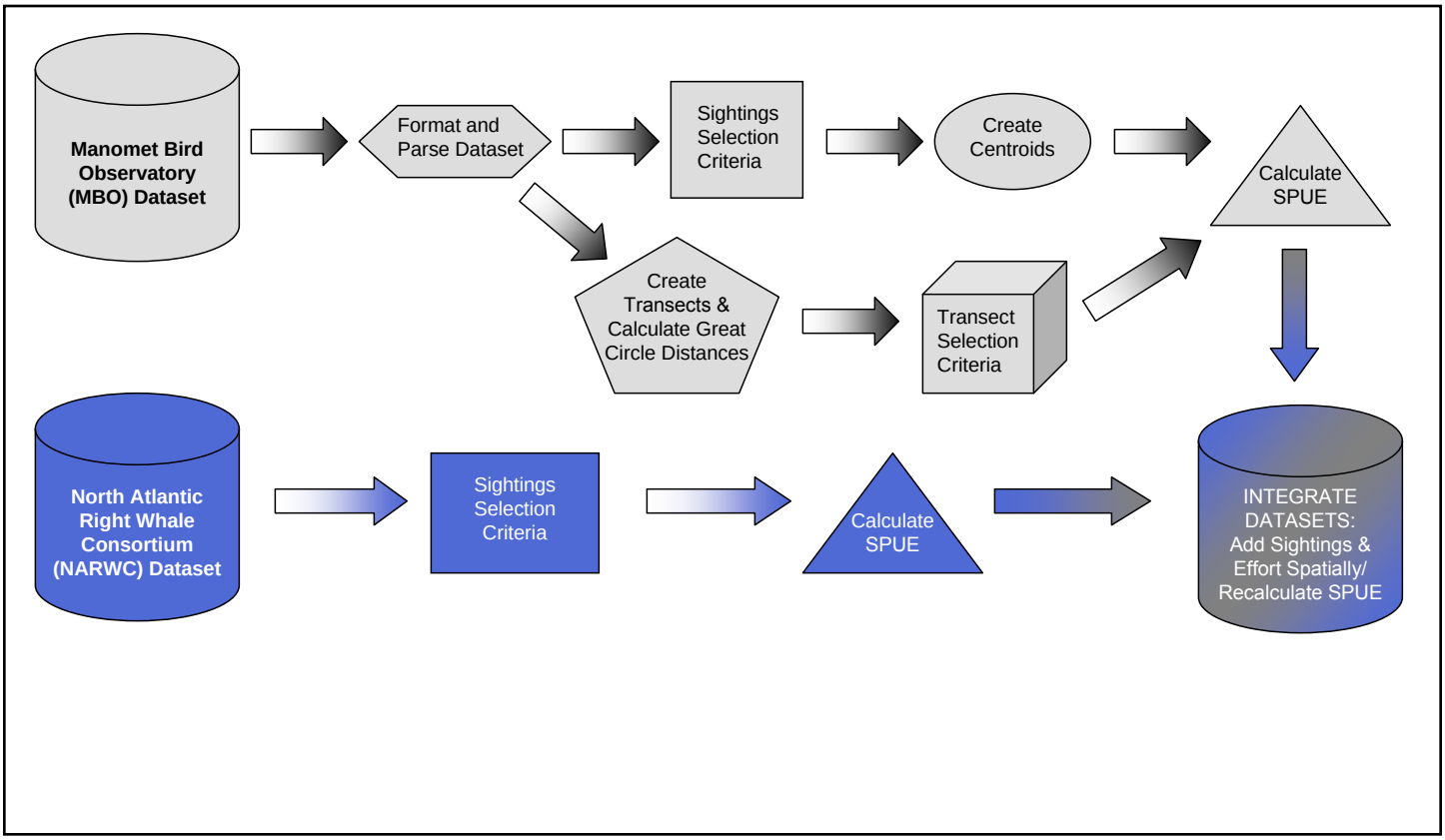


Figure 5.2.2. Sequence of procedures used to select records and process effort to integrate the MBO and NARWC datasets.

The altitude criterion did not apply to the MBO data since all surveys were conducted from ships. Visibility data were not provided, therefore we assumed acceptable visibility (visibility of at least less than two nautical miles) for all transects that were recorded as "on effort". The small and large cetacean classes were the same as listed for the NARWC database, with two additions to the small category: unidentified large dolphin and unidentified patterned dolphin. These selection criteria resulted in exclusion of 145 sightings.

Furthermore, the locations of cetacean sightings in the original MBO data were not assigned unique locations along a transect, but instead were assigned the same geographic location as the beginning of the transect. This

presented a problem, particularly where transects crossed two or more grid cells, since the sighting may have occurred anywhere along a transect. In order to explore the extent of the problem, we calculated the proportion (%) of the total transect length that fell within each grid cell that it intersected (Equation 2).

$$\%D = \frac{Di}{D} \times 100 \qquad \text{(Eq. 2)}$$

Where:
%D = proportion of transect length (%)
Di = intersected transect length
D = total transect length

Next, we decided on an appropriate error threshold by calculating the effect of excluding transects with less than 50%, 70% and 90% of their total length falling within an individual 5 x 5 minute cell. In order to maximize the number of transects in the analyses, but minimize uncertainty in our spatial assignment of cetacean density, transects (and consequently sightings along those transects) that had ≥ 70% of their length in a single 5 x 5 minute cell were selected and exported for use in the biogeographic assessment. This selection criterion removed 596 out of 2,162 transects and 341 sightings out of 1,431 sightings in our area of interest (Table 5.2.1). Each polyline transect was converted to a centroid using XTools Pro 3.0 (Data East, 2006) "convert shapes to centroids" function. Marine mammal sightings attributes were transferred to the corresponding centroid for each transect (Figure 5.2.3).

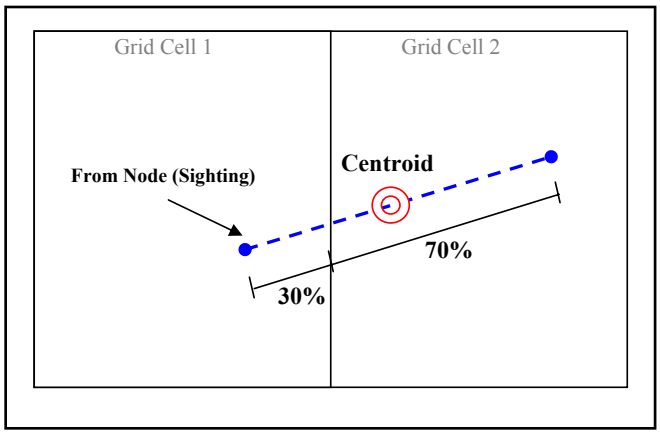


Figure 5.2.3. Assigning marine mammal sightings to transect centroids. The blue dashed line is the survey transect. The red circle is the center of the survey transect. Note that the beginning of the transect (~ first 30%) is located in one grid cell and the last 70% of the transect is located in another grid cell. The probability of the sighting occurring in the second part of the transect is higher and is represented by assigning data to a centroid in grid cell 2.

Table 5.2.1. Dataset and logical error summary for the cetacean component of the Manomet Bird Observatory Database (Manometc.txt). Sightings without effort data (1,922) and without transect coordinates (1,217) were also excluded.

Attributes of the MBO data	Original MBO dataset	Subset for study area	Included in final analysis
Total number of transects	33,062	2,162	1,593
Total cetacean observations	4,304	1,431	636
Total survey distance (km)	133,125	9,171	5,210

Combining MBO and NARWC data

The sightings data were aggregated in 5 x 5 minute grid cells by month (1997-2004) and season (1978-2005):

Fall = September, October and November
Winter = December, January and February
Spring = March, April and May
Summer = June, July and August

by cetacean species:

Atlantic white-sided dolphin (*Lagenorhynchus acutus*)
Fin whale (*Balaenoptera physalus*)
Humpback whale (*Megaptera novaengliae*)
Minke whale (*Balaenoptera acutorostrata*)
North Atlantic right whale (*Eubalaena glacialis*)
Sei whale (*Balaenoptera borealis*)

and by cetacean group:

Dolphin/porpoise group:

Atlantic white-sided Dolphin (*Lagenorhynchus acutus*)
Bottlenose dolphin (*Tursiops truncatus*)
Common dolphin (*Delphinus delphis*)
Harbor porpoise (*Phocoena phocoena*)
Risso's dolphin (*Grampus griseus*)
Unidentified dolphin or porpoise
Unidentified *Lagenorhynchus*
Unidentified *Stenella*
White-beaked dolphin (*Lagenorhynchus albirostris*)

Baleen whale group:

Blue whale (*Balaenoptera musculus*)
Fin whale (*Balaenoptera physalus*)
Humpback whale (*Megaptera novaengliae*)
Minke whale (*Balaenoptera acutorostrata*)
North Atlantic right whale (*Eubalaena glacialis*)
Sei whale (*Balaenoptera borealis*)
Unidentified *Balaenoptera*
Unidentified Fin or Sei whale
Unidentified Rorqual

Next, the number of animals and amount of effort were added together using unique grid cell IDs to link the two data sets geographically. The sightings were corrected for effort using the SPUE Index (Equation 1). Cells with less than 2.5 km of effort were considered to have "no effort" and were removed from the analysis.

Combined valid survey effort was 567,955 km of survey track for small-bodied cetaceans and 658,935 km for large-bodied cetaceans in the southern Gulf of Maine. The largest amount of effort occurred in the spring and the lowest amount occurred in fall (Table 5.2.2; Figures 5.2.4 and 5.2.5).

Calculating diversity indices

We used the total number of animals and number of species per grid cell to calculate species richness and diversity (Shannon-Wiener H') for each season (for equations see Chapter 3 - Marine Fishes). These data were not

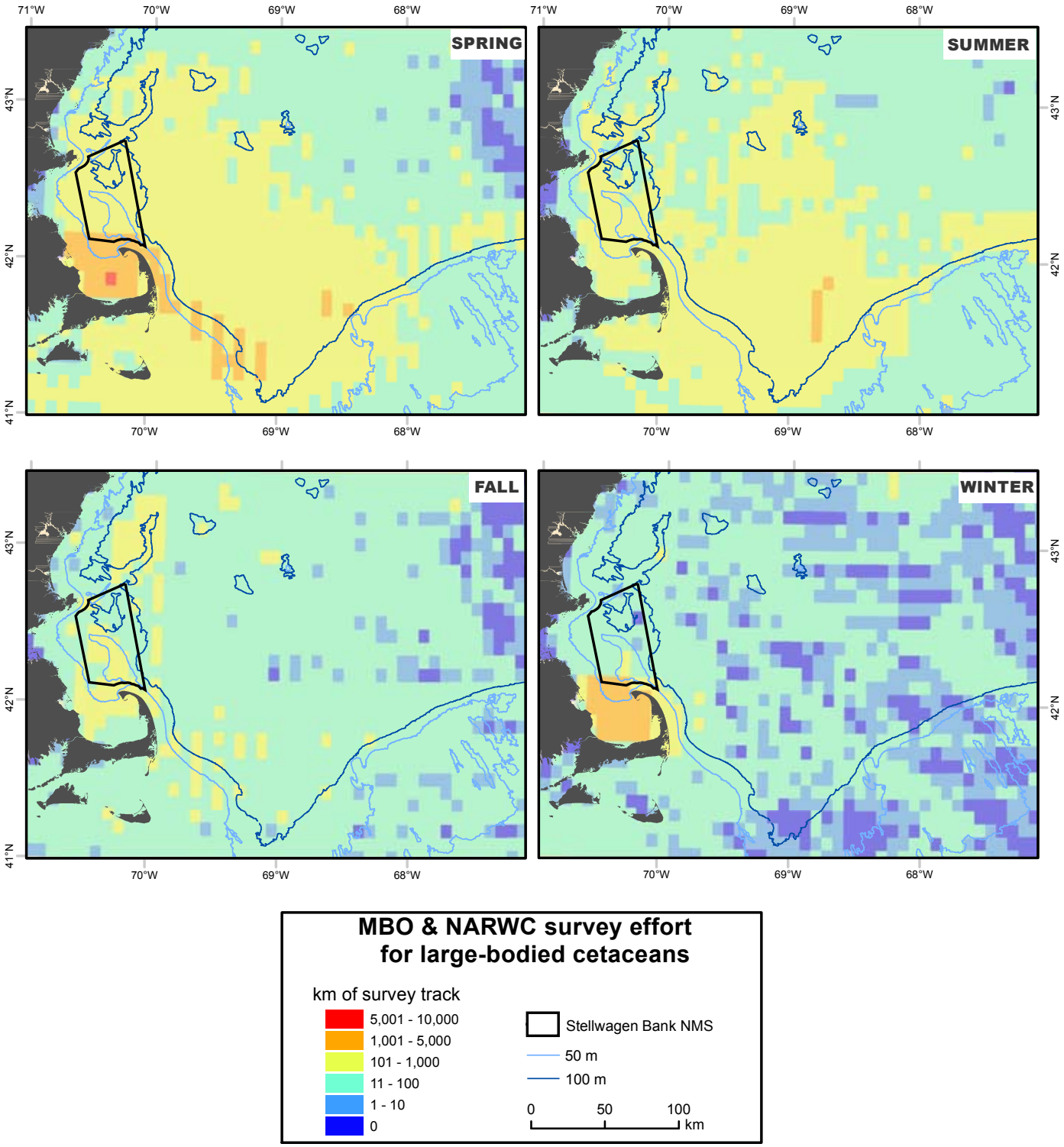


Figure 5.2.4. Spatial patterns of survey effort (1970 – 2005) for large cetaceans in the southern Gulf of Maine derived from the integration of NARWC and MBO data. Total survey track length is summed for each 5 x 5 min cell for a) spring; b) summer; c) fall; and d) winter.

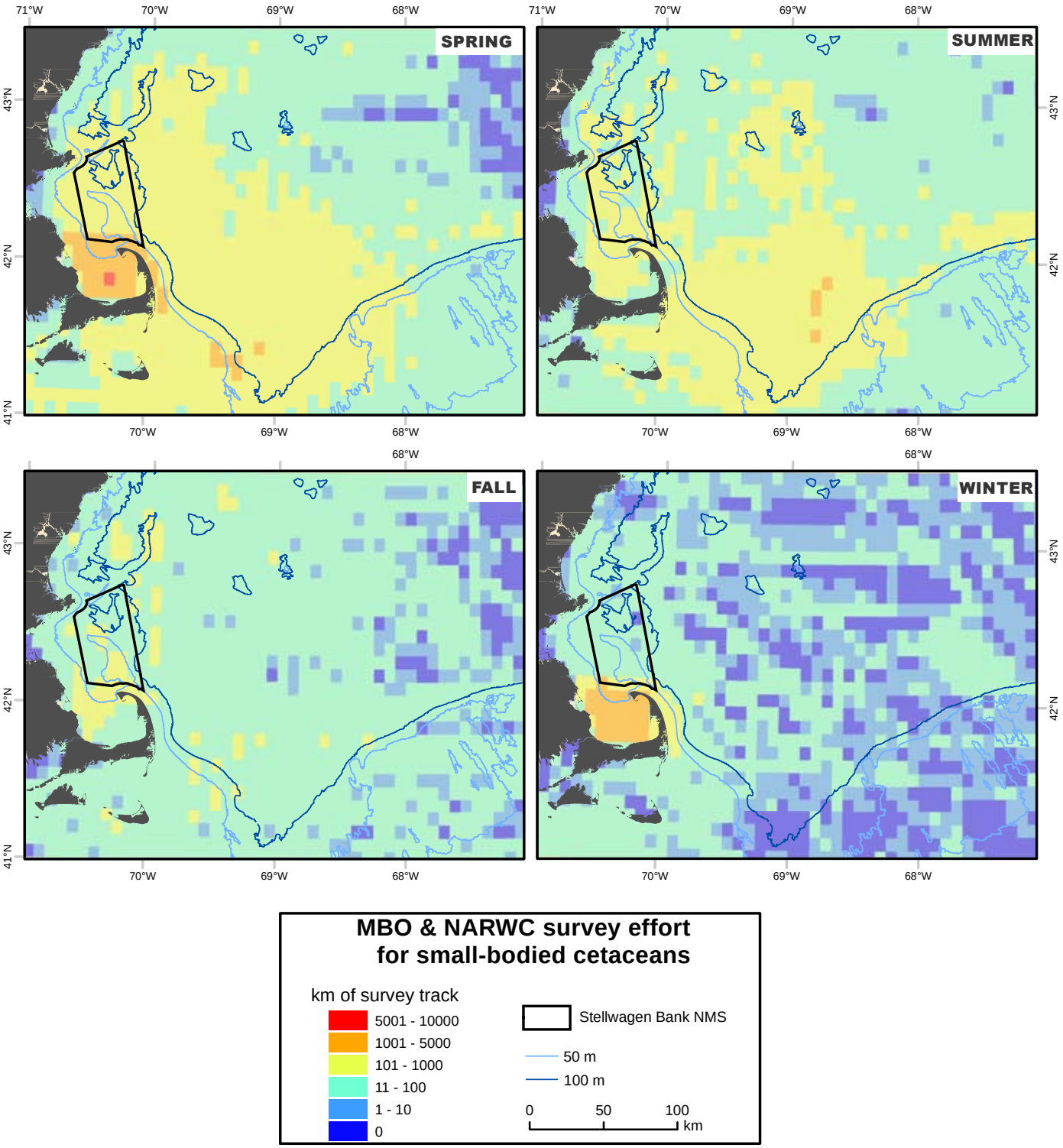


Figure 5.2.5. Spatial patterns of survey effort (1970 – 2005) for small cetaceans in the southern Gulf of Maine derived from the integration of NARWC and MBO data. Total survey track length is summed for each 5 x 5 min cell for a) spring; b) summer; c) fall; and d) winter.

corrected for effort and therefore, spatial patterns of species diversity should only be interpreted alongside the effort maps to consider the influence of effort on the number of species seen in an area.

Table 5.2.2. Total track length (km) surveyed with the southern Gulf of Maine study area by season (MBO and NARWC data combined 1970-2005).

Group	Season			
	Spring	*Summer*	*Fall*	*Winter*
Small cetaceans	305,297.31	138,839.19	51,662.19	72,156.02
Large cetaceans	352,972.66	157,625.04	61,921.68	86,415.26

Interpolating grid cell data

Cetaceans are highly mobile animals with complex and continuous patterns of movement. In order to better convey this continuity, we interpolated the binned marine mammal relative abundance values to produce a conterminous surface. The centroids of each cell within the grid were first converted to points using XTools Pro 3.0 (Data East, 2006), then these points were interpolated spatially using an Inverse Weighting Distance (IDW) algorithm in ESRI's Geostatistical Analyst.

Environmental Data

In order to develop cetacean-environment models to explain patterns of relative abundance, we processed spatial data on a range of environmental variables considered *a priori* to be ecologically meaningful to cetaceans. Thirty environmental variables representing means and variability (standard deviation) were calculated for each 5 x 5 minute grid cell using a Visual Basic (VB) script to interface with Spatial Analyst's Zonal Stats in ArcView v9.1. Environmental data included prey abundance (fish and zooplankton), water depth, bathymetric slope, seasonal water stratification, chlorophyll *a* concentration, sea surface temperature, turbidity, variety and area of substratum type, distance to shore, and distance to the 200- and 100-meter isobaths (Table 5.2.3).

Slope was calculated in degrees using the surface analysis slope function of ESRI's Spatial Analyst. Distances to the shore and to the 200- and 100-meter isobaths were calculated using a VB script called Minimum Distance 2 Layers (Chasen, 2005). Seasonal water stratification was calculated by interpolating water density values at 0 meters and 50 meters, and subtracting the resulting raster surfaces (see Chapter 1 - Physical and Oceanographic Setting). In addition, we converted pixel values from SeaWIFS (chlorophyll *a* and turbidity) and AVHRR (SST) satellite derived imagery to standard units and reclassed land and no data values as null values. These two processes were combined as a VB script in order to batch process the remotely sensed imagery. The first part of the script used Spatial

Table 5.2.3. Environmental variables used to explain spatial patterns in cetacean densities in the southern Gulf of Maine study area. The mean and range of values calculated for all 5 x 5 minute cells across the study area are shown. Prey abundance data was provided by NOAA's National Marine Fisheries Service (bottom trawl 1975 to 2000; zooplankton from 1977 to 1988); bathymetric data was provided by United States Geological Survey; and oceanography data were provided by NOAAs Center for Coastal Monitoring and Assessment.

RELATIVELY STATIC PREDICTORS	
Explanatory variables	*Mean (range)*
Mean water depth (m)	127 (3.19 to 346.5)
Variance of water depth (m)	9.38 (1.07 to 47.2)
Mean slope (degree)	0.36 (0.04 to 1.77)
Variance in slope (degree)	0.23 (0.03 to 1.24)
Number of sediment types	1.7 (1 to 6)
Amount of each sediment type (%)	10.7 (0 to 100)
Minimum distance to shore (km)	90.7 (0.03 to 259.4)
Minimum distance to 100 m isobath (km)	31.2 (0.006 to 109.3)
Minimum distance to shelfbreak (km)	188.9 (36.6 to 356.9)

Table 5.2.3. (Continued). Environmental variables used to explain spatial patterns of cetacean densities in the southern Gulf of Maine study area. The range in values (mean and standard deviation) calculated for all the 5 x 5 minute cells across the study area are shown. Prey abundance data were provided by NOAA's National Marine Fisheries Service (bottom trawl 1975 to 2000; zooplankton from 1977 to 1988); bathymetric data were provided by United States Geological Survey; and oceanography data were provided by NOAAs Center for Coastal Monitoring and Assessment.

HIGHLY VARIABLE PREDICTORS BY SEASON				
Explanatory variables	*Mean (range)*			
Potential prey	**Spring**	**Summer**	**Fall**	**Winter**
Mean fish abundance (all species) 1975-2000	201.9 (0 to 10935)	280.7 (0 to 6174)	298.5 (0 to 10160)	22.4 (0 to 2756)
Interpolated fish abundance (all species) 1975-2000	201.3 (0 to 4456.9)	75.4 (0 to 2456)	297.7 (0 to 5959)	21.6 (0 to 2000)
Mean sandlance abundance 1975-2000	54.6 (0 to 21437)	67.6 (0 to 6129)	13.6 (0 to 4311)	0.16 (0 to 179.5)
Interpolated sandlance abundance 1975-2000	54.2 (0 to 8433.7)	18.8 (0 to 2406)	13.6 (0 to 2965)	0.16 (0 to 71.2)
Mean herring abundance 1975-2000	16.6 (0 to 1593)	20.4 (0 to 879)	47.1 (0 to 4482)	2.02 (0 to 1460)
Interpolated herring abundance 1975-2000	16.5 (0 to 649.4)	5.68 (0 to 371)	47.1 (0 to 1890)	1.93 (0 to 602.7)
Mean mackerel abundance 1975-2000	13.1 (0 to 5792)	1.44 (0 to 313)	9.17 (0 to 3677)	0.02 (0 to 22)
Mean hake (silver, red & white) abundance 1975-2000	20.5 (0 to 743.4)	11.8 (0 to 221.1)	27.1 (0 to 1018.2)	0.75 (0 to 230)
Mean sandlance, herring, hake combined 1975-2000	146 (0 to 21444.5)	124.9 (0 to 6131)	151.3 (0 to 6863.5)	4.48 (0 to 1467)
Mean zooplankton density (m^3) 1980-1988	3.5×10^6 (1090 to 360)	1.4×10^6 (196.7 to 280)	4.3×10^6 (1599 to 300)	3×10^6 (789 to 209)
Mean interpolated zooplankton density (m^3) 1980-1988	4.75 (3.86 to 6.15)	4.89 (3.75 to 5.73)	4.68 (4.12 to 5.05)	4.94 (3.81 to 7.58)
Mean log *C. finmarchicus* density (m^3) 1980-1988	4.1 (3.22 to 4.93)	4.11 (2.37 to 5.05)	n/a	n/a
Oceanography				
Mean water stratification 1912-2004 (Sigma t)	-0.6 (0.1 to -2.03)	-1.9 (0.09 to -3.67)	-0.69 (0.28 to -1.63)	-0.07 (0.16 to -0.54)
Variance of water stratification 1912-2004 (Sigma t)	0.06 (0.005 to 0.29)	0.08 (0.002 to 0.39)	0.07 (0.007 to 0.31)	0.02 (0.002 to 0.13)
Mean water stratification 1994-2004 (Sigma t)	-0.5 (0.13 to -2.09)	-1.9 (0.11 to -3.41)	-0.7 (0.22 to -1.64)	-0.09 (0.21 to -0.46)
Variance of water stratification 1994-2004 (Sigma t)	0.04 (0.004 to 0.32)	0.1 (0.005 to 0.76)	0.04 (0.0004 to 0.22)	0.01 (0.001 to 0.15)
Mean SST 1985-2004 (°C)	5.9 (3.91 to 8.85)	16 (12.4 to 25)	13.9 (11.7 to 19.6)	6.14 (2.54 to 7.56)
Variance of SST 1985-2004 (°C)	0.1 (0.32 to 2.15)	0.28 (0.02 to 7.64)	0.16 (0.01 to 3.18)	0.14 (0.01 to 7.56)
Mean chlorophyll *a* 1998-2005 (ug/L)	3.2 (1.35 to 13.84)	2.18 (0.73 to 16.9)	3.08 (1.42 to 19.03)	2.02 (0.74 to 12.1)
Variance of chlorophyll *a*1998-2005 (ug/L)	0.26 (0.02 to 3.83)	0.24 (0.008 to 7)	0.26 (0.05 to 3.67)	0.2 (0.03 to 5.8)

Analyst's Reclass function to reassign the 8-bit values 252 (land), 0, 251 and 253 (no data) as NULL. The second part of the script used Spatial Analyst's Raster Calculator to compute the standard unit values for each pixel (Equations 3, 4 and 5).

$$\text{Chl } a = 10\wedge((x\text{-}1) \times \left(\frac{3}{250}\right) - 1.3) \qquad \text{(Eq. 3)}$$

Where:
Chl *a* = Chlorophyll *a* concentration (micrograms/liter)
x = 8 bit value from geotiff

$$SST = ((x \times 0.15) + (-3)) \qquad \text{(Eq. 4)}$$

Where:
SST = Sea Surface Temperature (degrees Celsius)
x = 8 bit value from geotiff

$$T = 10\wedge((x\text{-}1) \times \left(\frac{3}{250}\right) - 4) \qquad \text{(Eq. 5)}$$

Where:
T = Turbidity (steradians $^{-1}$)
x = 8 bit value from geotiff

Predictive modeling

We developed a relatively generalized and single scale approach for analyzing the linkages between cetaceans and their environment. The intention was to: 1) identify the most influential environmental variables that determine cetacean distributions and relative abundance; 2) characterize the attributes of the environment that support highest mean abundance; and 3) identify thresholds in the statistical representation of the cetacean-environment relationship. To achieve these objectives we first used regression trees (CART™ - Salford Systems Inc.) (Breiman *et al.,* 1998) to derive a set of breakpoints that quantitatively described the multivariate environmental conditions associated with varying levels of cetacean abundance. Second, we used multivariate adaptive regression splines (MARS™ - Salford Systems Inc.) (Friedman, 1990) to fit more precisely to the data, in order to determine the form of nonlinear relationships. MARS is a novel and flexible multivariate nonparametric regression technique that combines the most useful aspects of recursive partitioning and spline fitting to perform piecewise linear regressions. The algorithm offers considerable power, particularly in situations where there are additive, low-order nonlinear interactions between predictors. The technique is capable of ignoring redundant variables and reliably tracking the very complex data structures that are often ensconced in high-dimensional ecological datasets. MARS estimates variable importance by comparing the estimated cost of omission of each variable with the highest cost of omission of all variables. The cost of omission is estimated by calculating the model goodness of fit after the variable has been excluded.

SPUE data from 1997 to 2005 were used for the predictive modeling. This allowed us to align the study period with the temporal extent available for much of our environmental data., but excluded a large proportion of the available data. Prey data were least overlapping with SPUE. Data were first examined for extreme outliers using a matrix of bivariate scatterplots and correlation coefficients were calculated to identify extreme collinearity between all pairs of predictor variables. To minimize collinearity

Table 5.2.4. Log transformed cetacean sightings-per-unit-effort (SPUE) grouped by season using combined MBO and NARWC data (1997-2005). Log transformed SPUE was used as the response variable in model development.

	Season	
Species/Group	***Spring***	***Summer***
Humpback whale	0.23 (0-2.6)	0.32 (0-2.5)
Fin whale	0.3 (0-2.2)	0.4 (0-2.35)
Minke whale	0.12 (0-1.63)	0.18 (0-2.1)
North Atlantic right whale	0.29 (0-2.17)	0.19 (0-2.22)
Sei whale	0.09 (0-2.53)	0.177 (0-2.96)
All Mysticeti	0.63 (0-2.80)	0.77 (0-2.98)
Atlantic white-sided dolphin	0.72 (0-3.74)	0.74 (0-3.74)
All dolphin & porpoise	1 (0-4.3)	1.08 (0-3.8)

amongst predictor variables, only one variable of a strongly correlated (r = >0.7) pair was retained for the analyses (i.e., mean and variance of depth replaced slope; mean chlorophyll *a* concentration replaced the variance of chlorophyll concentration; stratification index 1994 to 2004 replaced the longer time series of 1912 to 2004; mean and variance of sand lance abundance replaced the composite variable representing mean and variance of all key prey species combined). SPUE data were log-transformed for this analysis (Table 5.2.4).

5.3 RESULTS

Summarizing total sightings-per-unit-effort (Table 5.3.1) by season show the seasonal use patterns for the southern Gulf of Maine study area as a whole. Total SPUE for all dolphin and porpoise species combined is highest in summer and fall and approximately 45% lower in winter than summer. Baleen whale abundance also peaks in summer with approximately 40% higher SPUE in the summer season than spring and approximately a six-fold decrease from summer to winter season.

Table 5.3.1. Total cetacean sightings-per-unit-effort (SPUE) grouped by season using combined MBO and NARWC data (1970-2005).

Species/Group	Season			
	Spring	*Summer*	*Fall*	*Winter*
Humpback whale	6,913	14,546	10,372	1,259
Fin whale	7,187	11,714	11,305	4,215
Minke whale	1,644	3,690	1,462	191
North Atlantic right whale	7,249	5,536	446	1,351
Sei whale	2,856	6,990	187	229
All Mysticeti	27,171	45,330	25,492	7,628
Pilot whale	3,484	39,715	54,809	312
Atlantic white-sided dolphin	120,183	229,060	126,997	46,806
All dolphin & porpoise	193,822	336,749	280,405	173,098

1-1,000
1,001-10,000
10,001-100,000
>100,000

Although some geographic areas consistently exhibited high densities for a number of species (see Appendix 10 for additional maps showing grid cell values), individual species exhibited distinctive spatio-temporal patterns across seasons as follows:

Spatial patterns of abundance

Humpback whale

The highest SPUE for humpback whales was distributed primarily along a relatively narrow corridor following the 100-m isobath across the southern Gulf of Maine from the northwestern slope of Georges Bank, south to the Great South Channel, and northward alongside Cape Cod to Stellwagen Bank and Jeffreys Ledge (Figure 5.3.1). The relative abundance of whales increased in the spring with highest SPUE (max SPUE = 379.4) along the slope waters (between the 40- and 140-m isobaths) off Cape Cod and Davis Bank, Stellwagen Basin and Tillies Basin (max SPUE = 133.6) and between the 50- and 200-m isobaths along the inner slope of Georges Bank (max SPUE = 99.1). High SPUE (max SPUE = 60.4) was also estimated for the waters around Platts Bank. In the summer months, abundance increased markedly over the shallow waters (<50 m) of Stellwagen Bank (max SPUE = 189), the waters (100 - 200 m) between Platts Bank and Jeffreys Ledge (max SPUE = 233.2), the steep slopes (between the 30- and 160-m isobaths) of Phelps and Davis Bank north of the Great South Channel towards Cape Cod (max SPUE = 322.2), and between the 50- and 100-m isobath for almost the entire length of the steeply sloping northern edge of Georges Bank (max SPUE = 221.8). This general distribution pattern persisted in all seasons except winter, when humpbacks remained at high SPUE in only a few locations including Porpoise and Neddick Basins adjacent to Jeffreys Ledge (max SPUE = 292.8), northern Stellwagen Bank and Tillies Basin (max SPUE = 131.6), and the Great South Channel (max SPUE = 114.4).

Fin whale

Spatial patterns of habitat utilization by fin whales were very similar to those of humpback whales. Spring and summer high-use areas followed the 100-m isobath along the northern edge of Georges Bank (between the 50- and 200-m isobaths; max SPUE = 106.5), and northward from the Great South Channel (between the 50- and 160-m isobaths; max SPUE = 167.8) (Figure 5.3.2). Waters around Cashes Ledge (max SPUE = 91.9), Platts Bank (max SPUE = 83.8), and Jeffreys Ledge (max SPUE = 76.6) are all high-use areas in the summer months. Stellwagen Bank was a high-use area for fin whales in all seasons, with highest SPUE occurring over the southern Stellwagen Bank in the summer months (max SPUE = 136.6). In fact, the southern portion of the SBNMS was used more frequently than the northern portion in all months except winter, when high SPUE was recorded over the northern tip of Stellwagen Bank (max SPUE = 386.9). In addition to Stellwagen Bank, high SPUE (max SPUE = 64.2) in winter was estimated for Jeffreys Ledge and the adjacent Porpoise Basin (100- to160-m isobaths), as well as Georges Basin and northern Georges Bank (max SPUE = 158.7).

Minke whale

Like other piscivorous baleen whales, highest SPUE for minke whale was strongly associated with regions between the 50- and 100-m isobaths, but with a slightly stronger preference for the shallower waters along the slopes of Davis Bank, Phelps Bank, Great South Channel (max SPUE = 59.1) and Georges Shoals on Georges Bank (max SPUE = 125.2) (Figure 5.3.3). Minke whales were sighted in the SBNMS in all seasons, with highest SPUE estimated for the shallow waters (approximately 40 m) over southern Stellwagen Bank in the summer (max SPUE = 43.5) and fall months (max SPUE = 50.1). Platts Bank (max SPUE = 41.9), Cashes Ledge (max SPUE = 38.6), Jeffreys Ledge, and the adjacent basins (Neddick, Porpoise and Scantium) also supported high relative abundance (max SPUE = 64.2). Very low densities of minke whales remained throughout most of the southern Gulf of Maine in winter.

North Atlantic right whale

North Atlantic right whales are generally distributed widely across the southern Gulf of Maine in spring with highest SPUE (max SPUE = 132.4) located over the deeper waters (100- to 160-m isobaths) on the northern edge of the Great South Channel and deep waters (100 – 300 m) parallel to the 100-m isobath of northern Georges Bank (max SPUE = 88.4) and Georges Basin (max SPUE = 147) (Figure 5.3.4). High SPUE was also found in the shallowest waters (< 30 m) of Cape Cod Bay (max SPUE = 59.8), over Platts Bank and around Cashes Ledge (max SPUE = 78.9). Lower relative abundance was estimated over deep-water basins including Wilkinson Basin, Rodgers Basin and Franklin Basin. In the summer months, right whales moved almost entirely away from the coast to deep waters over basins in the central Gulf of Maine (Wilkinson Basin, Cashes Basin between the 160- and 200-m isobaths) and north of Georges Bank (Rogers, Crowell and Georges Basins). Highest SPUE was found north of the 100-m isobath at the Great South Channel (max SPUE = 165) and over the deep slope waters and basins along the northern edge of Georges Bank (max SPUE = 137.5). The waters between Fippennies Ledge and Cashes Ledge were also estimated as high-use areas (max SPUE = 97.4). In the fall months, right whales were sighted infrequently in the Gulf of Maine, with highest densities (max SPUE = 57.7) over Jeffreys Ledge and over deeper waters near Cashes Ledge and Wilkinson Basin (max SPUE = 49.7). In winter, Cape Cod Bay (max SPUE = 47.7), Scantum Basin, Jeffreys Ledge (max SPUE = 168.6), and Cashes Ledge (max SPUE = 51.1) were the main high-use areas. Although, SBNMS does not appear to support highest SPUE of right whales, sightings within SBNMS are reported for all four seasons, albeit at low relative abundance (max SPUE < 26.1). Highest SPUE within SBNMS occured along the southern edge of the Bank.

Sei whale

Sei whale distributions are broadly similar to right whale distribution, except sei whales exhibited a more distinct preference for offshore waters. In addition, sei whales were conspicuously absent from Cape Cod Bay and other coastal regions throughout the study area (Figure 5.3.5). SPUE increased gradually through spring, with highest SPUE in the spring and summer months along the steep slopes of northern Georges Bank (max SPUE = 207) and over the adjacent deep waters (200- to 300-m isobaths) of Georges Basin and Franklin Basin (max SPUE = 381). Sei whales were also frequently sighted immediately north of the 100-m isobath at the entrance to the Great South Channel in both the spring and summer seasons. High SPUE in summer also occurred over the complex of basins, ledges and ridges in the south central Gulf of Maine over Wilkinson Basin (100- to 160-m isobaths) (max SPUE = 62.6), Cashes Basin and Ledge, Fippennies Ledge and Peck Ridge (max SPUE = 70.9). In fall, sei whales were found at relatively low SPUE (max SPUE = 36.4) in a very few isolated locations and were almost absent from the region in the winter.

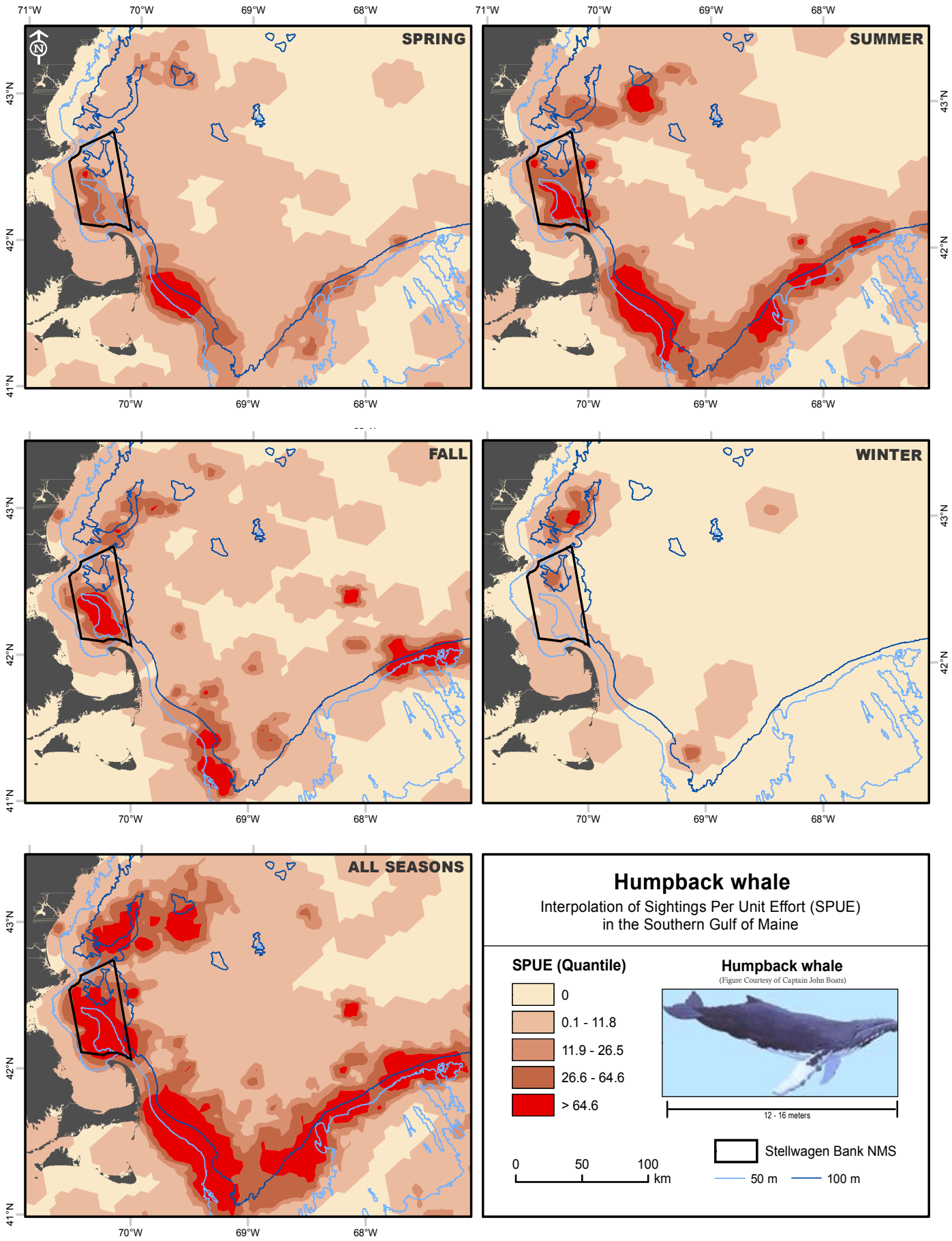


Figure 5.3.1. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for Humpback whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

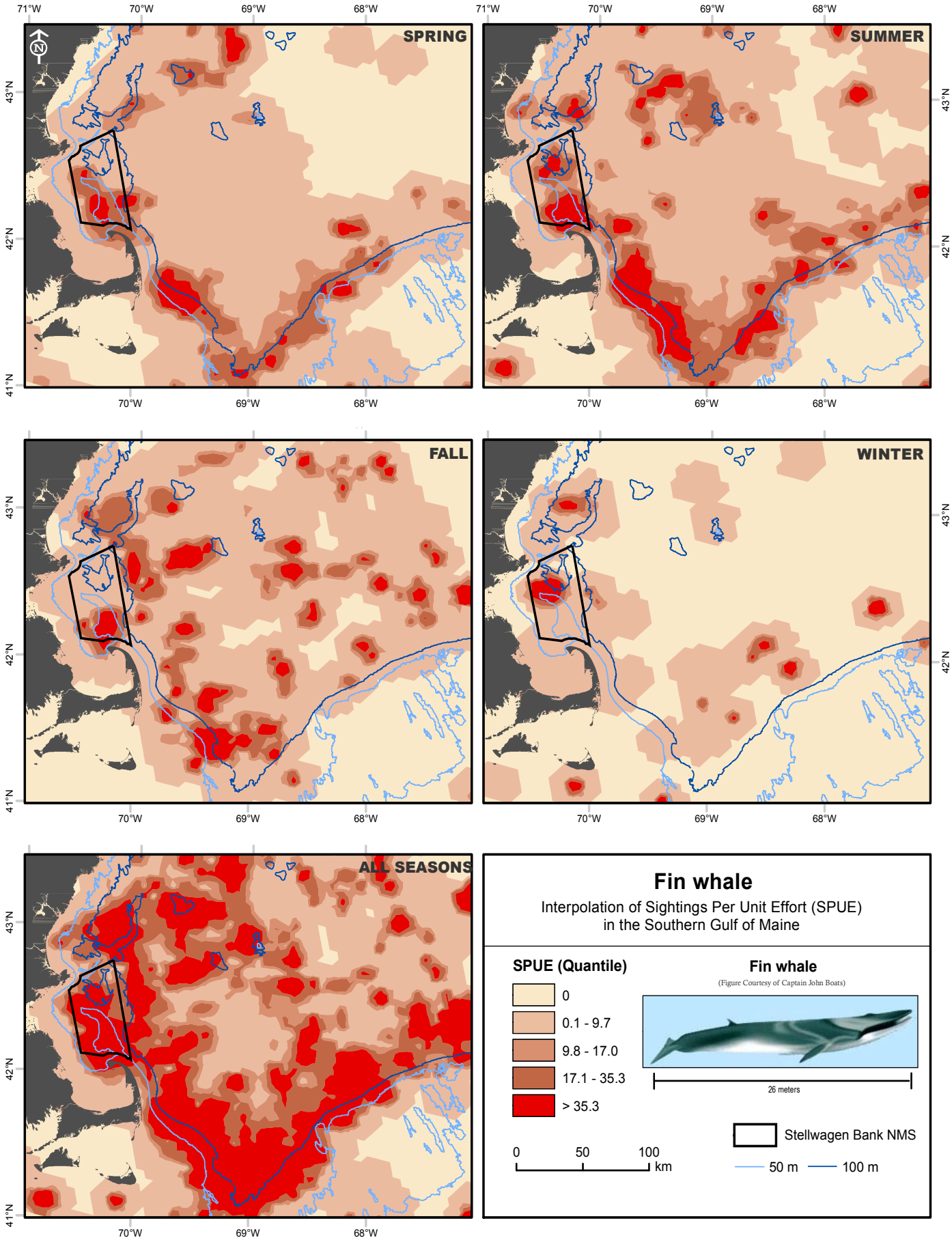


Figure 5.3.2. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for Fin whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

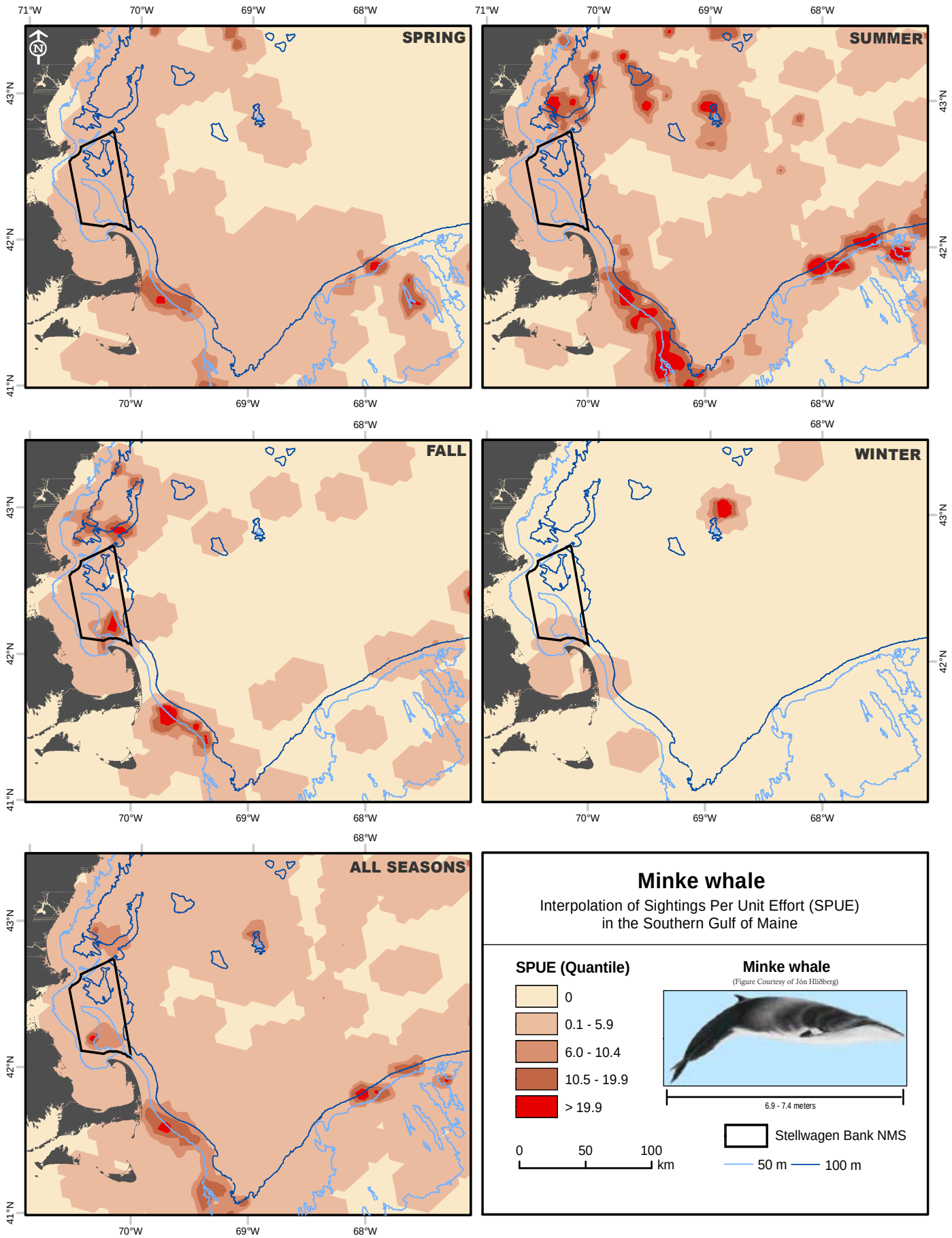


Figure 5.3.3. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for Minke whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

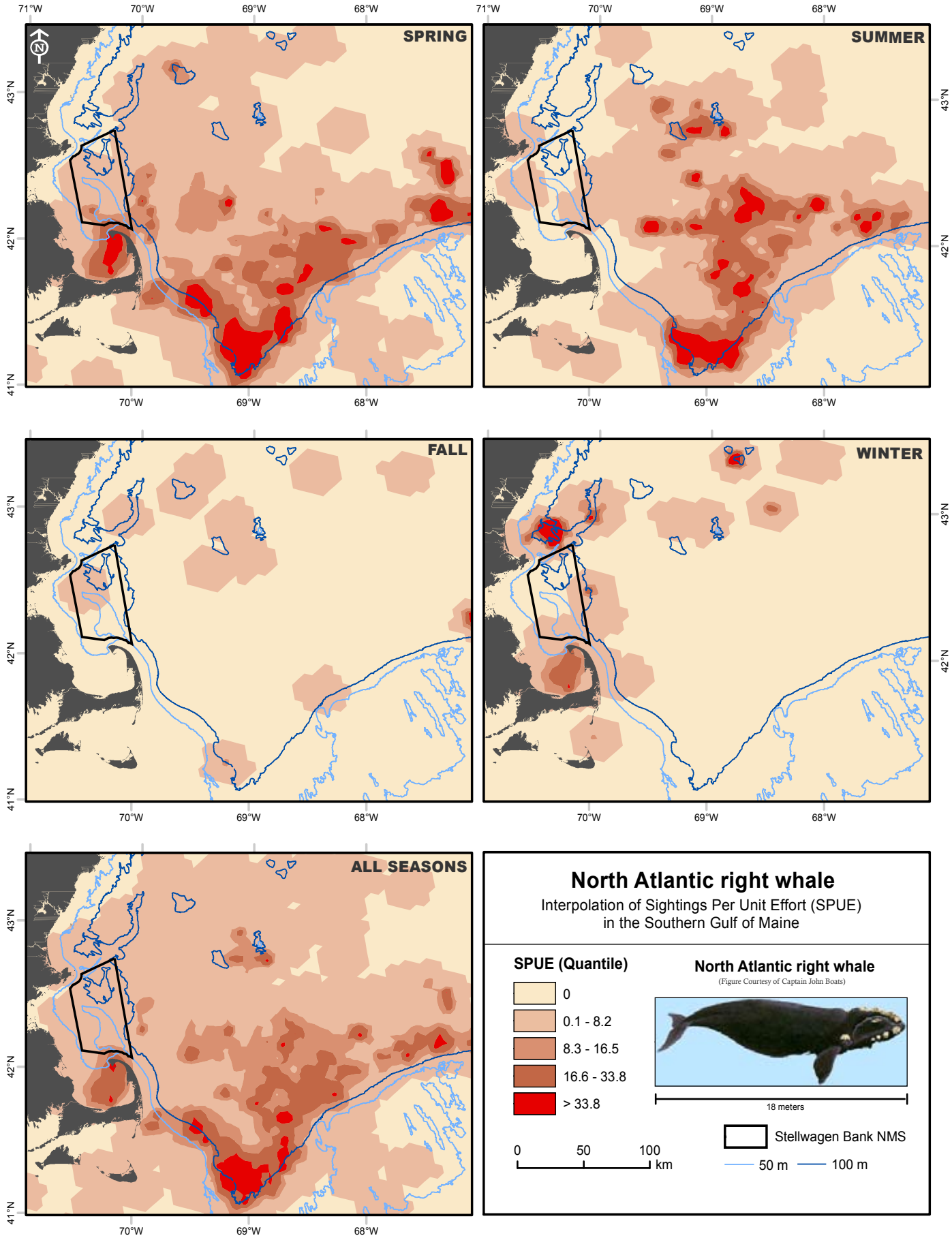


Figure 5.3.4. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for North Atlantic right whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

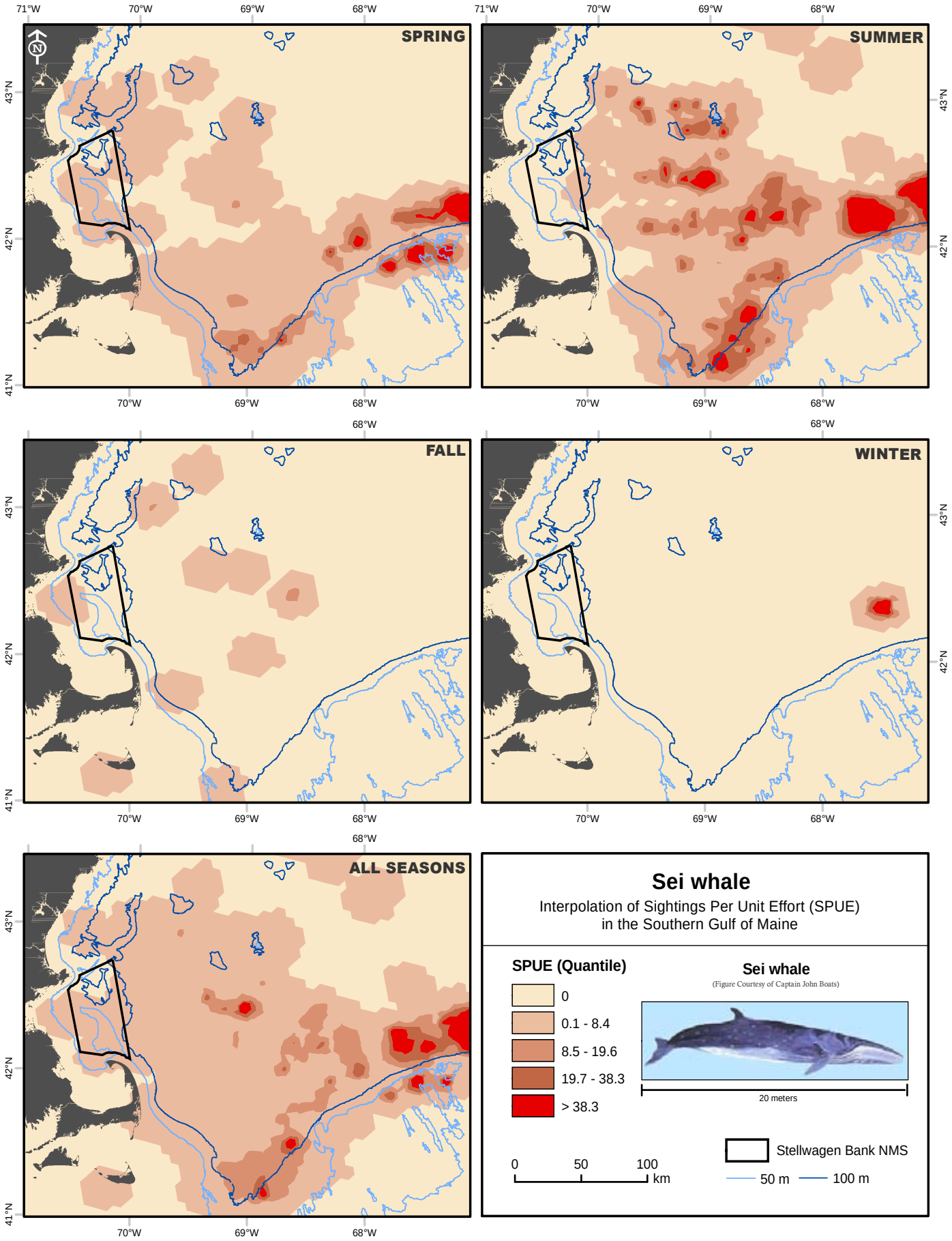


Figure 5.3.5. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for Sei whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

Pilot whale

Pilot whales arrive in the southern Gulf of Maine in spring, with highest SPUE in the region occurring in summer and fall (Table 5.3.1). Summer high-use areas included the slopes of northern Georges Bank along the 100-m isobath and pilot whales made extensive use of the shoals of Georges Bank (<60 m depth) (Figure 5.3.6). Similarly, fall distributions were also primarily along the slopes of northern Georges Bank, but with high-use areas also occurring amongst the deep-water basins and ledges of the south-central Gulf of Maine. Within SBNMS, pilot whales were sighted infrequently and were most often estimated at low density (max SPUE = <73). Cape Cod Bay and southern SBNMS were the only locations with pilot whale sightings for winter.

Atlantic white-sided dolphin

In spring, summer and fall, Atlantic white-sided dolphins were widespread throughout the southern Gulf of Maine, with the high-use areas widely located either side of the 100-m isobath along the northern edge of Georges Bank, and north from the Great South Channel to Stellwagen Bank, Jeffreys Ledge, Platts Bank and Cashes Ledge (Figure 5.3.7). In spring, high-use areas exist in the Great South Channel (max SPUE = 1762.3), northern Georges Bank (max SPUE = 1923.1), the steeply sloping edge of Davis Bank and Cape Cod (max SPUE = 2136.9), southern Stellwagen Bank (max SPUE = 1019.7) and the waters between Jeffreys Ledge and Platts Bank (max SPUE = 4046.2). In summer, there is a shift and expansion of habitat toward the east and northeast. High-use areas were identified along most of the northern edge of Georges Bank between the 50- and 200-m isobaths and northward from the Great South Channel along the slopes of Davis Bank and Cape Cod. High SPUE was also recorded over Truxton Swell, Wilkinson Basin, Cashes Ledge and the bathymetrically complex area northeast of Platts Bank. High SPUE of white-sided dolphin was recorded within SBNMS in all seasons, with highest density in summer (max SPUE = 1246.9) and most widespread distributions in spring located mainly over the southern end of Stellwagen Bank (max SPUE = 1019). In winter, high SPUE (max SPUE = 168.6) was recorded at the northern tip of Stellwagen Bank and Tillies Basin.

All baleen and all dolphins and porpoise

A comparison of spatial distribution patterns for all baleen whales (Mysticeti) and all porpoises and dolphins combined showed that both groups have very similar spatial patterns of high- and low- use areas (Figures 5.3.8 and 5.3.9). The baleen whales, whether piscivorous or planktivorous, were more concentrated than the dolphins and porpoise. They utilized a corridor that extended broadly along the most linear and steeply sloping edges in the southern Gulf of Maine indicated broadly by the 100 m isobath. Stellwagen Bank and Jeffreys Ledge supported a high abundance of baleen whales throughout the year. Species richness maps indicated that high-use areas for individual whales and dolphin species co-occurred, resulting in similar patterns of species richness primarily along the southern portion of the 100-m isobath extending northeast and northwest from the Great South Channel (Figure 5.3.10). The southern edge of Stellwagen Bank and the waters around the northern tip of Cape Cod were also highlighted as supporting high cetacean species richness. Intermediate to high numbers of species are also calculated for the waters surrounding Jeffreys Ledge, the entire Stellwagen Bank, Platts Bank, Fippennies Ledge and Cashes Ledge. Note that the number of species data used here were not effort-corrected and therefore should be interpreted alongside effort maps, since diversity estimates are known to be influenced by sampling effort.

Cetacean-environment modeling

We used two statistical modeling techniques (CART and MARS) to quantitatively characterize the relationship between cetacean species and their environment. Both CART and MARS modeling techniques performed best for seasons with the highest cetacean abundance (spring and summer) (MARS max. adj. r^2 = 0.36 to 0.73). Within seasons, model performance was best (higher r^2) for the most abundant species/groups (all dolphins/porpoise; all Mysticeti and humpback whale), with the exception of North Atlantic right whale (Table 5.3.2). The relationship between total SPUE for each species/group and model performance was relatively strong (r^2 = 0.48). In contrast, for most species, winter and fall models performed poorly (MARS max. adj. r^2 = <0.3). Hence, only the model results for the spring and summer are presented.

Overall, there was significant non-linearity in the relationships between cetaceans and their environment. Comparisons between model performance using linear regression and non-linear regression revealed that an average of 16% more variation in cetacean abundance was explained using non-linear models in the spring and 14% more in the summer (Table 5.3.3). Non-linearity in the relationship between SPUE and environmental vari-

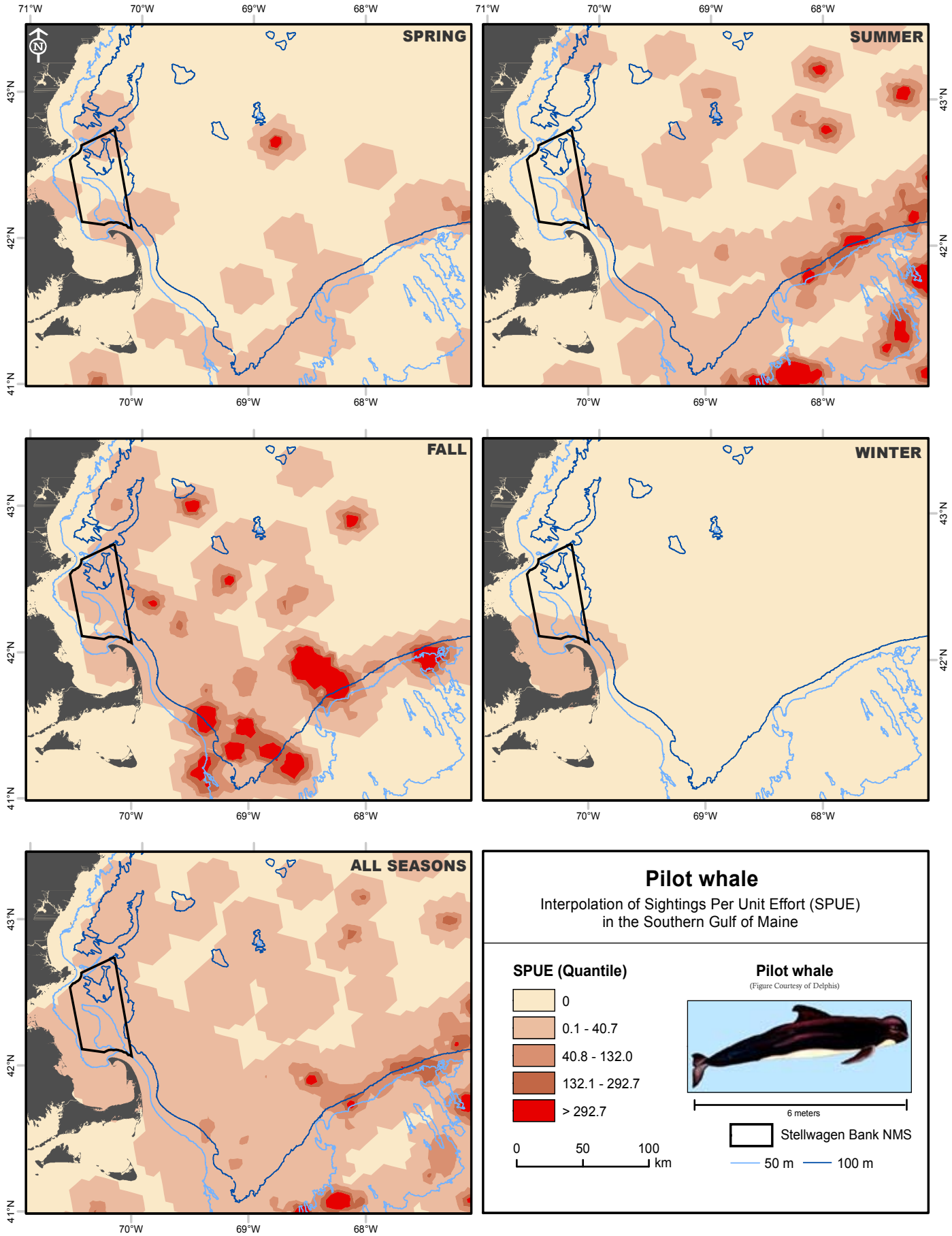


Figure 5.3.6. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for Pilot whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

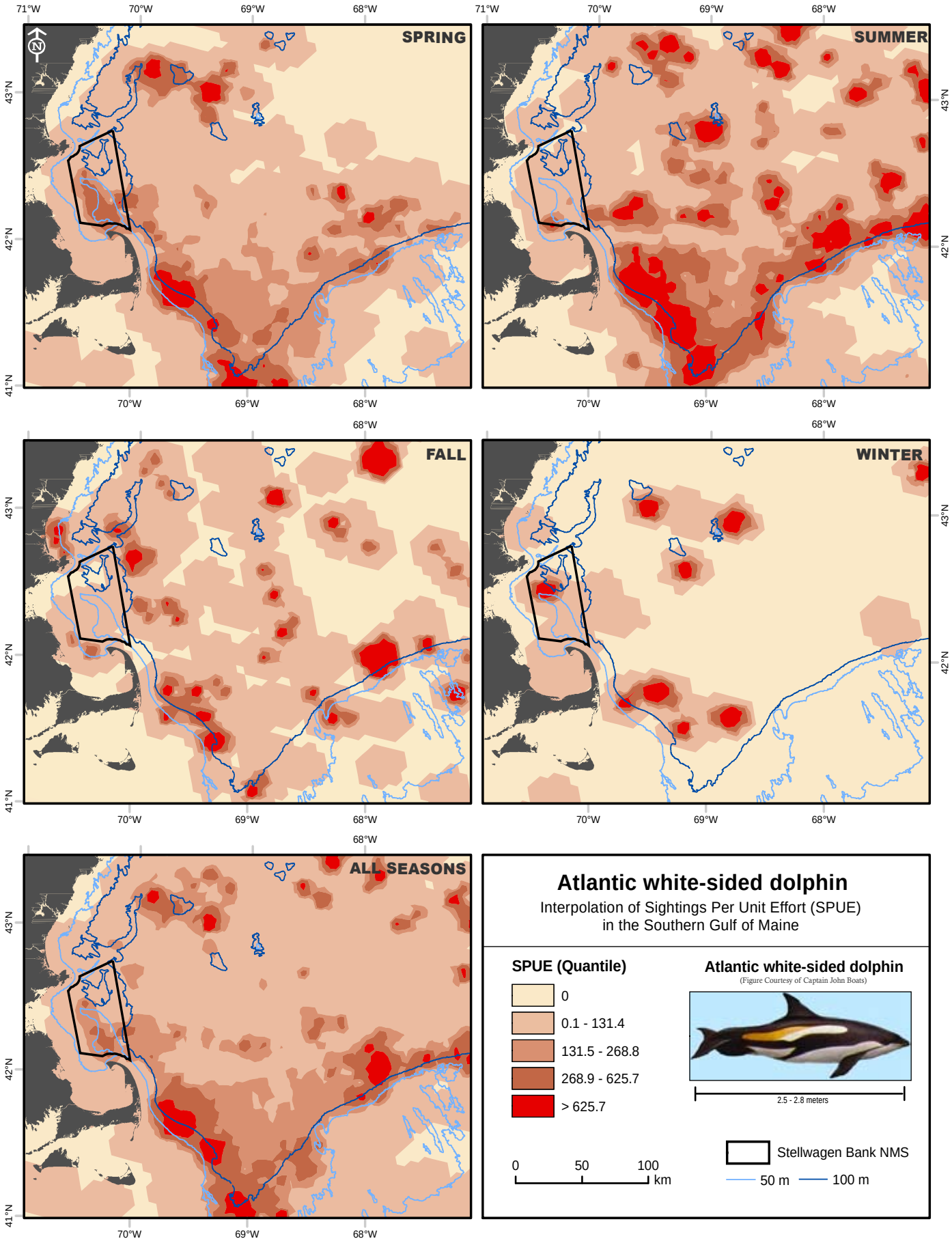


Figure 5.3.7. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for Atlantic white-sided dolphin in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

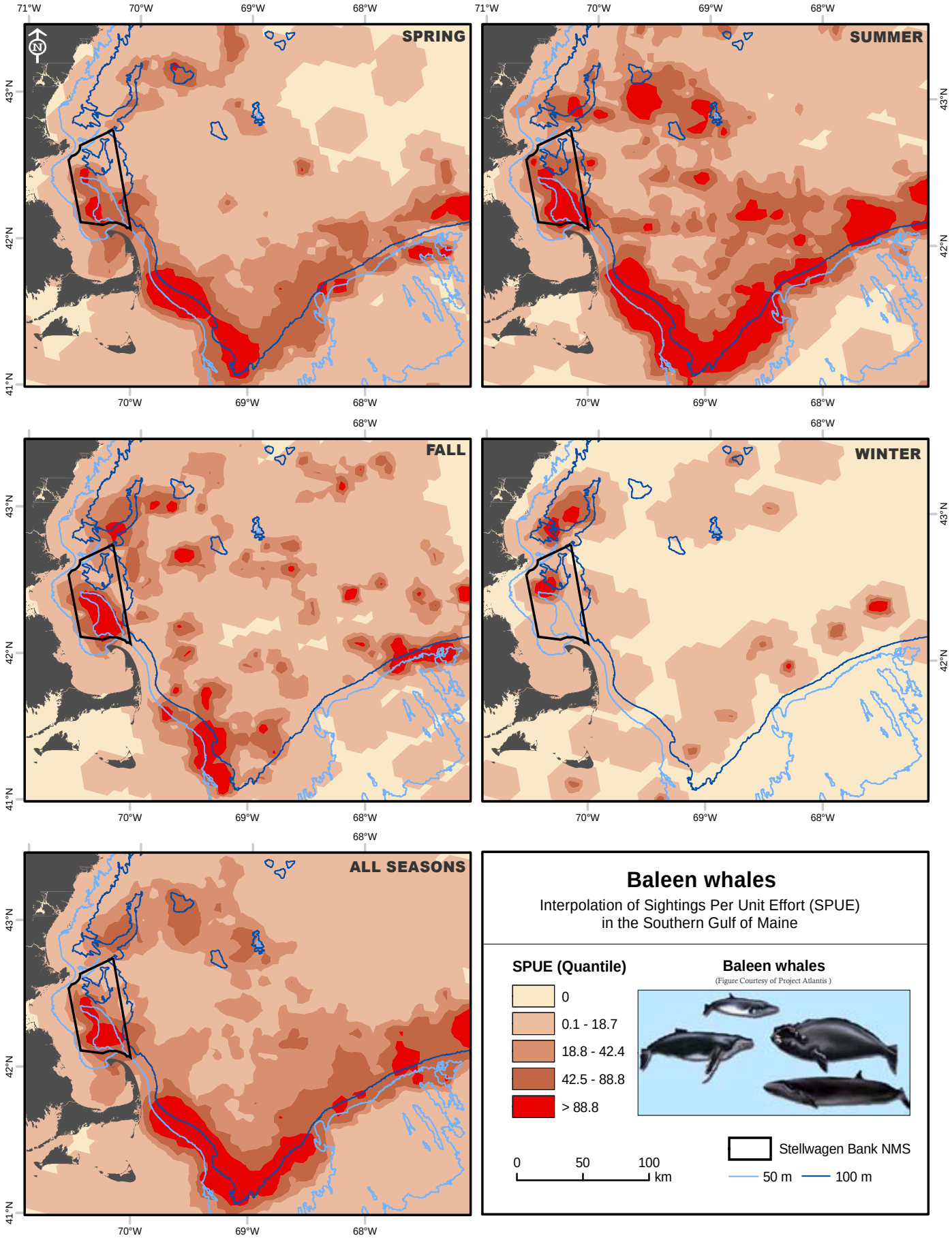


Figure 5.3.8. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for all Baleen whales (Mysteceti) in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

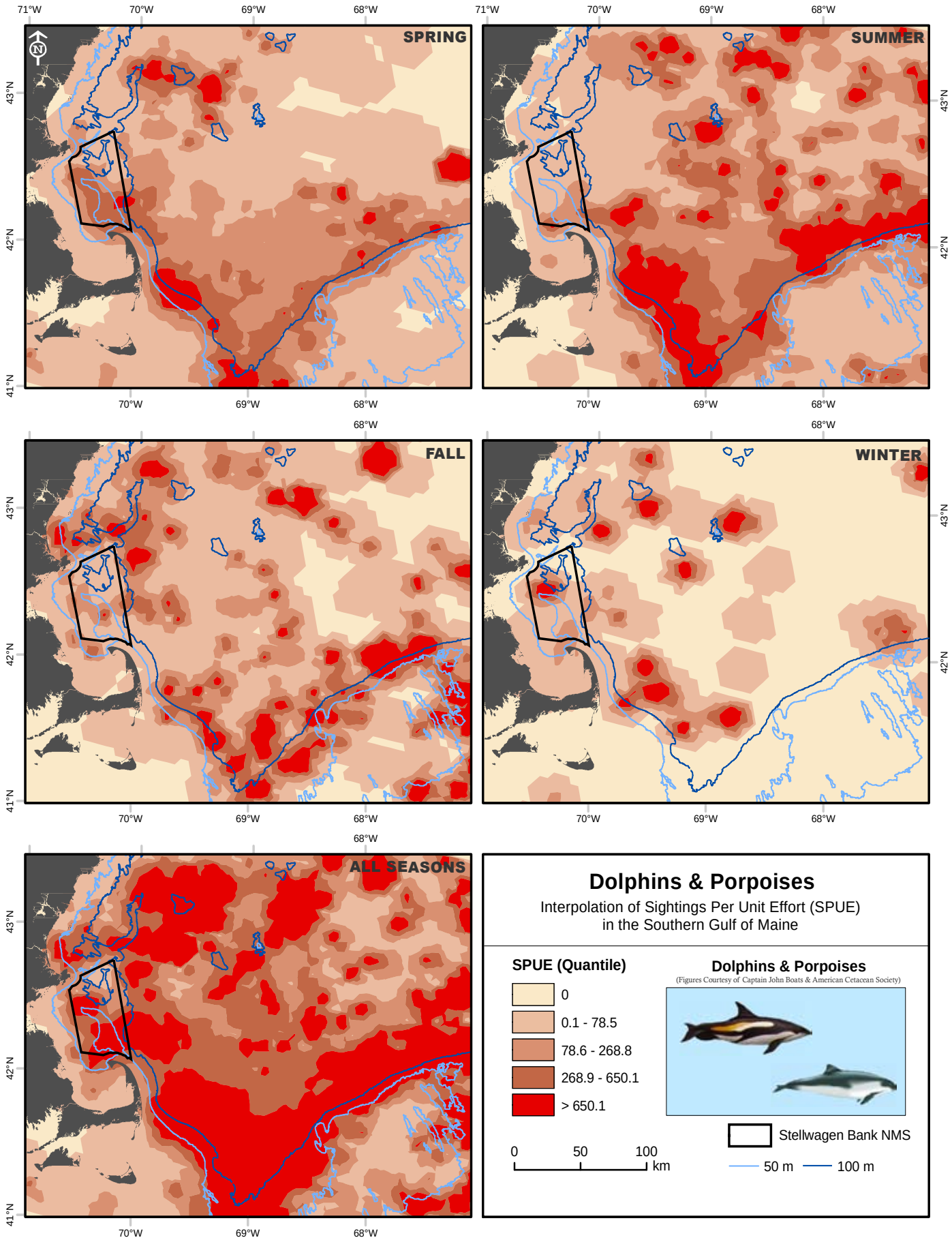


Figure 5.3.9. Seasonal patterns of interpolated sightings-per-unit-effort (SPUE) data for all dolphins and porpoise in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

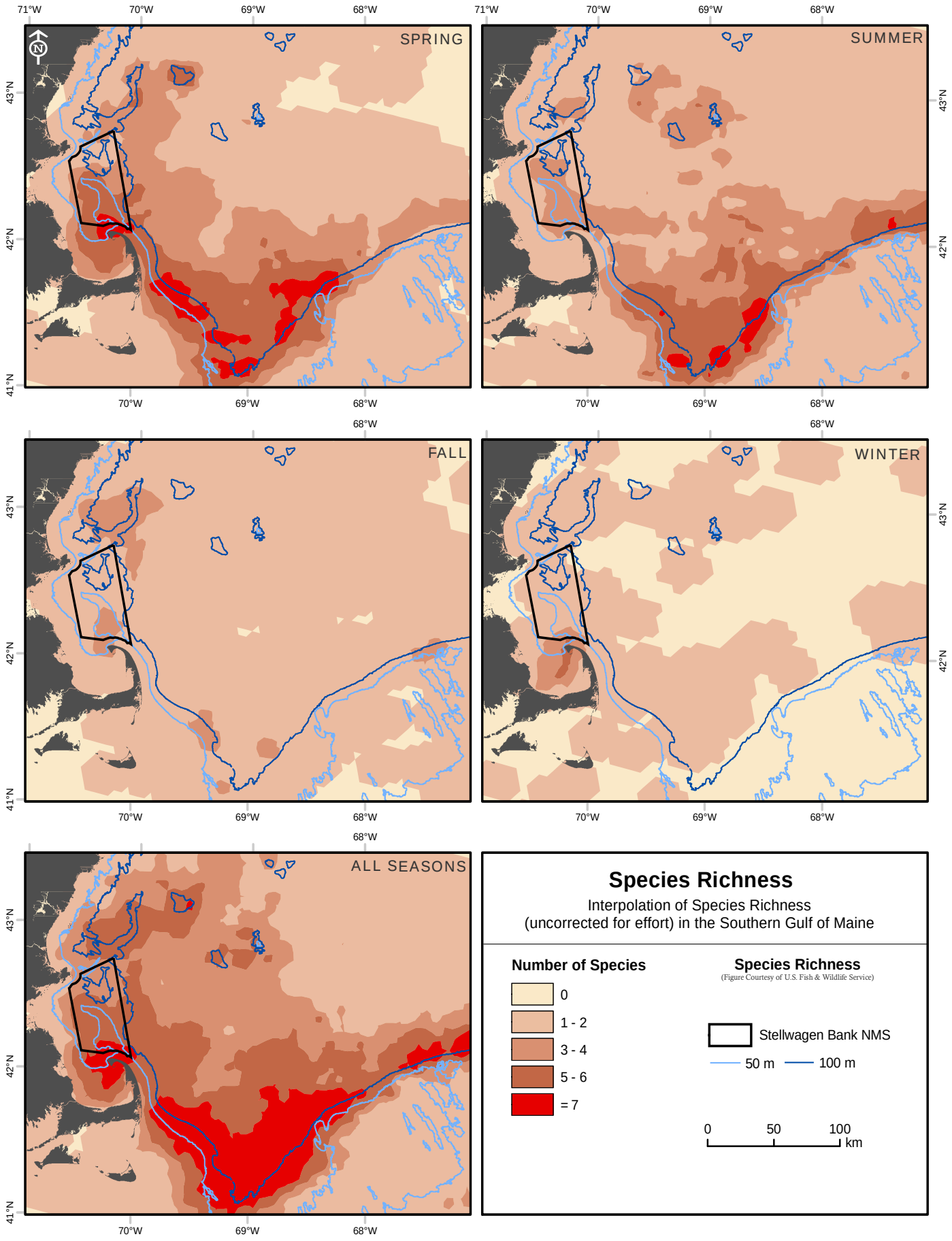


Figure 5.3.10. Seasonal patterns of cetacean species richness (number of species) in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005). SPUE values are animals per 1000 km of standardized survey track.

ables was greatest for humpback whales in spring and sei whales in the summer (Table 5.3.3). However, linear models for all baleen whales (Mysticeti) combined, all dolphins and porpoise combined, and North Atlantic right whale for both spring and summer performed reasonably well, explaining approximately 42 to 57 percent of the variation in abundance. Overall, static environmental variables were more useful predictors of spatial patterns in cetacean SPUE than more dynamic environmental predictors (Table 5.3.4). Below is a summary of the model outputs from MARS and CART models for each of the baleen whale species, and for the Atlantic white-sided dolphin.

Table 5.3.2. Comparison between model performance (measured by r^2) using linear and non-linear regression techniques within MARS™ software. Coefficients of determination equal to and more than 0.6 are shown in bold.

Species/Group	Model performance			
	Spring		*Summer*	
	Linear	*Non-linear*	*Linear*	*Non-linear*
Humpback whale	0.31	**0.63**	0.39	**0.60**
Fin whale	0.35	0.47	0.31	0.43
Minke whale	0.23	0.36	0.23	0.37
North Atlantic right whale	0.42	**0.61**	0.42	0.51
Sei whale	0.24	0.41	0.17	0.42
All Mysteceti	0.46	**0.61**	0.42	0.54
Atlantic white-sided dolphin	0.37	0.46	0.35	0.47
All dolphin & porpoise	0.57	**0.73**	0.33	0.46

Table 5.3.3. Summary of MARS model results showing model performance (r^2) and the most influential environmental variables determined by calculating the change in model performance when each variable is excluded from the model. Only predictors that contributed more than 50% to models are listed.

Species/Group	Season	r^2	Best model predictors (>50% contribution)
Humpback whale	Spring	0.63	Dist. 100 m isobath, Dist. shelf, Dist. shore
	Summer	0.60	Dist. 100 m isobath
Fin whale	Spring	0.47	Dist. 100 m isobath
	Summer	0.43	Dist. 100 m isobath, SST
Minke whale	Spring	0.36	Dist. 100 m isobath, Water depth, Dist. shore, Zooplankton abund.
	Summer	0.37	Dist. 100 m isobath
North Atlantic right whale	Spring	0.61	Dist. shelf, water depth, SST
	Summer	0.51	Chlorophyll *a*, Dist. shelf, Water depth
Sei whale	Spring	0.41	Dist. shelf, Water depth
	Summer	0.42	Water depth, Dist. shelf, Dist shore
Atlantic white-sided dolphin	Spring	0.46	Water depth, Dist. shelf, Dist shore, All fish abund., SST
	Summer	0.47	Zooplankton abund., SST, Dist. shelf, Water depth

Humpback whale

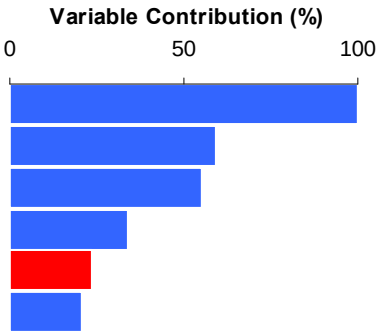
Spring: MARS (r^2 = 0.63) determined that the spatial patterns in humpback whale relative abundance (SPUE) were explained primarily by: 1) distance to the 100 m isobath; 2) distance to the shelfbreak; and 3) distance to shore (Table 5.3.4a.). Along the 100-m isobath, higher SPUE was found between the 100- and 220-m depth zone (Figure 5.3.11a), with a pronounced threshold evident at approximately 30 km from the 100-m isobath, beyond which the influence of the 100-m isobath was minimal (Figure 5.3.11a). In addition, positive linear relationships were found between SPUE and: 1) the amount of sand and gravely sand; 2) the abundance of all fish species combined; and 3) with sand lance abundance (interpolated) (Figure 5.3.11a). CART analysis determined that the highest mean SPUE existed <18.2 km from the 100 m isobath, 20.9 to 158 km from shore, and where sand lance were present even at low relative abundance.

Summer: Distance to the 100-m isobath was also the most important predictor for the summer model of humpback whale SPUE (MARS, r^2 = 0.56) (Table 5.3.5b), with highest abundance found within 30 km of the 100-m isobath. SST was less influential than bathymetry, but exhibited a positive relationship with humpback SPUE, as few individuals were sighted in water less than 14°C (Table 5.3.4b and Figure 5.3.11b). In addition, CART analysis determined that the highest mean SPUE was found within 16 km of the 100-m isobath, in water deeper than 164 m deep, and where SST was greater than 14.7°C.

Table 5.3.4 List of the most influential variables determining spatial patterns in Humpback whale abundance in the southern Gulf of Maine for a) spring and b) summer based on the cost of omission calculated by MARS™ software. Only variables with more than 20% contribution are listed. Contribution was based on non-linear models. Directionality (blue = negative; red = positive) was derived from the linear relationship.

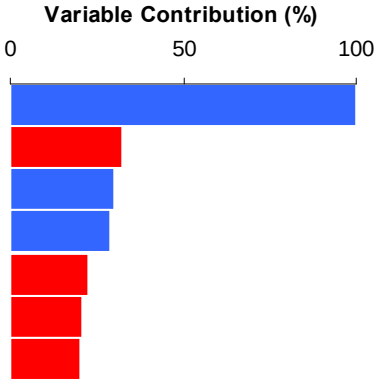
A.

Variable	Cost of omission
Distance 100 m isobath	0.218
Distance to shelfbreak	0.149
Distance to shore	0.144
Mean depth	0.124
Fish abundance (all species)	0.117
Chlorophyll *a* concentration	0.116



B.

Variable	Cost of omission
Distance 100 m isobath	0.414
Sea surface temperature	0.195
Distance to shelfbreak	0.191
Mean stratification	0.189
Distance to shore	0.181
C. finmarchicus abundance	0.179
Mean depth	0.179



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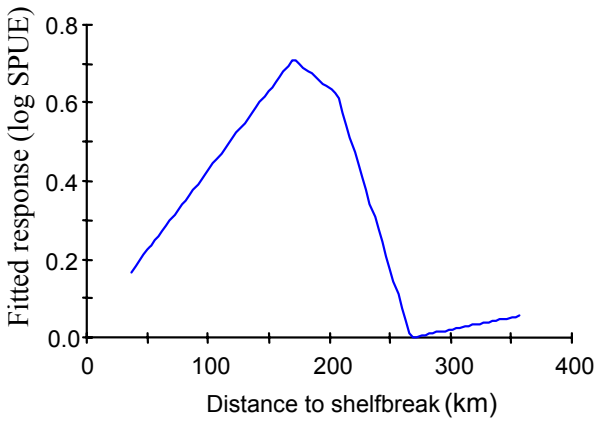
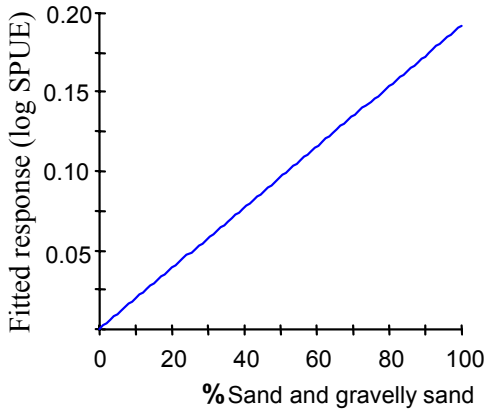
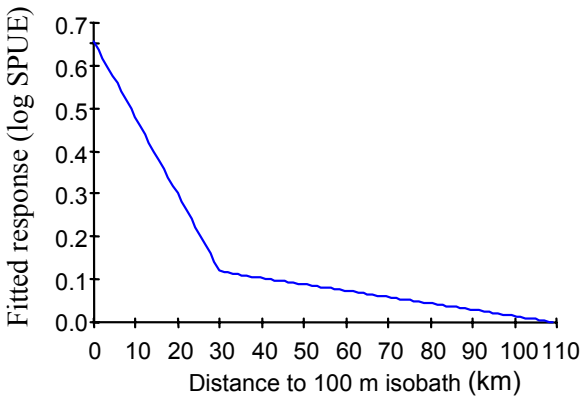
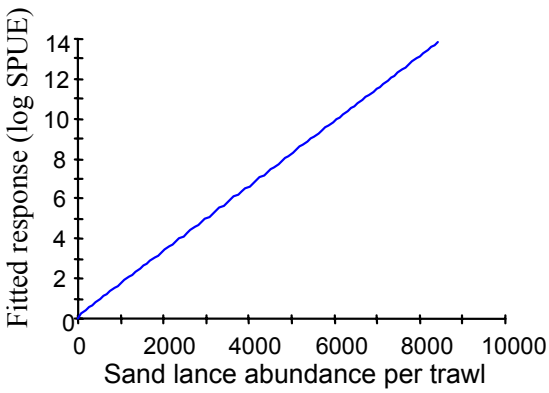
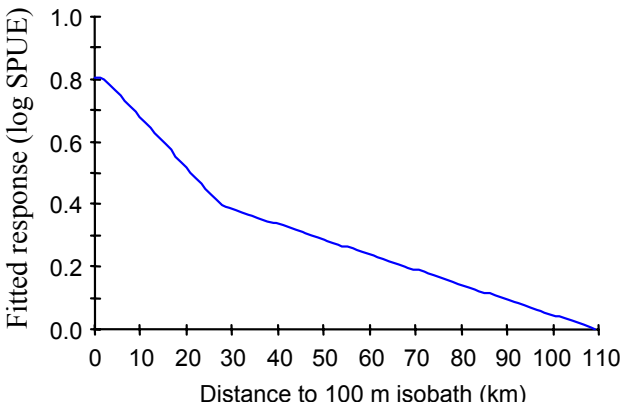








B.



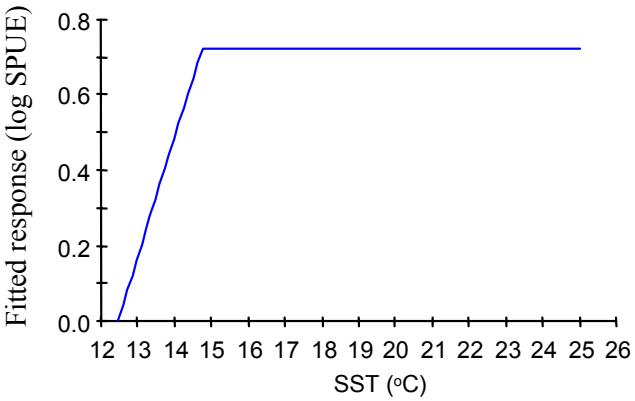


Figure 5.3.11. Plots showing the MARS™ model fit between Humpback whale and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

Fin whale

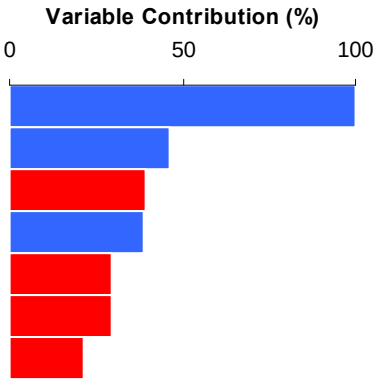
Spring: The spring model (MARS, r^2 = 0.47) determined that the highest SPUE for fin whale occurred within 30 km of the 100-m isobath, and between 100 and 250 km from the shelfbreak (Table 5.3.5a and Figure 5.3.12a). Highest SPUE was also related to intermediate levels of stratification and the presence of sand lance (Figure 5.3.12a). The final CART model determined that highest SPUE was found within 16.2 km of the 100-meter isobath, over substrata with more than 97% sand and gravelly sand, and with mean sand lance abundances greater than 13.9 individuals per trawl.

Summer: In the summer, distance to the 100-m isobath and SST were the most important contributors to the model (MARS, r^2 = 0.43) (Table 5.3.5b). SPUE for fin whale responded strongly to distance from the 100 m isobath, with few individuals utilizing areas beyond 35 km away. Highest SPUE was also associated with proximity (< 200 km) to the shelfbreak and across a wide range of water depths, with a peak at depths of 80-100 m (Figure 5.3.12b). CART identified thresholds for highest fin whale SPUE for grid cells that were less than 16.2 km from the 100-m isobath, and where mean SST was more than 14.7°C.

Table 5.3.5. List of the most influential variables determining spatial patterns in Fin whale abundance in the southern Gulf of Maine for a) spring and b) summer based on the cost of omission calculated by MARS™ software. Only variables with more than 20% contribution are listed. Contribution was based on non-linear models. Directionality (blue = negative; red = positive) was derived from the linear relationship.

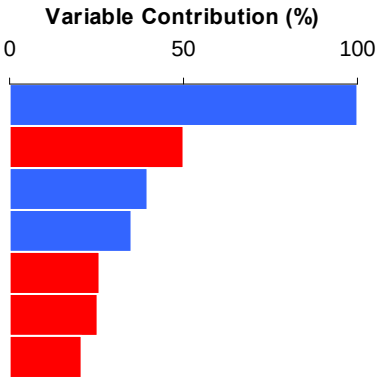
A.

Variable	Cost of omission
Distance 100 m isobath	0.28
Distance to shelfbreak	0.212
Mean stratification	0.207
Distance to shore	0.206
Sand lance abundance	0.201
Herring abundance	0.201
Zooplankton abundance	0.198



B.

Variable	Cost of omission
Distance 100 m isobath	0.423
Sea surface temperature	0.286
Distance to shelfbreak	0.27
Chlorophyll a concentration	0.263
Mean water depth	0.253
Sandy silt and clay	0.252
Zooplankton abundance	0.249



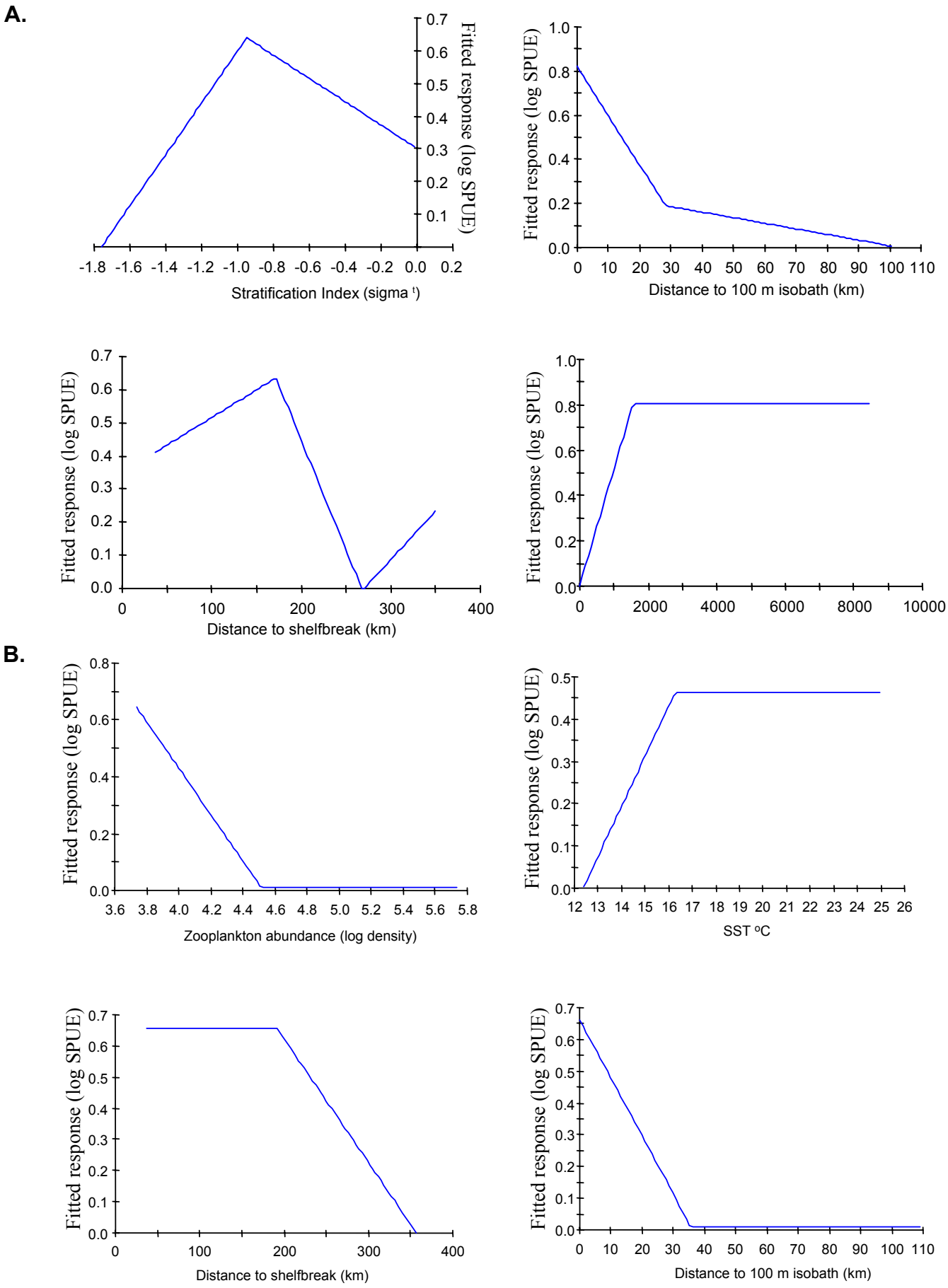


Figure 5.3.12. Plots showing the MARS™ model fit between Fin whale and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

Minke whale

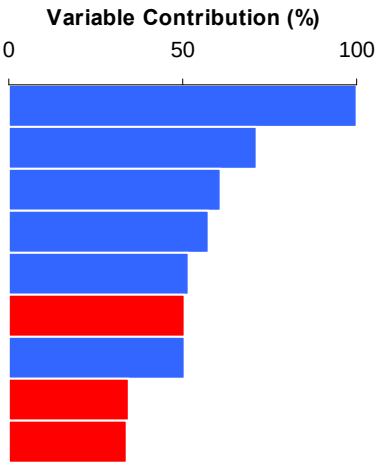
Spring: The best spring model (MARS, r^2 = 0.36) identified distance to the 100-m isobath and mean water depth as key variables explaining spatial patterns in SPUE for minke whale (Table 5.3.6a and Figure 5.3.13a). SPUE declined steeply within the first 20 km from the 100-m isobath, with higher SPUE in waters shallower than 100 m. A strong threshold effect was evident between SPUE and the amount of sand on the seafloor, whereby minke SPUE increased only over substrata with more than 95% sand. A positive linear relationship was also found with sand lance. CART splitting rules characterized high minke SPUE for shallow (<38 m) and sandy (>97.6 %) areas more than 12.8 km from the 100-m isobath, with a mean sand lance abundance of less than 32.1 per trawl. In addition, high mean SPUE cells were found over deeper water (>106 m), less than 12.8 km from the 100-m isobath, and where mean sand lance abundance was greater than 32.1 per trawl.

Summer: The summer minke SPUE model (MARS, r^2 = 0.37) revealed a strong affinity for the shallower waters along the 100-m isobath (Table 5.3.6b and Figure 5.3.13b), with an increase in minke SPUE in the presence of high fish abundance (all species combined). CART identified highest minke SPUE cells within 9.4 km of the 100-m isobath, with SST above 15°C, and with *Calanus finmarchicus* (hereafter *Calanus*) abundance below 3.6 (log density) and chlorophyll *a* concentration above 1.4 ug/l. Additional high SPUE areas, located farther than 9.4 km from the 100-m isobath, were characterized by zooplankton abundance less than 4 (log density) and *Calanus* abundance more than 2.8 (log density m^3).

Table 5.3.6. List of the most influential variables determining spatial patterns in Minke whale abundance in the southern Gulf of Maine for a) spring and b) summer based on the cost of omission calculated by MARS™ software. Only variables with more than 20% contribution are listed. Contribution was based on non-linear models. Directionality (blue = negative; red = positive) was derived from the linear relationship.

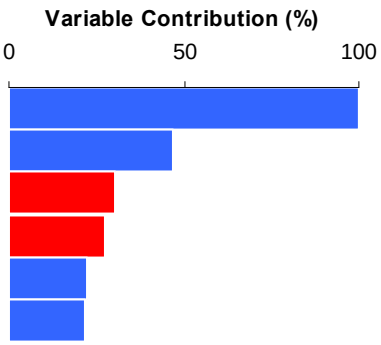
A.

Variable	Cost of omission
Distance 100 m isobath	0.092
Mean depth	0.084
Distance to shore	0.082
Zooplankton abundance	0.081
Gravel	0.08
Gravelly sand	0.08
Chlorophyll *a* concentration	0.08
Sand lance abundance	0.078
Variance in water depth	0.077



B.

Variable	Cost of omission
Distance 100 m isobath	0.183
Distance to shelfbreak	0.144
C. finmarchicus	0.138
Abundance of all fish	0.137
Mean water depth	0.136
Chlorophyll *a* concentration	0.135



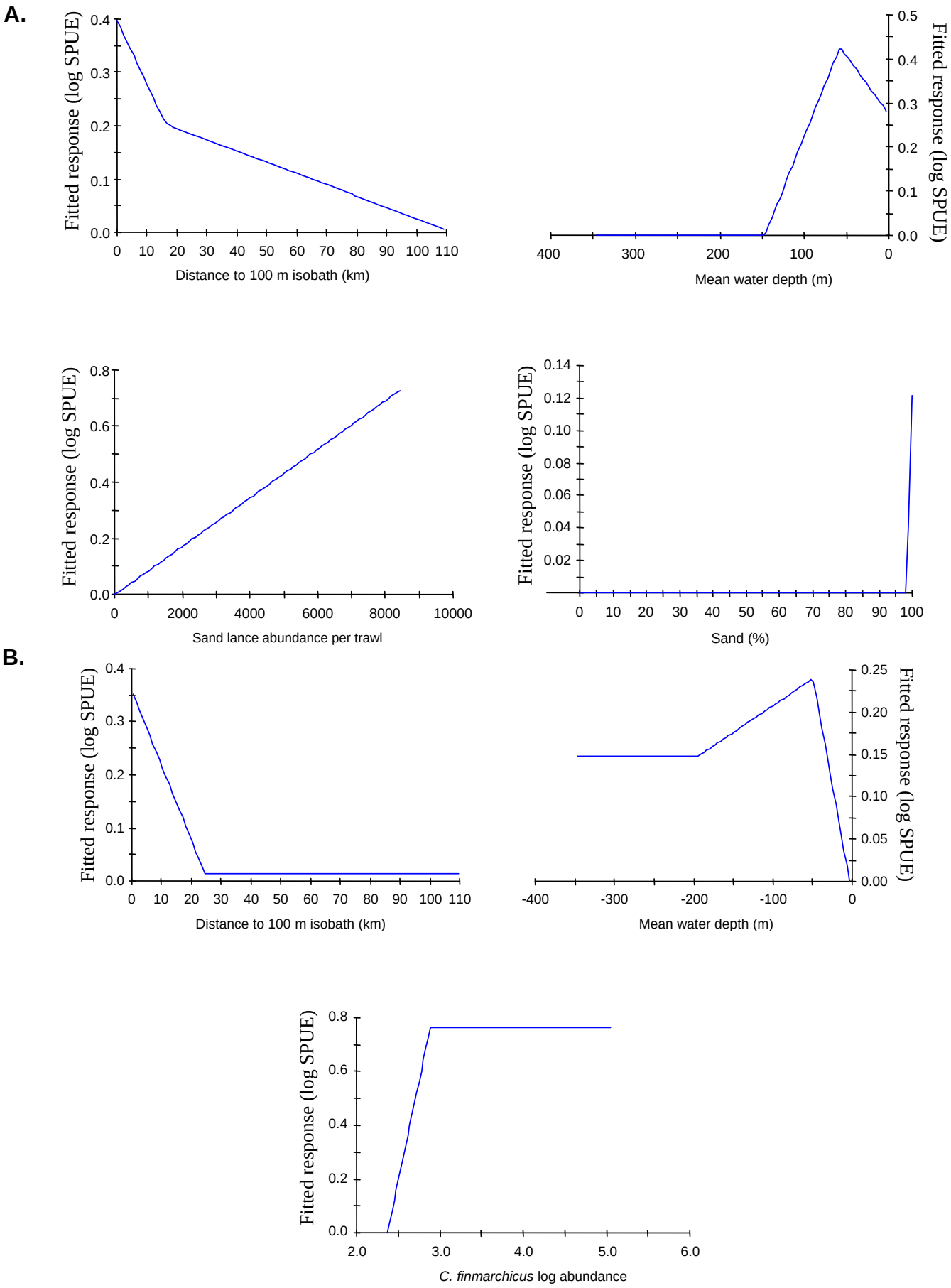


Figure 5.3.13. Plots showing the MARS™ model fit between Minke whale and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

North Atlantic right whale

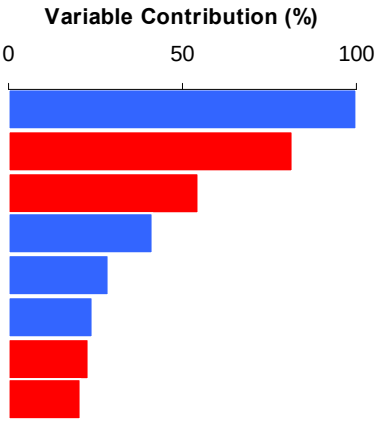
Spring: The best spring model (MARS, r^2 = 0.61) for North Atlantic right whale SPUE used: 1) distance to the shelfbreak; 2) mean water depth; and 3) SST as the main predictors (Table 5.3.7a). Graphs (Figure 3.3.14a) of bivariate relationships showed high SPUE in shallow waters (<50 m) close to shore as well as over deeper waters (100-200 m). The relationship with SST showed low utilization of waters colder than 5°C. CART characterized high SPUE environments where: 1) SST was greater than 6.3°C; 2) mean water depth was less than 85.3 meters; and 3) where the substratum was more than 18.5 % sand and gravelly sand. Additional high right whale SPUE cells were characterized by: 1) SST lower than 6.3°C; 2) mean sand lance abundance higher than 0.6; 3) mean stratification index between -1.1 and -0.2; 4) chlorophyll *a* concentration more than 2.4; and 5) *Calanus* abundance greater than 3.9 (log density).

Summer: For the summer right whale SPUE model, chlorophyll *a* concentration and distance to shelf break together contributed most to the final model (MARS, r^2 = 0.51) (Table 5.3.7b). SPUE decreased with distance from the 100-m isobath, but less steeply than in spring (Figure 5.3.14b). SPUE increased with mean stratification of the water, with highest SPUE associated with the well-stratified waters (Figure 5.3.14b). Zooplankton abundance (all species combined) and abundance of *Calanus* contributed 46% and 45% to the model respectively, with SPUE increasing when zooplankton abundance was greater than 4.4 (log density) (Figure 5.3.14b).

Table 5.3.7. List of the most influential variables determining spatial patterns in North Atlantic right whale abundance in the southern Gulf of Maine for a) spring and b) summer based on the cost of omission calculated by MARS™ software. Only variables with more than 20% contribution are listed. Contribution was based on non-linear models. Directionality (blue = negative; red = positive) was derived from the linear relationship.

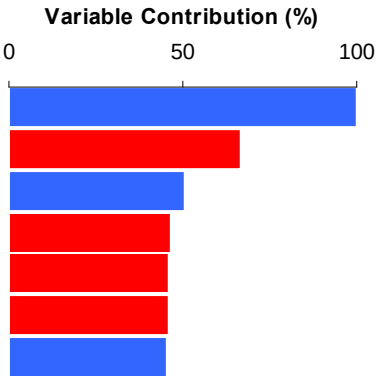
A.

Variable	Cost of omission
Distance to shelfbreak	0.192
Mean water depth	0.165
Sea surface temperature	0.136
Distance to shore	0.126
Variance in water depth	0.119
Distance to 100 m isobath	0.117
Mean stratification	0.117
Chlorophyll *a* concentration	0.116



B.

Variable	Cost of omission
Chlorophyll *a* concentration	0.092
Distance to shelfbreak	0.082
Mean water depth	0.081
Sea surface temperature	0.08
Zooplankton abundance	0.08
C. finmarchicus abundance	0.078
Clay	0.077



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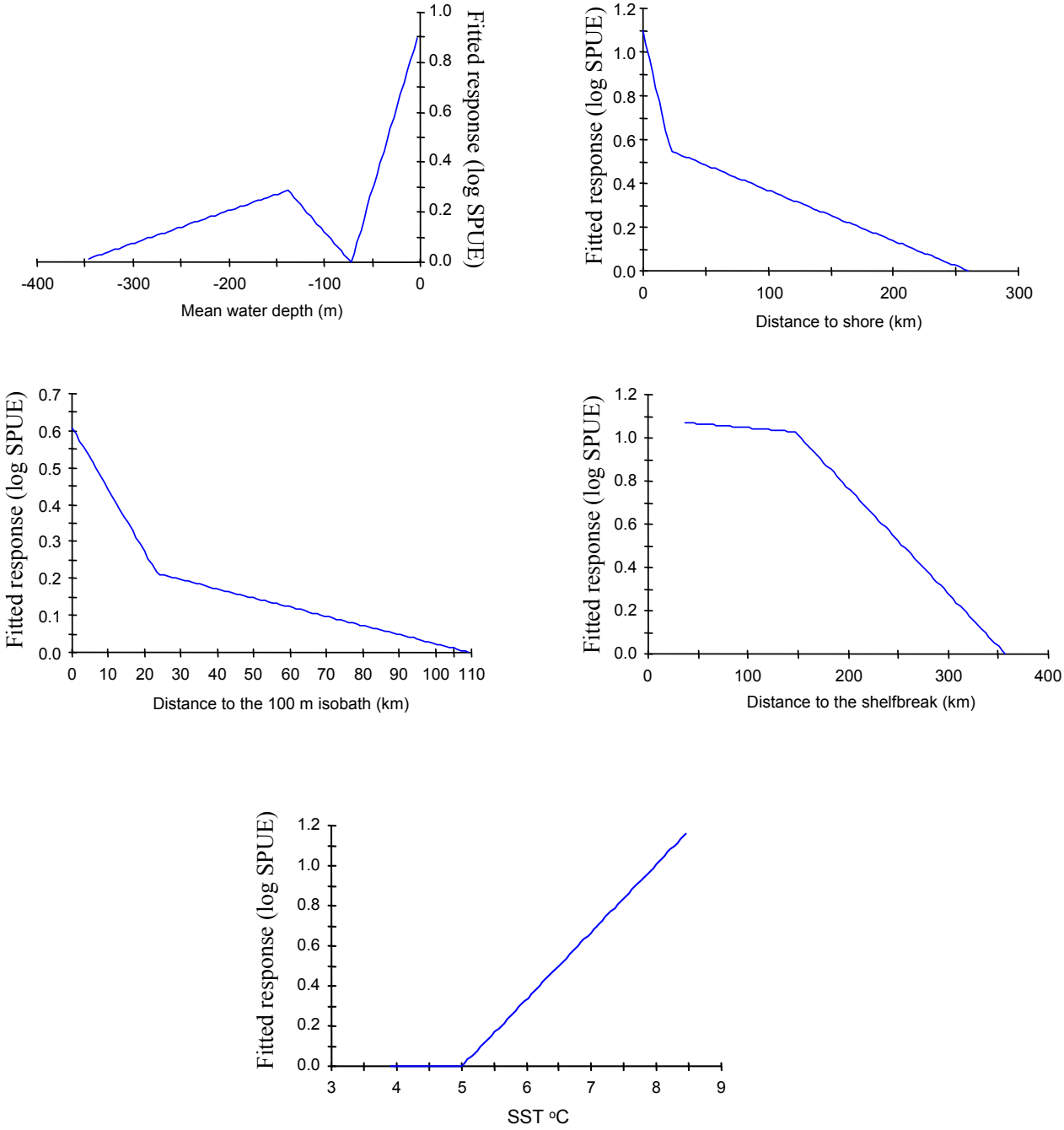


Figure 5.3.14. Plots showing the MARS™ model fit between North Atlantic right whale and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

B.

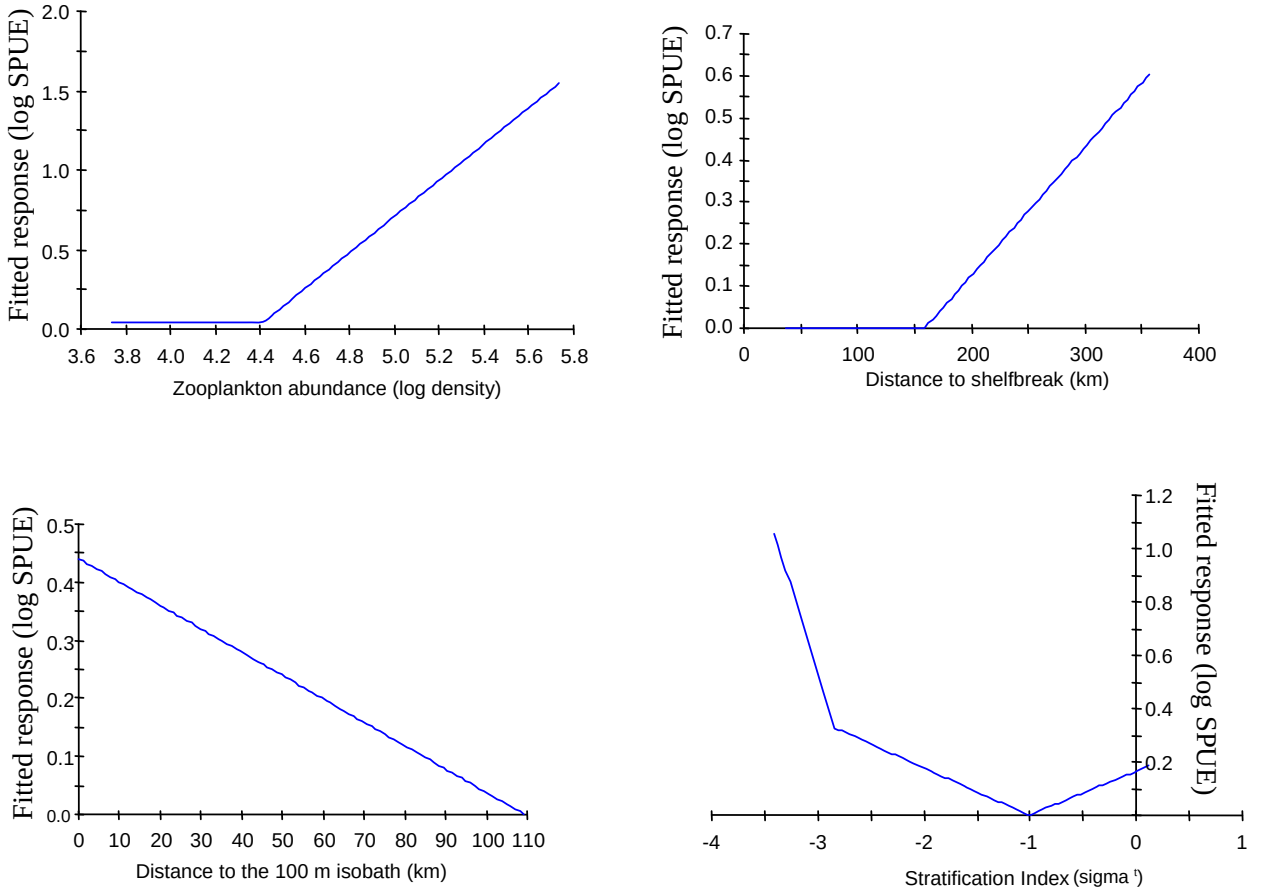


Figure 5.3.14 (Continued). Plots showing the MARS™ model fit between North Atlantic right whale and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

Sei whale

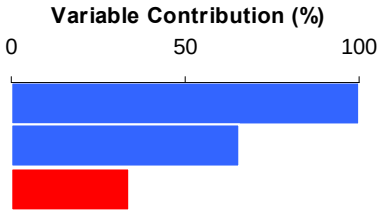
Spring: For the spring model of sei whale SPUE (MARS, r^2 = 0.41) only distance to the shelfbreak and mean water depth contributed substantially to the explanation of spatial patterns (Table 5.3.8a). Generally, sei whale SPUE declined with increasing distance from the shelfbreak, with highest SPUE associated with mean water depths between 200 m and 350 m (Figure 5.3.15a). Sei whales showed an affinity to the 100-m isobath, whereby SPUE declined steeply with increasing distance from this bathymetric feature, with few individuals utilizing waters more than 35 km from the 100-m isobath (Figure 5.3.15a). CART determined that high sei whale SPUE was characterized by: 1) proximity (<25.9 km) to the 100-m isobath; 2) waters shallower than 173 m; 3) SST less than 6.3°C; and 4) substratum with more than 60.3% sand and gravelly sand.

Summer: The summer sei whale SPUE model (MARS, r^2 = 0.42) was largely driven by: 1) mean water depth; 2) distance to the shelfbreak; 3) distance to shore; and 4) zooplankton abundance (Table 5.3.8b). Plots of the fitted relationship (Figure 5.3.15b) indicated a preference for deeper water (> 250 m) and well-stratified water away from shore (>100 km), with a high abundance of *Calanus*. In contrast to the spring model, a gradual decline in summer sei whale SPUE occurred with distance away from the 100-m isobath (Figure 5.3.15b).

Table 5.3.8. List of the most influential variables determining spatial patterns in Sei whale abundance in the southern Gulf of Maine for a) spring and b) summer based on the cost of omission calculated by MARS™ software. Only variables with more than 20% contribution are listed. Contribution was based on non-linear models. Directionality (blue = negative; red = positive) was derived from the linear relationship.

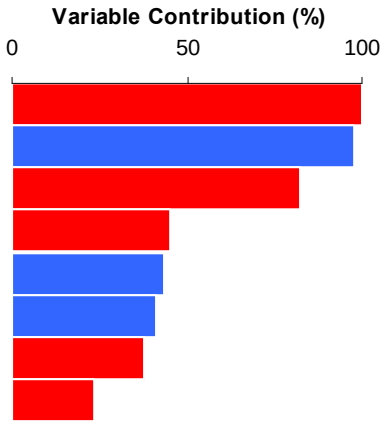
A.

Variable	Cost of omission
Distance to shelfbreak	0.108
Mean water depth	0.087
Distance 100 m isobath	0.075



B.

Variable	Cost of omission
Mean water depth	0.252
Distance to shelfbreak	0.25
Distance to shore	0.234
Zooplankton abundance	0.208
Distance to 100 m isobath	0.207
Variance in water depth	0.206
Mean stratification	0.205
Abundance of all fish	0.2



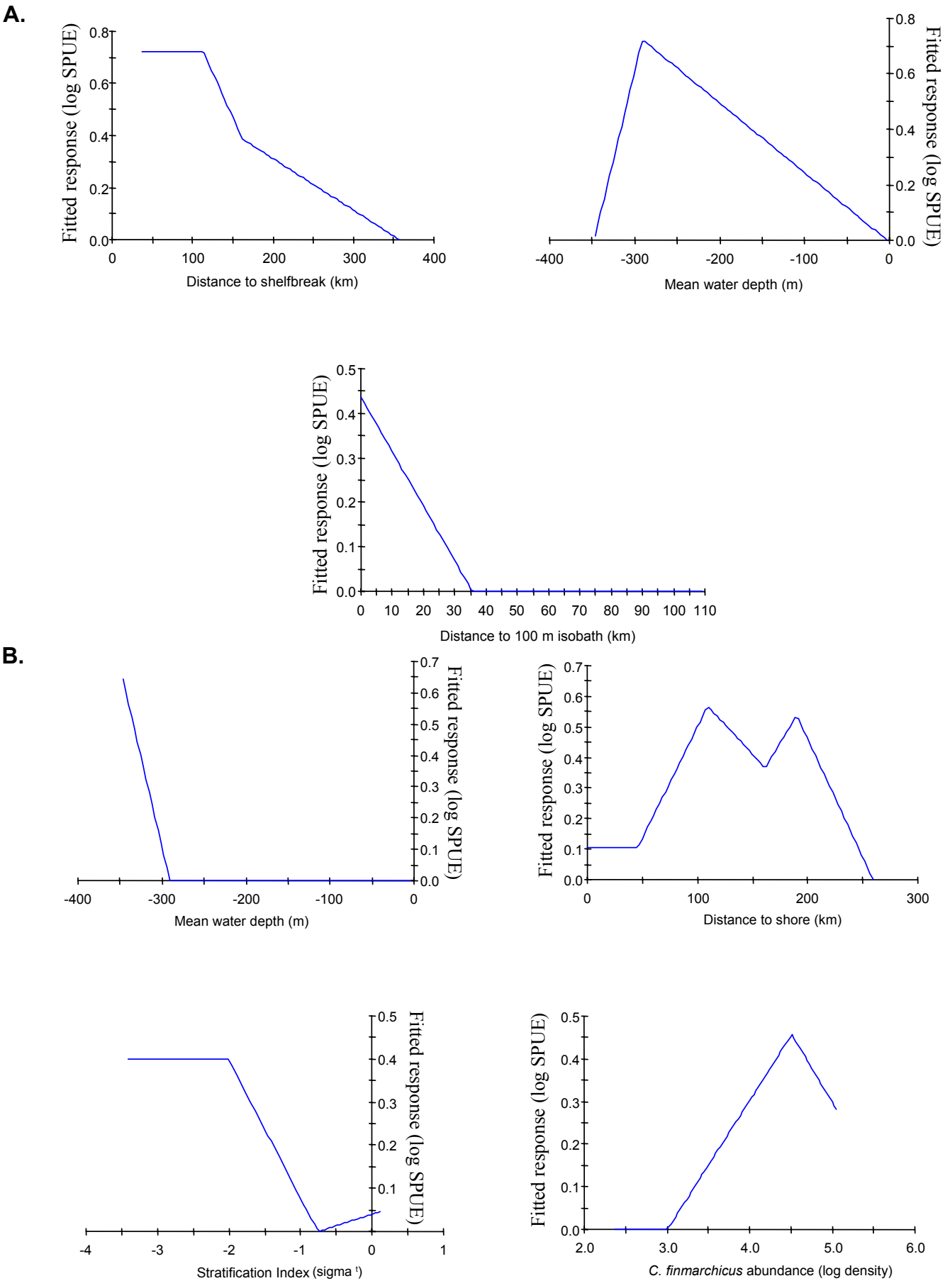


Figure 5.3.15. Plots showing the MARS™ model fit between Sei whale and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

Atlantic white-sided dolphin

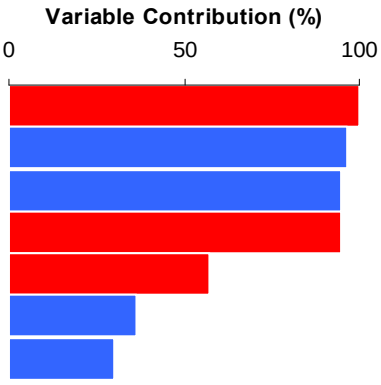
Spring: The spring model for white-sided dolphin (MARS, r^2 = 0.46) was largely driven by: 1) the influence of mean water depth; 2) distance to shelfbreak; 3) distance to shore; and 4) the combined abundance of sand lance, hake, mackerel and herring (Table 5.3.9a). Bivariate relationships between response and predictors indicated a preference for relatively shallow (100 m), well-mixed waters (i.e., low stratification index), close to shore, with a high abundance of small-bodied schooling fish (Figure 5.3.16a). CART characterized high white-sided dolphin SPUE environments as relatively shallow waters (< 59.2 m), less than 15.6 km from the 100-m isobath, and between 85.6 km and 183.5 km from the shelfbreak, with SST more than 6.1°C.

Summer: In summer, the best model (MARS, r^2 = 0.46) for white-sided dolphin SPUE determined that zooplankton abundance, SST and distance to the shelf break explained the largest proportion of variation in SPUE (Table 5.3.9b). Examination of summer bivariate model fitting indicated that peak SPUE occurred over warmer and slightly deeper waters (100 to 200 m) in summer than in spring (Figure 5.3.16b). Highest SPUE was also within 200 km of the shelfbreak (Figure 5.3.16b). CART analysis characterized highest SPUE environments in summeras being within 15.6 km of the 100-m isobath, and with zooplankton abundance less than 4.8 (log density).

Table 5.3.9. List of the most influential variables determining spatial patterns in Atlantic white-sided dolphin abundance in the southern Gulf of Maine for a) spring and b) summer based on the cost of omission calculated by MARS™ software. Only variables with more than 20% contribution are listed. Contribution was based on non-linear models. Directionality (blue = negative; red = positive) was derived from the linear relationship.

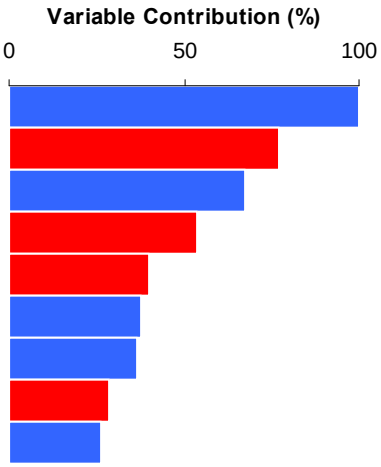
A.

Variable	Cost of omission
Mean water depth	1.215
Distance to shelfbreak	1.193
Distance to shore	1.183
Sand lance, hake, mackerel, herring	1.183
Sea surface temperature	0.999
Distance to 100 m isobath	0.936
Chlorophyll *a* concentration	0.922



B.

Variable	Cost of omission
Zooplankton abundance	1.016
Sea surface temperature	0.973
Distance to shelfbreak	0.958
Mean water depth	0.94
Mean stratification	0.926
Distance to shore	0.924
Clay	0.923
Variance in water depth	0.917
Chlorophyll *a* concentration	0.916



A.

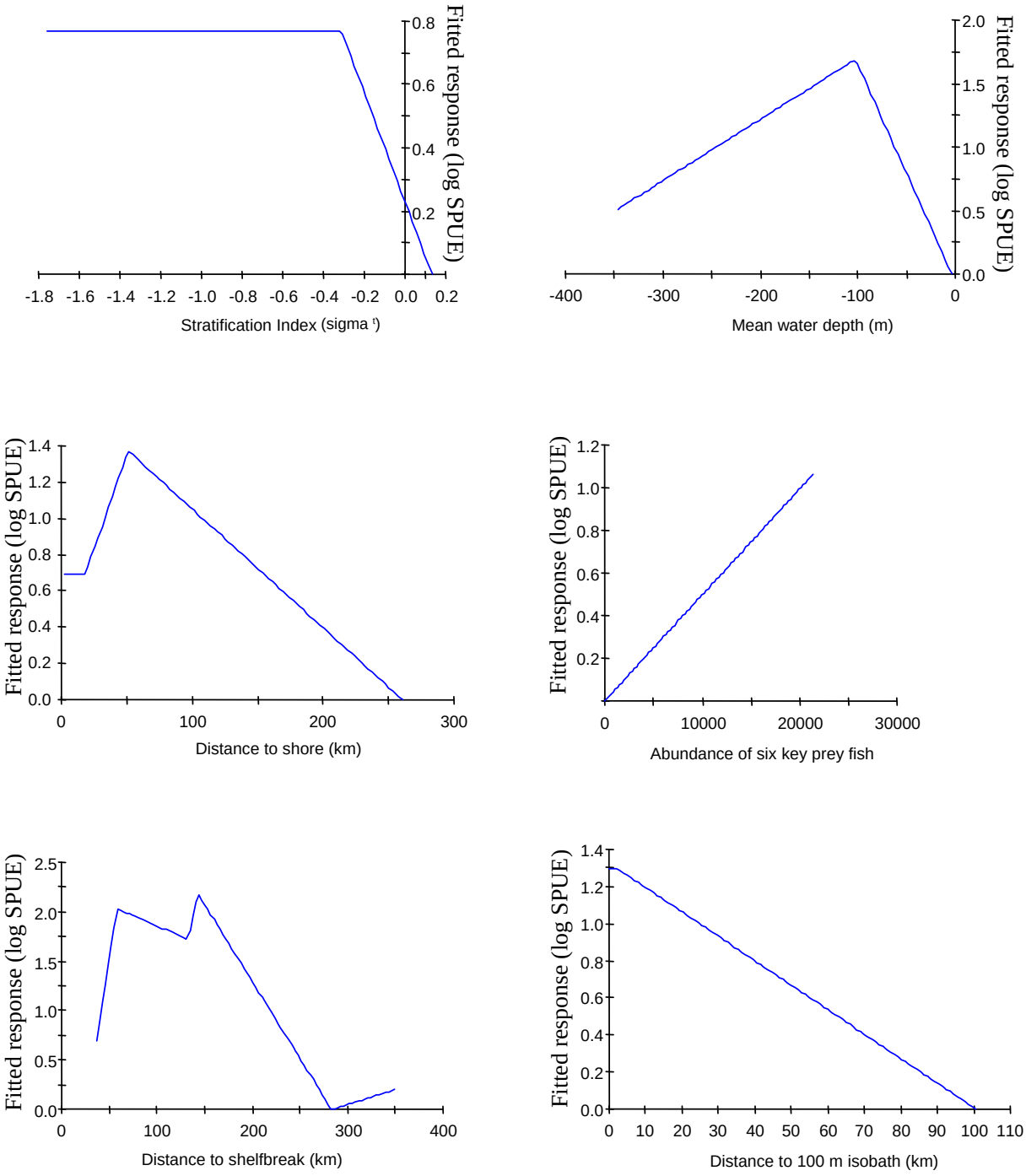


Figure 5.3.16. Plots showing the MARS™ model fit between Atlantic white-sided dolphin and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

B.

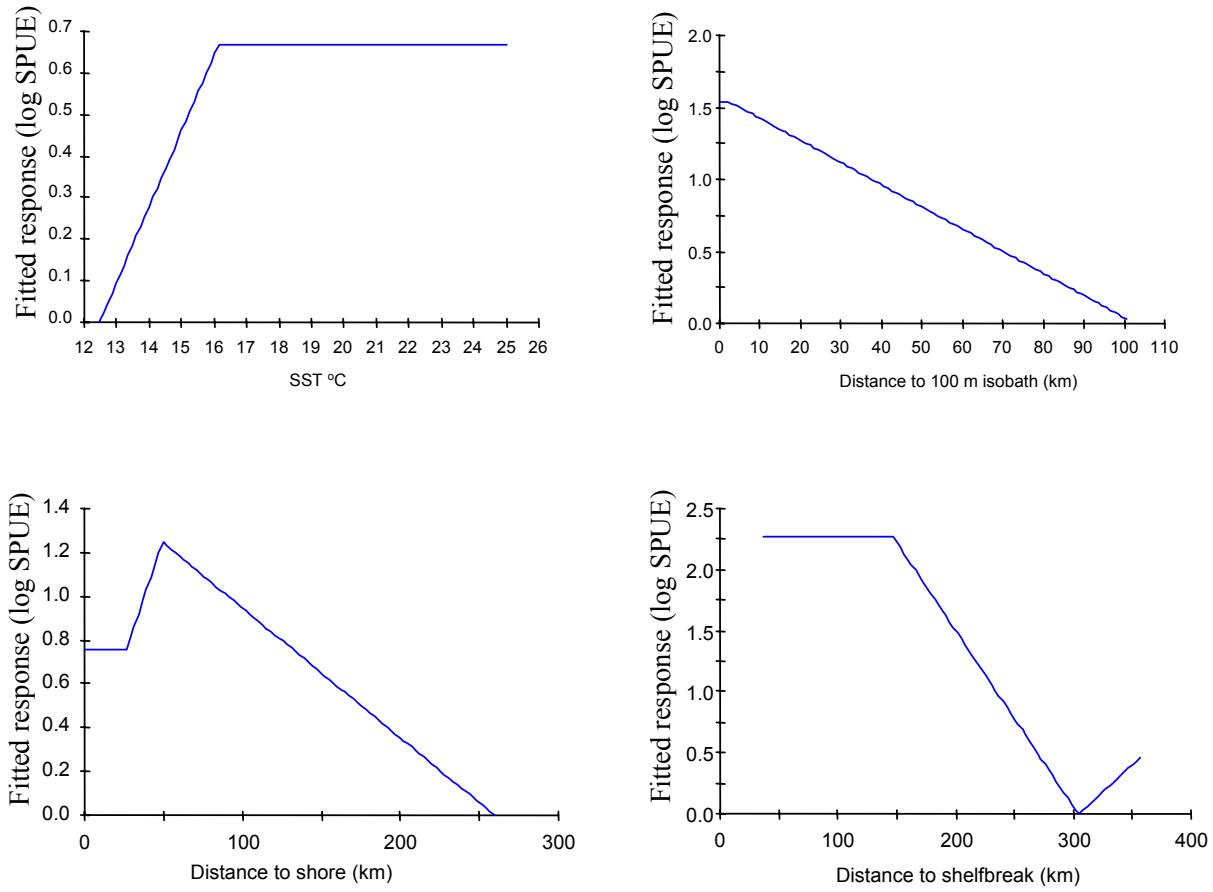


Figure 5.3.16 (Continued). Plots showing the MARS™ model fit between Atlantic white-sided dolphin and several key environmental variables for a) spring b) summer. To improve visual interpretation these plots were generated from additive models, where no interactions between predictors were allowed.

5.4 DISCUSSION

The approach to spatially-explicit modeling developed in this analysis provides a powerful and flexible analytical framework for exploring cetacean-environment linkages and facilitates the integration of a wide range of environmental data with varying spatio-temporal resolutions. We incorporated a wide range of physical, chemical and biological datasets selected to extract the key characteristics of cetacean habitat in the southern Gulf of Maine. Some environmental variables included in this analysis were relatively static features, such as derivatives of bathymetric structure. Others were relatively dynamic, such as prey abundance, sea surface conditions and water column structure (stratification). In general, we found that static features, most notably the 100-m isobath and the continental shelf edge, were better predictors of cetacean SPUE distribution patterns than were dynamic features, such as SST and chlorophyll *a* concentration. Relatively static high relief areas appear to generate heterogeneous boundary conditions that facilitate elevated secondary productivity that is relatively persistent in time. Cetaceans are likely to respond to these features in both evolutionary and ecological time frames leading to the development of predictable high-use areas. Prey abundance patterns were important components of most models, but unexpectedly made only relatively minor contributions to explaining spatial patterns in cetacean SPUE. The absence of a strong relationship may be due to high spatial and temporal variability in prey abundance, sampling error or scale mismatch between response and predictor. Nevertheless, the interactions between bathymetry, hydrodynamic processes, temperature regimes, phytoplankton, zooplankton and planktivorous fish need to be understood in order to explain spatial patterns in the relative abundance of cetaceans in the southern Gulf of Maine.

Bathymetric features

The shoals and slope waters adjacent to the 100-m isobath were identified as key high-use areas for all abundant cetacean species in the southern Gulf of Maine. In both the spring and summer seasons, all cetacean species and groups exhibited a strong relationship with proximity to the 100-m isobath, with SPUE rapidly declining as distance increased. For much of the study area, the 100-m isobath represents the edge of a steep sandy slope that forms a boundary, or ecotone, between the well-stratified deep-water basins of the Gulf of Maine, the shallow shoals of Nantucket and Georges Bank in the south, and the nearshore coastal shelf in the northwest. The ecotone is present year-round, but is most pronounced from late spring through fall (May to October), when the thermohaline density gradients are greatest (Flagg, 1987). The existence of a thermal front that parallels the 100-m isobath and the importance to cetaceans are well recognized (Winn *et al.,* 1986; Brown and Winn, 1989; Kenney, 2001). Relatively static features, such as bathymetric structure and associated water depth, have been found to be good predictors of the distribution of cetacean species (Hooker *et al.,* 1999; Hyrenbach *et al.,* 2001). Hooker *et al.* (1999) suggested that isobaths may be used effectively to delineate protected area boundaries for cetaceans.

To visually illustrate the influence of bathymetry on a suite of environmental variables, we show a sub-section of the summer ecotone along the 100-m isobath on the northern slopes of Georges Bank (Figure 5.4.1). In comparing attributes of deep waters north of the 100-m isobath to those in the south, we see that waters north of the 100-m isobath were warmer at the surface and well-stratified between 0 and 50 m depth. They also had lower chlorophyll *a* concentration, lower total zooplankton abundance, and supported a higher abundance of *Calanus*. Similar environmental interactions produce hydrographic fronts across the Great South Channel in the southern Gulf of Maine, as well as in the lower Bay of Fundy and Browns Bank region (northern Gulf of Maine). These areas have been identified as important feeding grounds for North Atlantic right whale (CETAP, 1982; Wishner *et al.,* 1988; Brown and Winn, 1989; Murison and Gaskin, 1989; Kenney, 2001).

Along the northern edge of Georges Bank, where depth increases rapidly from 60 m to 200 m in a relatively short distance (<30 km), a strong west-east current enhances the boundary (Flagg, 1987). Current speeds are highest along the shallow slopes and decrease at depths greater than 60 m. In a transect across the bank edge, Butman *et al.* (1987) reported markedly lower current speeds for waters north of the 100-m isobath (Butman *et al.,* 1987). The 100-m isobath, therefore, also represents a relatively stable transition zone between fast- and slow-moving water. The functional relationship between current speed and cetacean behaviour is unclear. In addition, little is known about the species-specific preferences for water movement. It is feasible that slower current speeds may reduce the energy required for cetaceans to maintain their position while feeding or resting. Alternatively, higher current velocities may disperse high-density zooplankton patches that are fed upon by planktivorous whales and

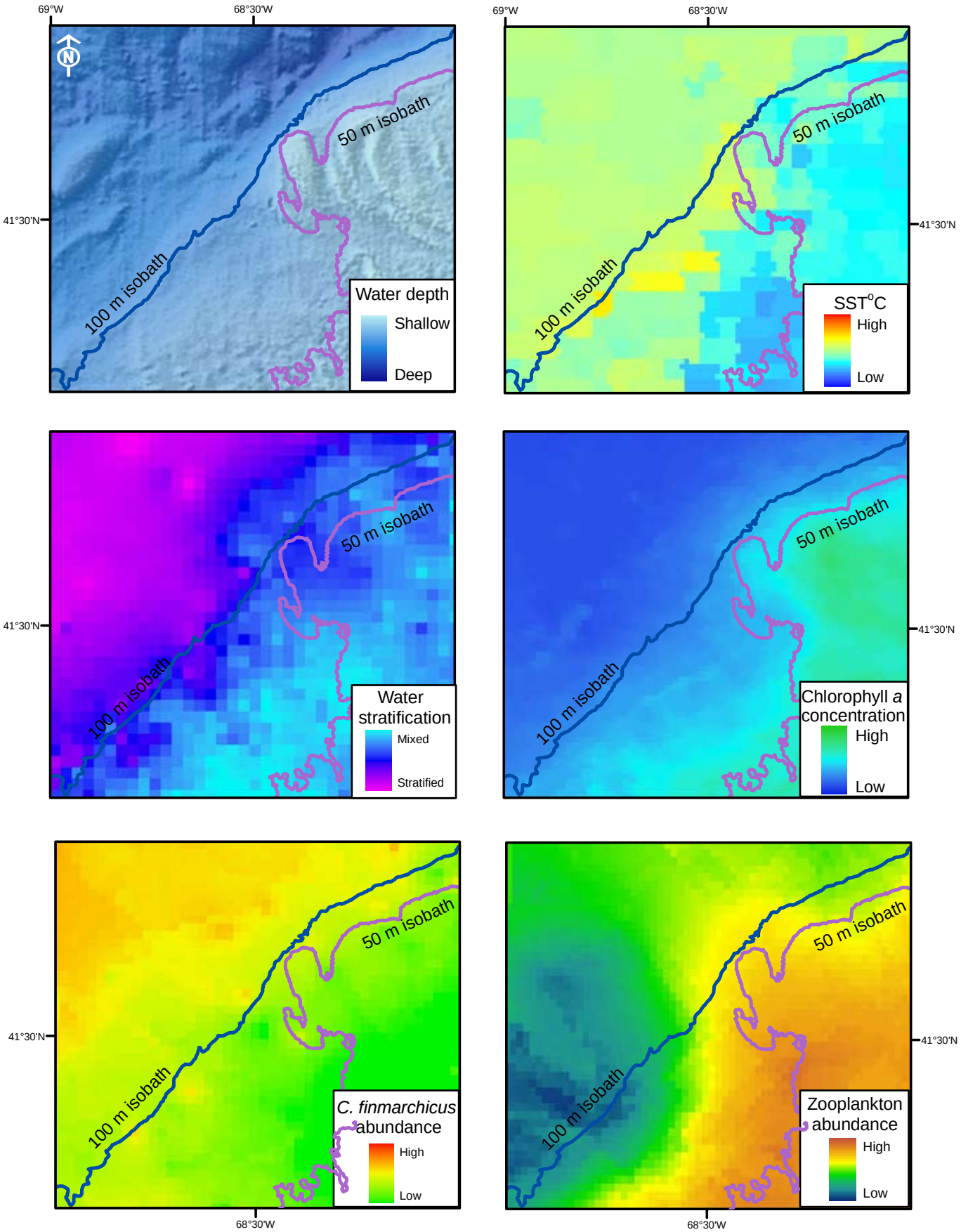


Figure 5.4.1. Environmental characterization of an ecotone along the 100m isobath of the flank of Georges Bank.

by the prey of piscivorous cetaceans. In the Bay of Fundy, Johnston *et al.* (2005a) observed that fin and minke whale were concentrated in areas with low current velocities associated with an eddy in the wake of Grand Manan Island. Subsequent trawl surveys revealed that herring and euphausiids aggregated in high concentrations in near-surface regions along the boundary between fast and slower moving water, and at the edges of the eddy (Johnston *et al.,* 2005b).

Slopes or fronts between water movements may also be used by cetaceans to help aggregate prey. The presence of vertical relief and well-stratified water nearby may restrict the vertical movements of prey resulting in an aggregating mechanism. Hastie *et al.* (2004) modelled the influence of bathymetry on foraging habits of bottlenose dolphins, and the resultant models predicted that foraging increased over areas with steep slope. In the St. Lawrence Estuary, Canada, Simard *et al.* (2002) suggested that the association between slope and fin whale occurrence related to tidal fluctuations, which forced prey (zooplankton followed by capelin) towards the slopes. To date, insufficient information is available to determine how tidal changes influence spatio-temporal patterns of food availability along the slopes in the southern Gulf of Maine, or whether cetaceans interact with the slope while feeding.

The bank edges with exposure to Gulf water circulation may also be sites of high horizontal and vertical movement of both water and plankton (Flagg, 1987). Upwelling has been reported along the northern flank of Georges Bank. In addition, the interaction between physical oceanography and bathymetry creates environmental conditions that result in the aggregation of large numbers of planktivorous fish in this region, such as sand lance and herring. Sand lance and herring are key prey species for fin, humpback and minke whales, as well as dolphins and porpoises. Mapping NMFS bottom trawl data revealed that highest herring abundance in the study area occurred within 25 km of the 100-m isobath (Figure 5.4.2). These data add support to the hypothesis that herring prefer the transition zones between well-mixed and well-stratified waters. The 100-m isobath also delimited a maximum depth for the distribution of sand lance, with few sand lance inhabiting waters deeper than 100 m. In contrast, sand lance abundance was also found to be markedly higher over adjacent sandy sediments in waters shallower than 100 m (Figure 5.4.2). High concentrations of zooplankton at boundary features have been reported elsewhere, yet such patterns were not detected for the southern Gulf of Maine using MARMAP trawl data. The absence of this pattern may relate to the resolution of the sampling, or to the fact that the vertically integrated plankton tows only provide an average of water-column abundance. In fact, most environmental variables exhibited intermediate values along the 100 m isobath essentially defining the mid-section of the gradient or ecotone. SST was the exception, with elevated temperatures occurring along the 100-m isobath in several regions.

Figure 5.4.3 shows differences in summer space-use patterns by five baleen whale species along a subsection of the 100-m isobath. High-use areas for piscivorous baleen whales straddle the 100-m isobath. However, the centers of high SPUE are parallel to the 100-m isobath in adjacent shallower waters (50 – 100 m). Planktivorous baleen whales (sei and right whales) also straddle the 100-m isobath, but with substantially greater utilization of areas located in adjacent deeper waters, with few sighted in waters less than 50 m. Note that the edge of the interpolated right whale SPUE approximately follows the edge of the stratified water shown in Figure 5.4.3. Interestingly, the summer abundance of *Calanus* increases five orders-of-magnitude from the shoals of Georges Bank across the northern edge into Georges Basin. Brown and Winn (1989) and Kenney *et al.* (1995) observed that right whales were nearly always on the stratified side (median 11.4 km away) of a persistent tidal-mixing front in the Great South Channel, which existed in 60-70 m water depths slightly south and parallel to the 100-m isobath. Furthermore, Gaskin (1987) illustrated a relationship between the distribution of right whales and areas thought to represent transition zones from mixed to stratified waters in both the Bay of Fundy and the Scotian Shelf.

For cetaceans, preferential utilization of edge environments may provide energetically cost-effective access to abundant food resources in both shallow well-mixed environments, as well as nearby well-stratified environments. Our results also indicate however, that the 100-m isobath and adjacent habitats become slightly less important for individuals of several cetacean species in the summer months. This pattern was particularly evident for planktivorous species (sei and right whale) and for Atlantic white-sided dolphin. It may be explained by seasonal shifts in prey abundance (calanoid copepods) to the deeper waters of the central Gulf of Maine and a seasonal movement beyond the study area to the Bay of Fundy and Nova Scotian shelf.

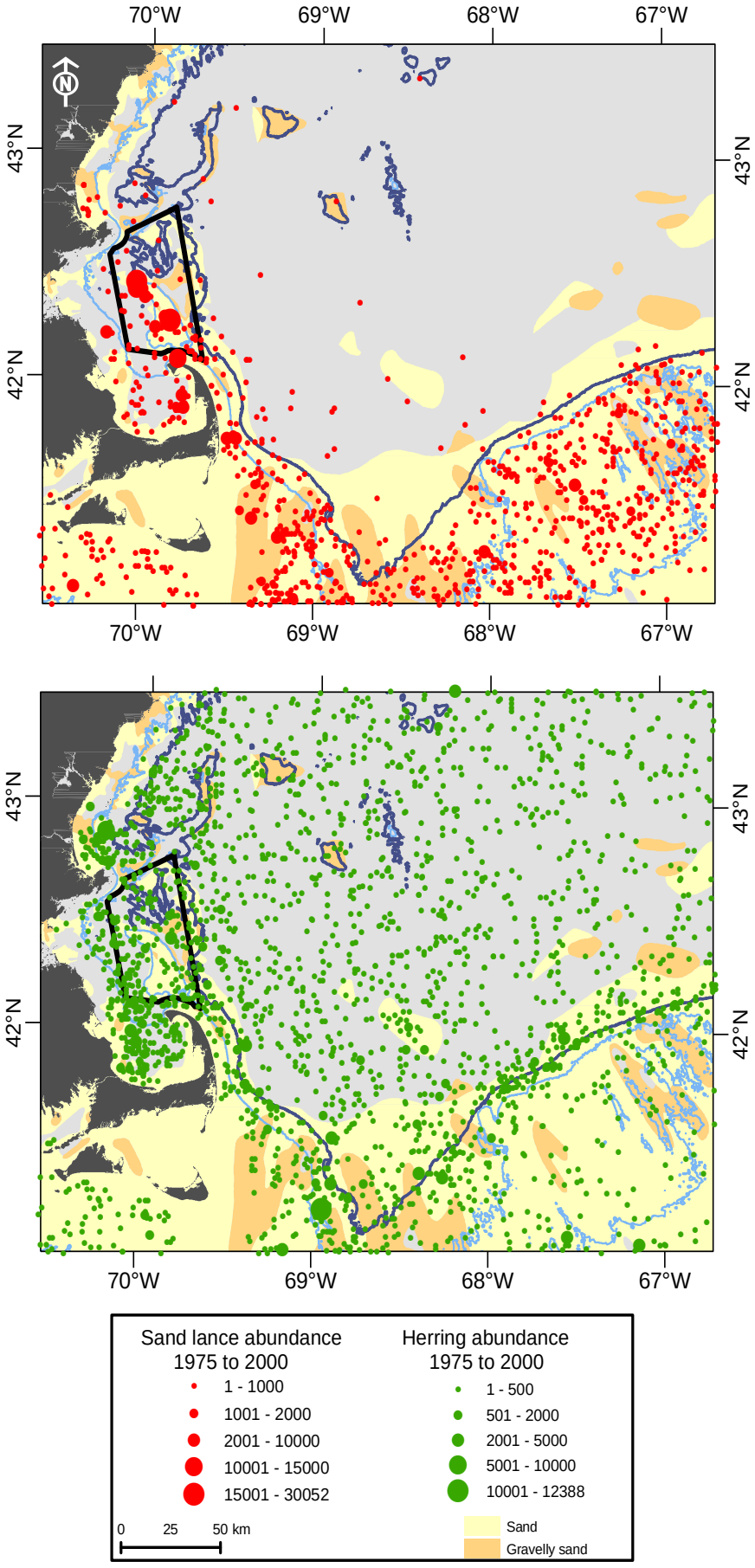


Figure 5.4.2. Distribution of key prey species for piscivorous cetaceans in the southern Gulf of Maine. Data provided by NMFS Northeast Fisheries Science Center trawl survey.

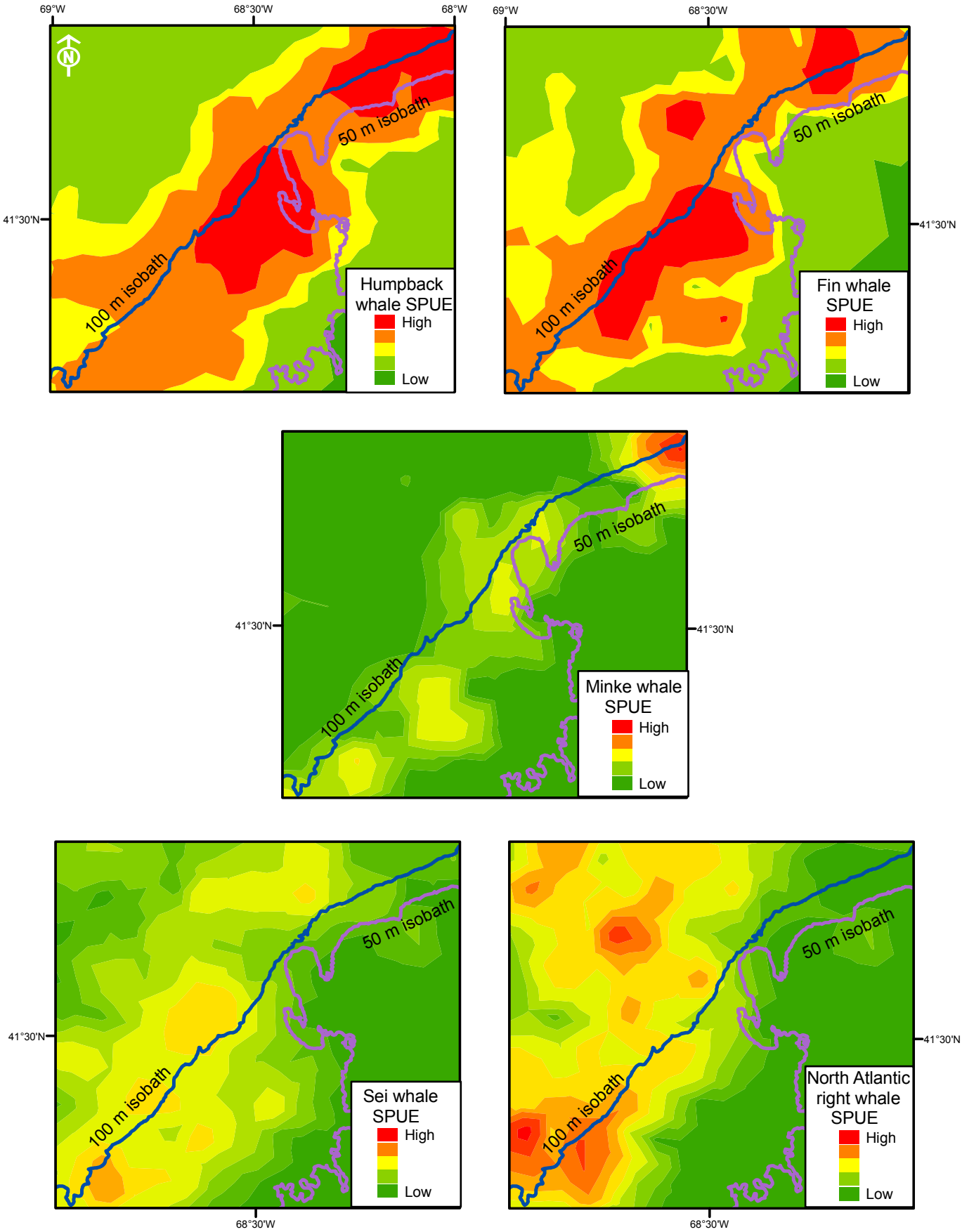


Figure 5.4.3. Spatial patterns of cetacean relative abundance (SPUE) along the 100m isobath of the northern flank of Georges Bank.. SPUE values are animals per 1000 km of standardized survey track.

Furthermore, this bathymetric feature may be used by cetaceans for navigation, both into and out of the Gulf of Maine (Kenney, 2001). Some evidence for this hypothesis comes from tracking studies of harbor porpoise in the Gulf of Maine, which showed individuals follow bathymetric features, such as a depth contour, when traveling long distances (Read and Westgate, 1997). Tracking of North Atlantic right whales suggested that animals have preferences for certain depths, and appear to respond to bathymetric features such as bank edges, basins and the continental shelf, as well as, to more dynamic features, such as sea surface temperature (Mate *et al.,* 1997).

Species-environment relationships

Humpback whales

High-use areas were distributed primarily along the edges of sandy banks and gravelly sand ledges along the 100-m isobath, with the exception of Stellwagen Bank, whereby the entire shallow bank was used intensively in the summer and fall seasons. At Stellwagen Bank, several studies have reported an exceptionally high abundance of sand lance in close proximity to feeding humpback whales (Overholtz and Nicolas, 1979; Payne *et al.,* 1990; Hain *et al.,* 1995). Our results showed a strong positive linear relationship between humpback whale SPUE in spring and summer, total fish abundance (strongly collinear with sand lance abundance), and the amount of sand and gravelly sand, which is known as preferred habitat for sand lance (Meyer *et al.,* 1979). A strong linear relationship between effort corrected humpback abundance and sand lance was also reported by Payne *et al.* (1986). The association between high-use areas for humpback whales and very low sand lance abundance suggest that whales are also associated with areas that have the potential for high presence of sand lance, but that may not be highlighted by the NMFS bottom trawl data. The spatial patterns of sand lance abundance may vary from year to year, but suitable substratum composition is likely to be a more static indicator of prey availability.

Conversely, not all sand lance hotspots were humpback whale high-use areas. For instance, sand lance abundance is substantially lower north of the 100-m isobath where humpback whales are frequently seen. However, the 100-m isobath is a hotspot for herring suggesting that humpback whales may switch prey depending on local availability. Alternatively, prey preference may be socially segregated with some individuals targeting herring and others targeting sand lance. Prey switching has been noted between seasons (Macleod *et al.,* 2004) and inter-annually (Payne *et al.,* 1986; Weinrich *et al.,* 1997), but it is unclear whether individuals respond to spatial patterns of prey availability at finer temporal scales (i.e., during daily foraging activity) (Lavigne 1995). In winter, there was a shift in SPUE to deeper waters over Tillies Basin (within SBNMS) and Jeffreys Ledge. These areas are productive commercial fishing grounds with abundant herring. This winter shift may result from decreased availability of sand lance prior to spawning and decreased accessibility because sand lance spend more time buried in the sand during winter. A geographically similar, but longer term shift from Stellwagen Bank to Jeffreys Ledge was reported for humpbacks between 1988 and 1994 (Weinrich *et al.*, 1997).

Fin whales

Fin whales showed a preference for intermediate levels of surface stratification as compared to the mean value for the entire study area. In all seasons, whales remained close to the 100-m isobath and over Stellwagen Bank and Jeffreys Ledge and in close proximity to high sand lance and herring abundance. In the southern Gulf of Maine, Overholtz and Nicolas (1979) observed fin and humpback whales feeding on sand lance over Stellwagen Bank. Interestingly, preferential utilization of the 100-m isobath has also been observed for fin whales in other regions. In the St. Lawrence Estuary, Canada, Michaud and Giard (1998) tracked 25 fin whales and found that individuals remained close to the 100-m isobath, particularly at peak high tide, where they frequently dived to 50 m or more to feed. In the northern Gulf of Maine, Woodley & Gaskin (1996) found that fin whales were distributed in relatively shallow, well-mixed waters over areas with high bathymetric variance. These high-use areas were also characterized by boundary conditions, with a high abundance of the preferred prey (herring and euphausiids), particularly in areas where the bottom topography was steep. In the Gulf of Maine, summer feeding concentrations of herring are associated with tidally induced temperature fronts where plankton productivity is elevated (Sinclair and Iles, 1985). Research elsewhere (North Sea) has shown that adult herring were more abundant in depths less than 150 m, at the edges of dense patches of plankton and over gravely-sand substrata, which was preferred for spawning (Maravelias, 1999). By fall and winter, we found that fin whale SPUE was more widely dispersed over deeper water basins and around ledges (i.e., Jeffreys and Cashes). Similar to humpbacks, fin

whales shifted to deeper waters possibly because of an increased reliance on herring and zooplankton, rather than sand lance, as a primary food source.

Minke whales

In spring, high SPUE for minke was more closely associated with the 100-m isobath than any other species, with a distinct preference for sand dominated substrata and high sand lance abundance. High SPUE was also found over shallower (<40 m) sandy sediments. In summer and fall, high SPUE also occurred near ledges, in deeper water and frequently over non-sandy sediments, with high *Calanus* abundance. In the Gulf of St. Lawrence, Canada, Naud *et al.* (2003) found that minke whales preferred areas with high relief and geomorphological structure resembling sand dunes in summer. These environmental characteristics were considered to be preferred habitat for the key prey species, capelin and sand lance. Naud *et al.* (2003) also found high abundance of minke whales in depth classes less than 100 m, with most whales at 20-40 m and 80-100 m. In the waters around the Isle of Mull, Scotland, Macleod *et al.* (2004) described seasonal shifts in minke whale distributions, with sediment type being a significant predictor in the spring when there was high sand lance abundance. Sediment however, was not a strong predictor in the summer when whales shifted geographically to exploit aggregations of pre-spawning herring.

North Atlantic right whales

The two peaks in the curve for the relationship between spring SPUE and water depth represent the two key high-use areas in the shallow waters of Cape Cod Bay and the deeper waters of the Great South Channel. Cape Cod Bay was characterized in the CART model as cells with waters that were at least a half degree warmer than the study area average (5.9^{o}C), water depth less than 85 meters and more than 18% of the substrata comprised of sand and gravelly sand. The Great Channel was denoted in the CART model as having cells with cooler and less stratified waters, with high zooplankton abundance and extremely high *Calanus* abundance when compared with the regional average. In the summer, high-use areas were characterized by high surface stratification (beyond -2.8), and zooplankton abundance that exceeded the regional average.

It is well known that the movements of North Atlantic right whale in the Gulf of Maine are closely linked to the life-history and spatial distribution of its main prey, the calanoid copepod *Calanus finmarchicus*. *Calanus* early life stages coincide with the spring phytoplankton blooms on which they feed, particularly over Georges Bank, Massachussets Bay and Cape Cod Bay. *Calanus* then begins a gradual move to deeper water until they enter diapause in the fourth and fifth copepodite stages (C4 and C5) in mid-summer and spend the remainder of the year at depths of 50-300 m in the Gulf of Maine (Bigelow, 1926). The *Calanus* population is therefore dominated by adults and pre-C4 stages in early spring, progressing to C4 and C5 copepodites in summer (May to August) (Meise and O'Reilly, 1996). Right whales are able to locate prey that are distributed vertically in discrete layers (Winn *et al.,* 1995; Woodly and Gaskin, 1996; Baumgartner and Mate, 2003). Preference for deeper, well-stratified waters in summer may reflect the proximity to colder, deeper waters supporting a high abundance of overwintering *Calanus*. Meise and O'Reilly (1996) demonstrated that average water-column abundance of late-stage *Calanus* was negatively correlated with average water column temperature in the summer. Baumgartner and Mate (2003) tracked right whales in the Gulf of Maine and found that they dove repeatedly to between 80 and 175 m, where the average depth of dive was strongly positively correlated with the average depth of peak *Calanus* C5 abundance.

Comparison of spatial patterns of North Atlantic right whale abundance and *Calanus* abundance (all life stages combined) for both spring and summer seasons showed a clear geographic shift in whale abundance that broadly tracked *Calanus* abundance hotspots (Figure 5.4.4). In spring, these hotspots were located along the northern slope of Georges Bank, the Great South Channel, Cape Cod Bay, western SBNMS and to a lesser extent, some of the deep basins in the central southern Gulf of Maine. The relatively high abundance of *Calanus* along the 100-m isobath in spring is thought to be related to the advection of a low-salinity surface plume that moves south along the 100-m isobath from the northern Gulf of Maine (Wishner *et al.,* 1988; Beardsley *et al.,* 1996). This plume has also been considered as a potential homing cue to migrating right whale (Kenney *et al.,* 2001).

In summer, *Calanus* hotspots shifted offshore towards the central, southern Gulf of Maine. A corresponding distributional shift was also evident for North Atlantic right whale, with fewer individuals in summer using nearshore regions such as Cape Cod Bay and the northeastern slopes of Nantucket Shoals. Although a clear shift is seen,

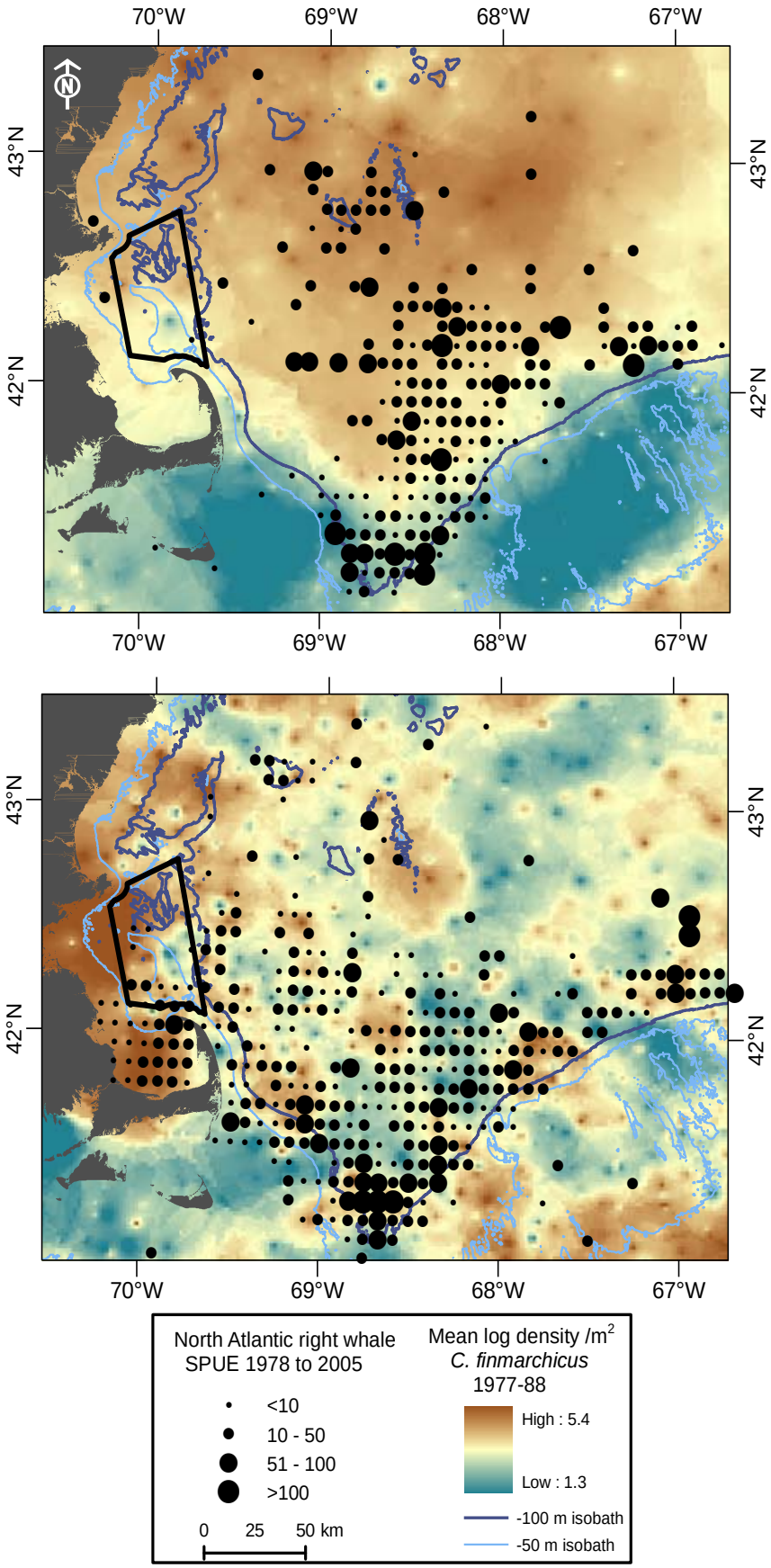


Figure 5.4.4. Overlay of spatial distribution of North Atlantic right whale relative abundance (SPUE) over the spatial distribution of *Calanus* abundance for the southern Gulf of Maine. The circles representing right whale SPUE are located at the cell centroid for each cell of the SPUE grid.

the strength of the association is possibly weakened by the fact that zooplankton trawls may not have adequately sampled the horizontal or vertical distribution of zooplankton, thereby underestimating the concentration of prey available to the whales. Furthermore, in developing our *Calanus* prediction, we did not differentiate between the different life-stages of *Calanus*. Studies by Wishner *et al.* (1995) have shown that the abundance and the proportion of the larger *Calanus* life stages (C4, C5 and adult) correlated more closely to right whale occurrence. In addition, recent time series analyses of *Calanus* abundance in the Gulf of Maine have documented substantial interannual population changes (Conversi *et al.,* 2001; Pershing *et al.,* 2005) that may explain some of the heterogeneity and disagreement between right whale SPUE and *Calanus* abundance. Nevertheless, it is clear that the arrival and departure of right whales from the Gulf of Maine and their space-use patterns within the Gulf of Maine are synchronized with the spatio-temporal distribution of the *Calanus* life-cycle.

Phytoplankton abundance measured as chlorophyll *a* concentration was also an important predictor (albeit a negative relationship) for right whales in the summer, and a minor contributor in the spring, exhibiting a weak positive relationship in spring. Overall, right whales did not frequent waters with high surface chlorophyll *a* concentrations. Baumgartner and Mate (2003) argue that phytoplankton abundance is irrelevant to *Calanus* in diapause during the summer and early fall, and thus right whales should not be expected to frequent areas that exhibit high surface chlorophyll *a* concentrations.

Sei whales

In contrast to the more abundant species, very little is known about the ecology of sei whale in the northwest Atlantic. Our results show that sei whale utilize the Gulf of Maine mainly in spring and summer, exhibiting similar patterns of habitat use as right whale, but with a greater affinity for offshore areas. Highest SPUE cells were located within 100 km of the continental shelf and over waters deeper than 250 m. Aerial observations of feeding whales in the Gulf of Maine have reported right and sei whales feeding together on patches of plankton (Watkins and Schevill, 1979). At a broader spatial scale, the southern Gulf of Maine is considered the southern boundary of sei whale distribution during spring and summer, with a population center thought to be located farther north on the Scotian Shelf (Mitchell and Chapman, 1977). In summer, a preference for well-stratified waters with high *Calanus* abundance supports existing information on the importance of copepods as a key prey item for this species. It has been observed that in years of high copepod abundance, sei whales which normally prefer deep waters move to inshore locations, particularly in the Great South Channel and Stellwagen Bank (Payne *et al.,* 1990; Schilling *et al.,* 1992). Further studies that incorporate euphausiid abundance as a predictor variable may further elucidate the linkages between prey abundance and the distribution of sei whales in the Gulf of Maine.

Atlantic white-sided dolphins

The Atlantic white-sided dolphin showed a similarly widespread distribution in both spring and summer months. The Great South Channel remained a high-use area in spring and summer, with additional high-use areas in deeper waters during the summer, an observation also reported by Seltzer & Payne (1988). This spatial distribution overlaps substantially with the distribution of the baleen whales, particularly the North Atlantic right whale and fin whale in both the spring and summer. In SBNMS and Jeffreys Ledge, Weinrich *et al.* (2001) noted that white-sided dolphins are usually sighted in large groups often association with fin or humpback whales.

Selzer and Payne (1988) reported that white-sided dolphin were more abundant in areas of high sea floor relief and in areas where SST and salinities were low. Our study found an association with topographic variance (as denoted by the 100-m isobath), but did not find a preference for low water temperature. In spring, high-use areas were characterized by SST greater than 6.1^{o}C, and a peak at 16^{o}C in summer, which was marginally higher than the average for the study area. A positive linear relation between SPUE and the abundance of sand lance, hake, mackerel and herring combined was evident in spring, indicating that dolphins may prefer areas with a wide variety of abundant fish. Analysis of the stomach contents of stranded animals has indicated that herring, mackerel and squid are the largest part of their diet, although white-sided dolphins have also been observed feeding on sand lance on Stellwagen Bank (Weinrich *et al.,* 2001). Cephalopod abundance may also provide a useful predictor when further refining future explanatory models.

Applications and limitations

Information on the specific environmental characteristics of high-use areas combined with maps of SPUE provide useful ecological insights and essential baseline information to support individual species management and

ecosystem-based management, where changes in the system may be predicted based on the cetacean-environment relationships outlined here. In addition, these cetacean-environment relationships may be used to help future studies develop targeted hypotheses to examine ecological mechanisms. Statistical modeling techniques used in this study provide numerical outputs in a format that can be easily incorporated into a GIS to develop spatial predictions (see Pittman *et al.,* in review). MARS provides a series of basis functions equivalent to beta weights in a linear regression and CART provides a set of binary splits on variables (i.e., decision rules). Such rules are available in the form of a simple logical query (i.e., SQL - Structured Query Language). MARS also has the additional flexibility to model relationships that are nearly additive or involve multiple interactions between predictors, and can produce continuous models with continuous derivatives (Friedman and Roosen, 1995).Overall, CART and MARS share the ability to extract high-order interactions and can deal with a large number of variables, nonlinear relationships and multi-colinearity amongst variables. We employed these statistical techniques because they have the demonstrated ability to detect strong signals amongst noisy data.

The combination of environmental variables included in our model appeared to have useful predictive power. In addition, the robustness of the resulting relationships were enhanced by the use of a spatially extensive, effort-corrected data set, aggregated by season to minimize variability in the response and to obviate much of the concern about bias in the sampling design. However, smaller sample sizes and lower abundance in fall and winter resulted in lower model performance. In addition, the use of aggregated data in both time and space is a potential limitation in the ability to accurately and precisely capture the ecologically important variability or heterogeneity in both animal distributions and environmental conditions. As such, our analyses focused on large and persistent differences between cetacean space-use patterns and dominant characteristics of their environment. Our conclusion that static features explained more of the variability than more dynamic features of the environment suggest that additional modeling efforts may gain improved model performance by using all years of data (1970-2005 instead of 1997-2005) regardless of the interannual variability.

Major limitations in the ecological interpretation we have presented here relate to the lack of information on individual behavior. That is, we currently do not know which high-use areas function for feeding, primarily corridors of movement, social aggregations, or any combination of these. Also, we have little information on the standard movement patterns of individual animals, which further limit our ability to evaluate the importance of environmental features, such as the slope waters above the 100-m isobath. Future tracking studies will allow us to map individual space-use patterns and provide information necessary to evaluate the ecological significance of areas that have been designated as high-use based on survey sightings. Individual movement data will also provide further insights for how animals respond to structural features in their environment.

Recent studies have indicated that marine animals respond to structure in their environment at multiple spatial scales (Kenney, 2001; Schneider, 2001; Pittman and McAlpine, 2003), we limited our study to a single resolution of 5 x 5 minute cells, however future animal-environment studies should be carried out at a range of spatial scales. The analytical framework we developed here can be easily adapted to conduct analyses at multiple spatial scales by aggregating cells or selecting different temporal resolutions. From a spatial prespective, our 5 x 5 minute spatial scale for resampling would have unavoidably subsumed much of the within-cell heterogeneity existing in the original data sets, thereby potentially smoothing out important fine-scale anomalies. This may have influenced the performance of the models and played down the importance of prey abundance.

From a temporal perspective, we were primarily interested in detecting seasonal patterns and found that available environmental information was more complete when aggregated by season. However, analyses by month may have more closely aligned spatial heterogeneity in the response, with spatial heterogeneity in the predictors. In addition, monthly data could reveal more details on the trajectories of the habitat shifts that were evident at the seasonal level of data aggregation. For example, Hamazaki (2002) modeled monthly cetacean sightings (from June to August), which showed the gradual northerly shift in the distribution of many cetacean species on the northeastern continental shelf.

Ultimately, model performance was based on a statistical relationship between cetacean sightings and predictor variables. The accuracy and precision of the models consequently will depend on the quality of predictor variables and sightings data, spatial and temporal resolution of the data, the relationship between response and predictor, and the algorithm used to develop the model. Measurement errors that occur during in-situ environ-

mental sampling and the acquisition process for remotely sensed data are very difficult to quantify. Additional errors are introduced when interpolating point data to provide continuous predictors. We recognize these issues and have only begun to examine the complex relationships using the best available data. We suggest that results from these analyses be used as a baseline for future research on the interactions between cetaceans and the environment.

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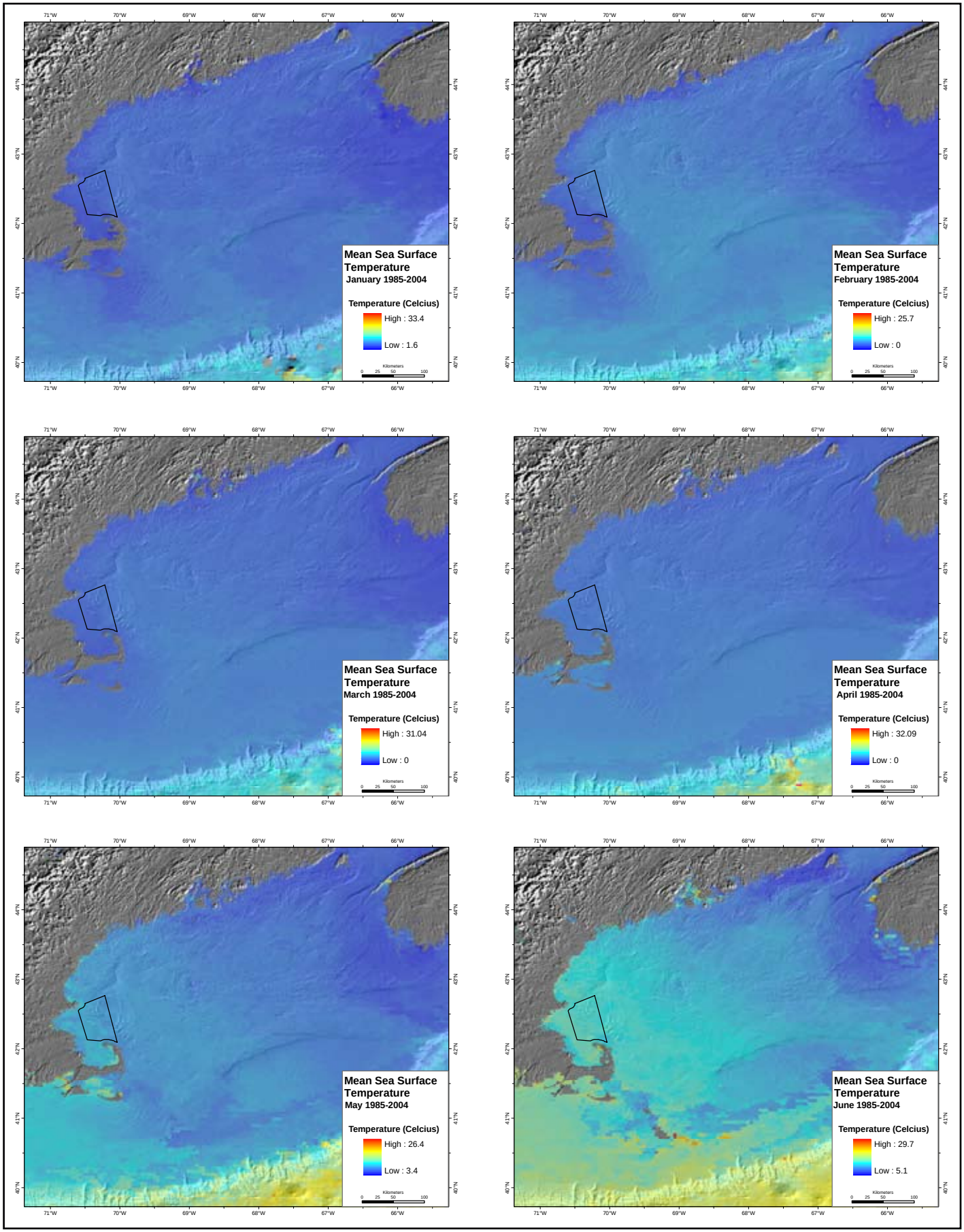
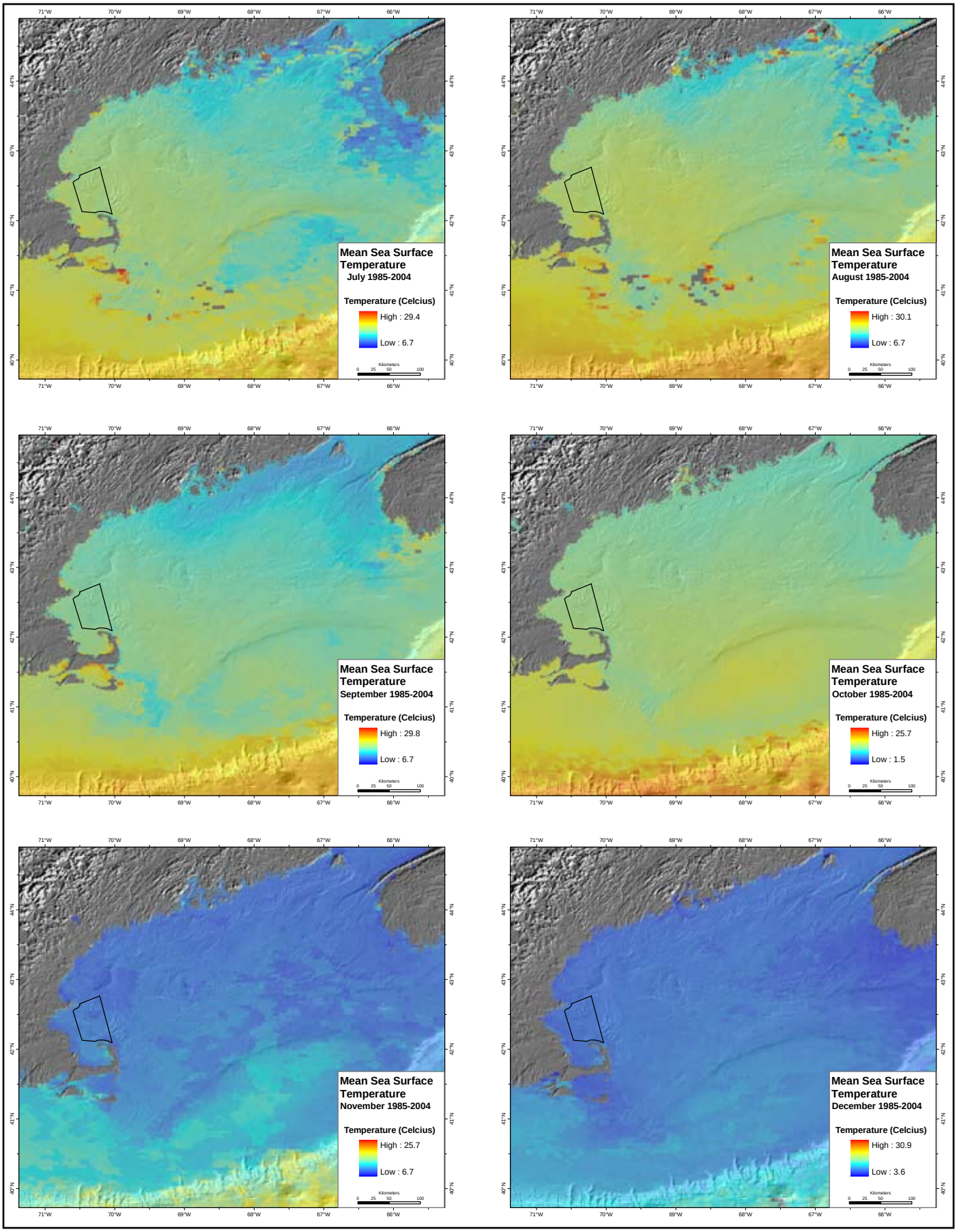
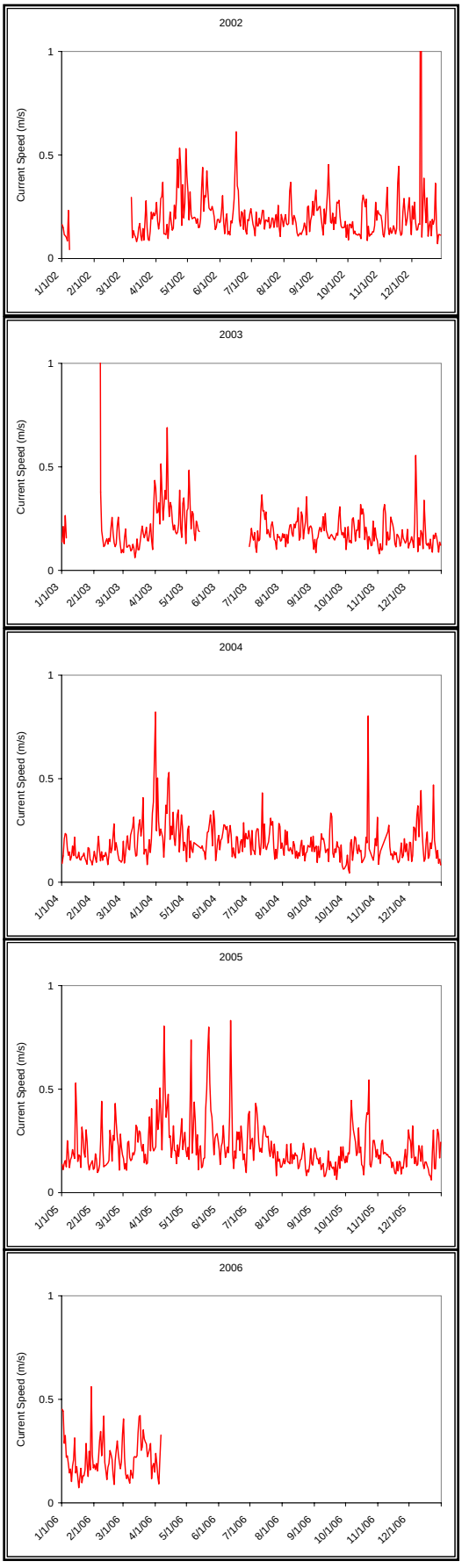
Appendix 1. Mean monthly sea surface temperature within the Gulf of Maine, January-June, 1985-2004.



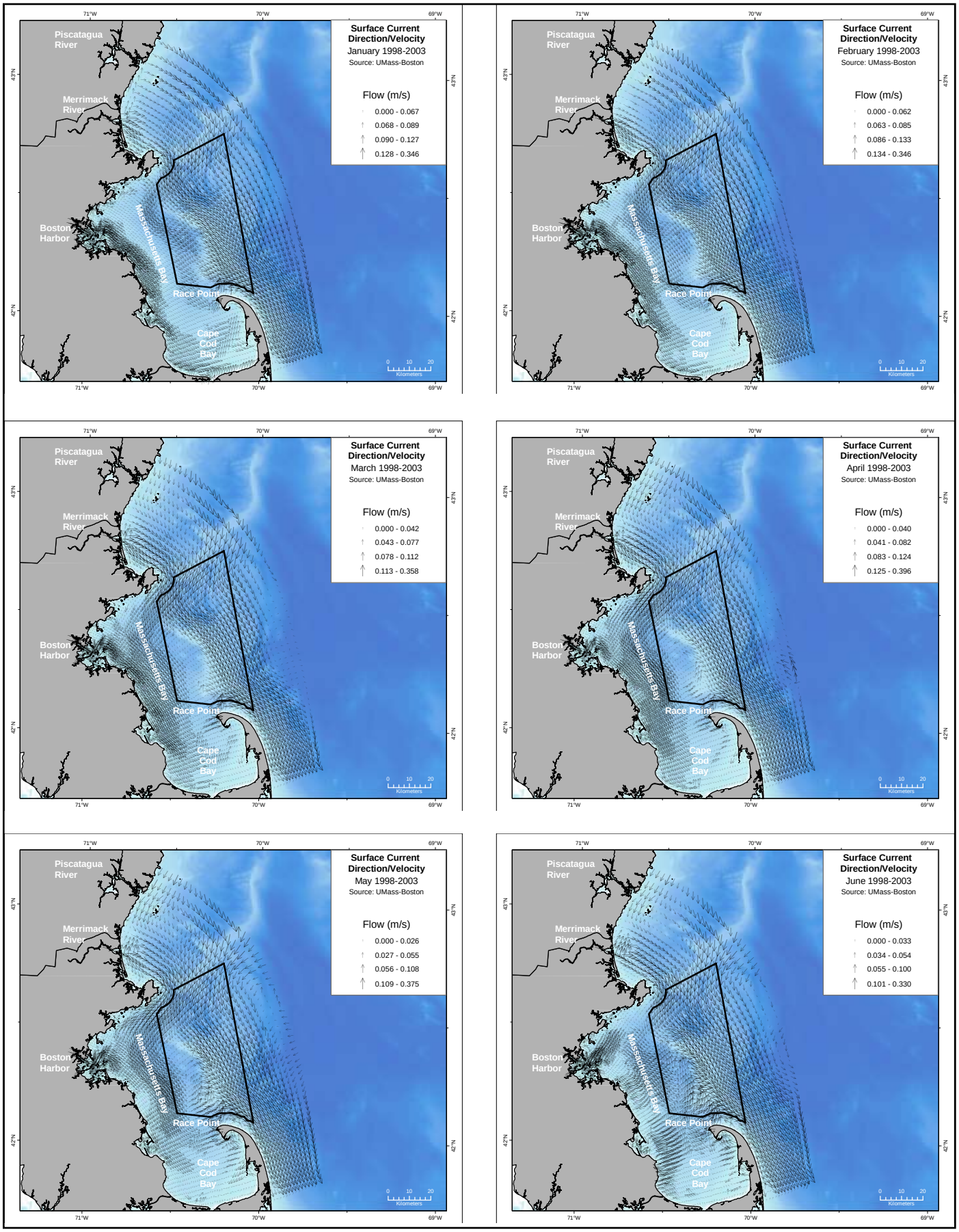
Appendix 1. Continued. Mean monthly sea surface temperature within the Gulf of Maine, July-December, 1985-2004.



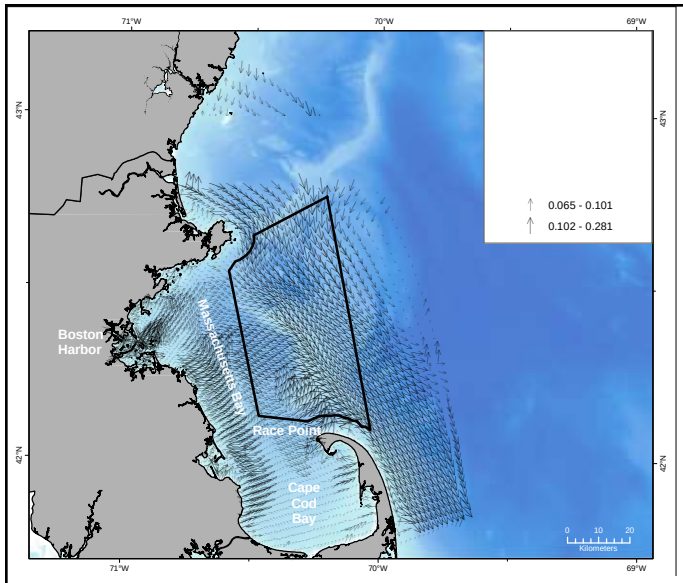
Appendix 2. Mean daily current velocity at GoMOOS Buoy A, 2002-2006.

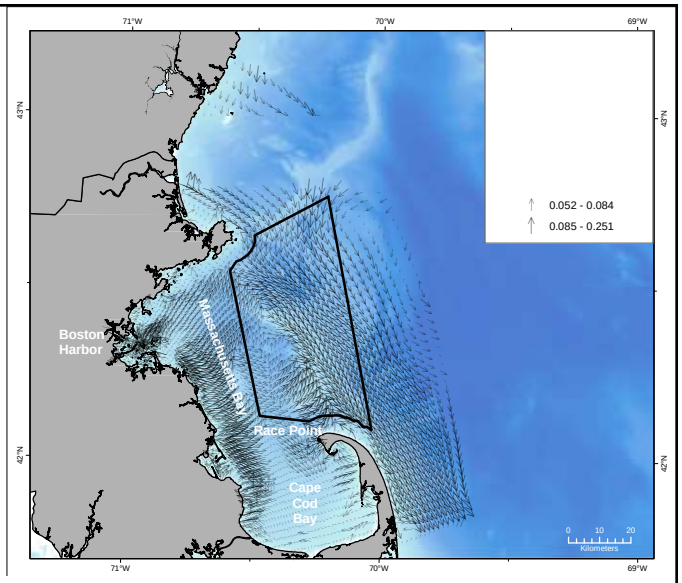


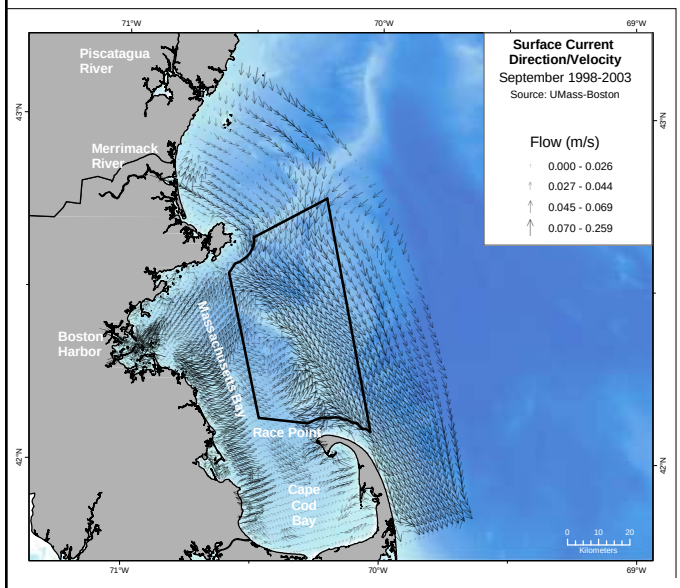
Appendix 3. Simulated mean monthly surface current magnitude and direction for January-June, 1998-2003.

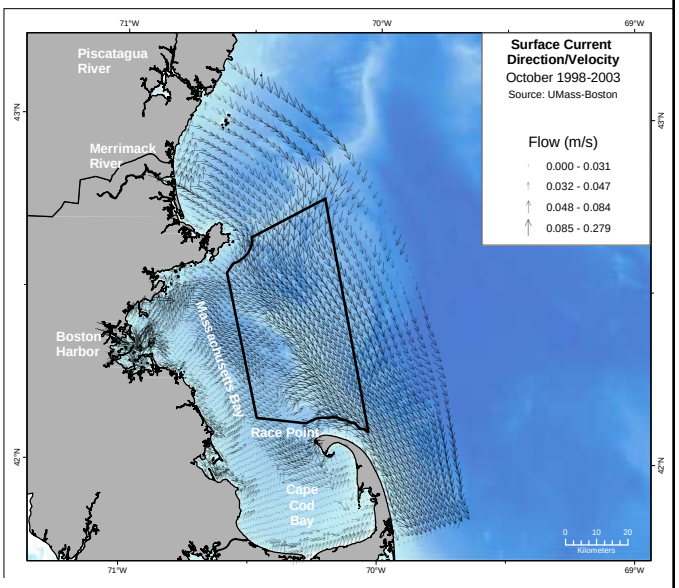


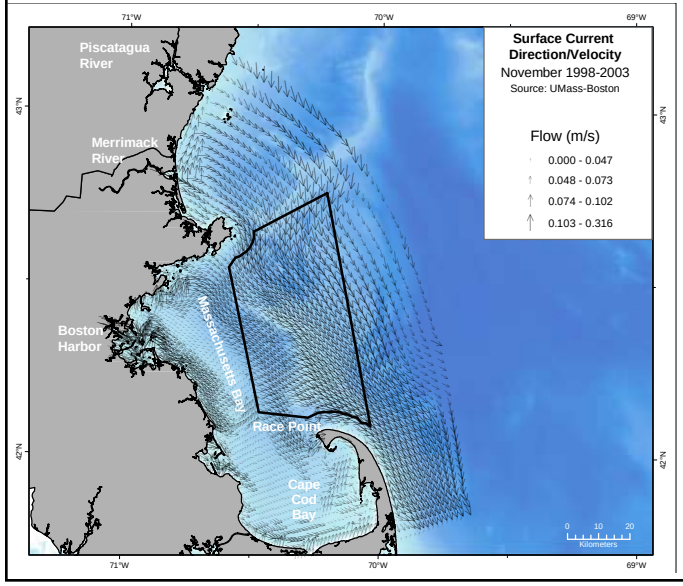
Appendix 3. Continued. Simulated mean monthly surface current magnitude and direction for July-December, 1998-2003.

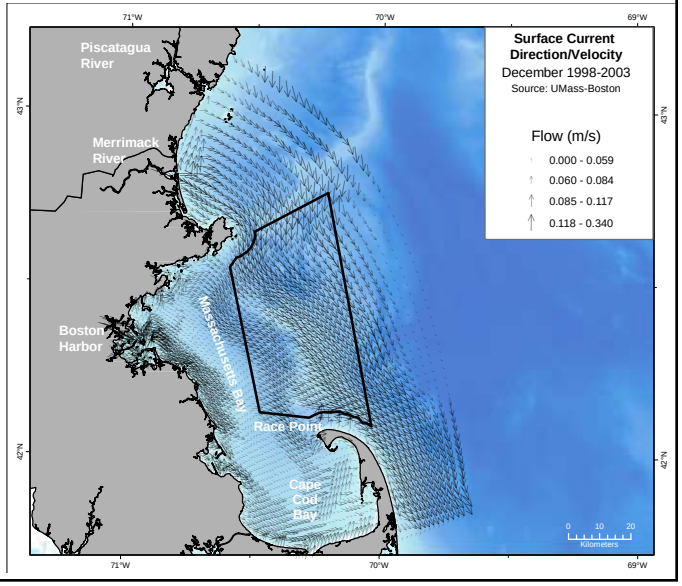




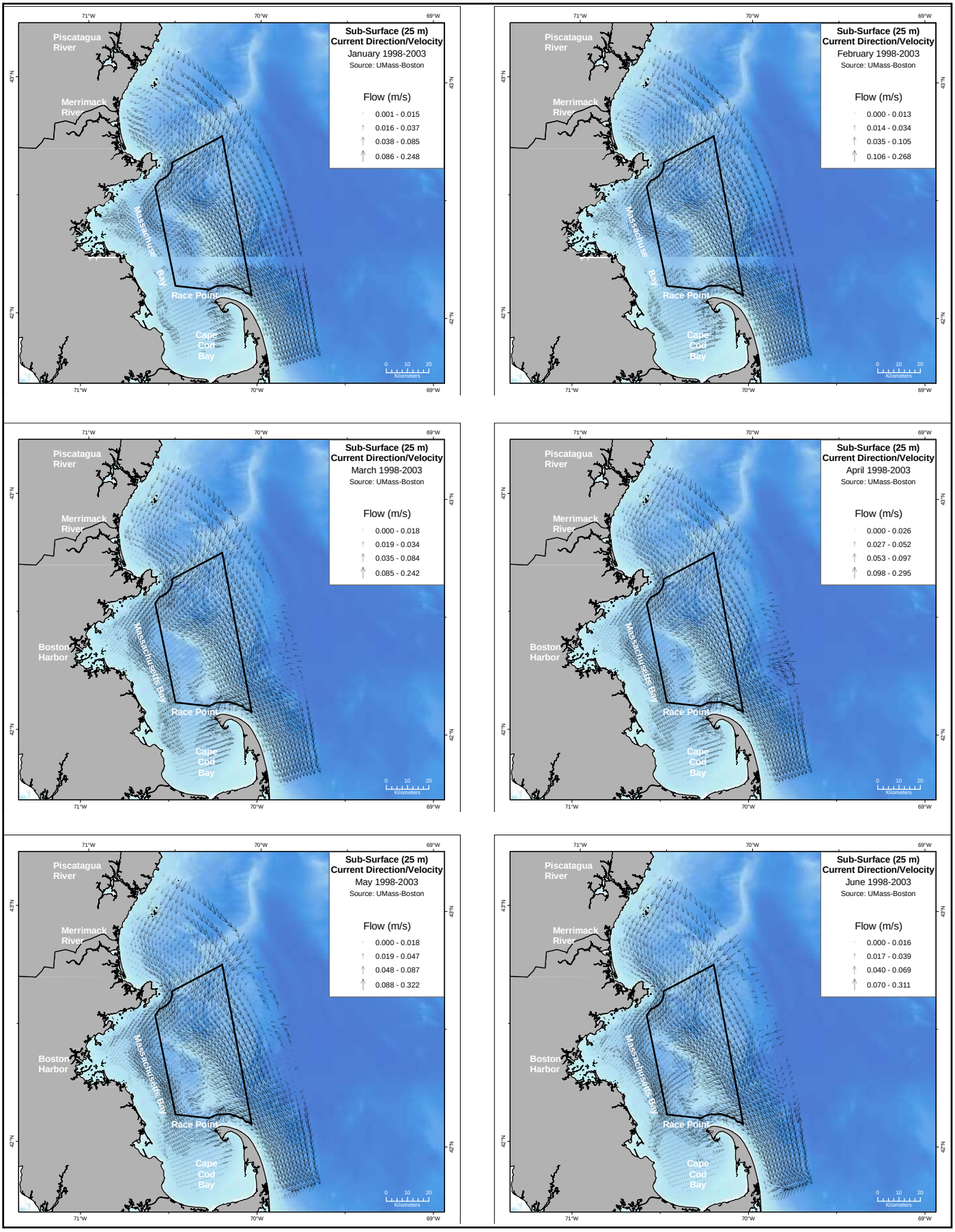




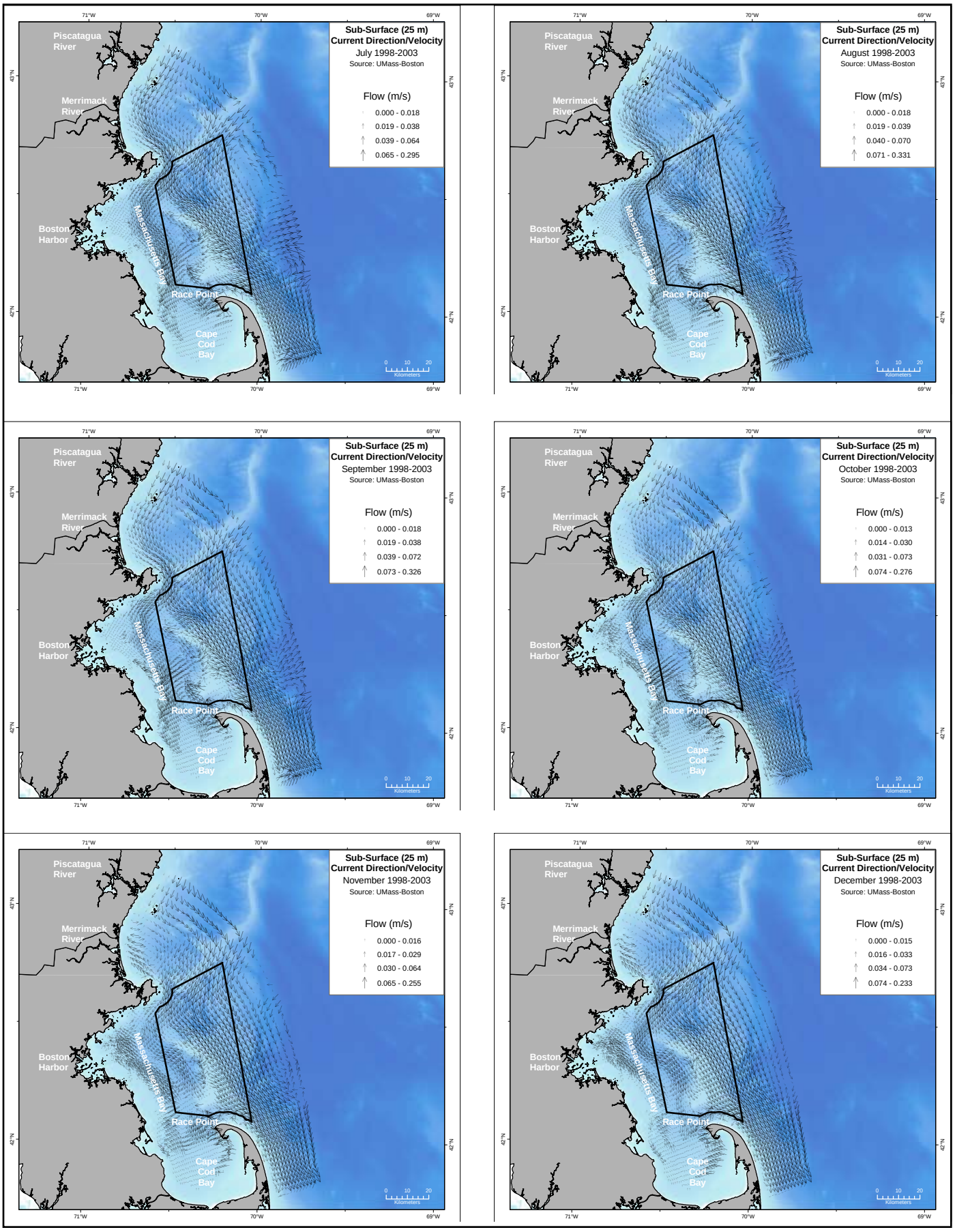




Appendix 4. Simulated mean monthly subsurface (25 m) current magnitude and direction for January-June, 1998-2003.

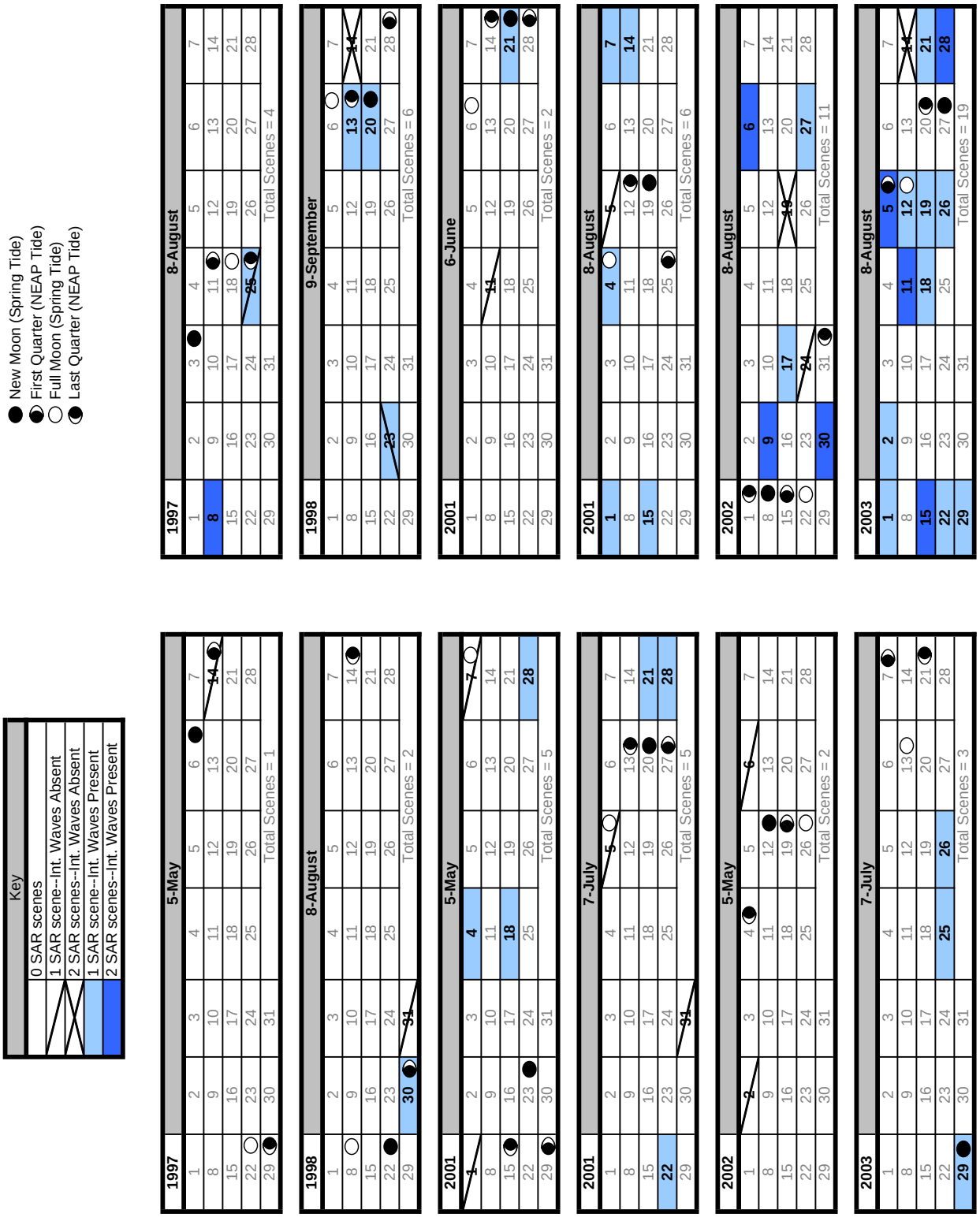


Appendix 4. Continued. Simulated mean monthly subsurface (25 m) current magnitude and direction for July-December, 1998-2003.

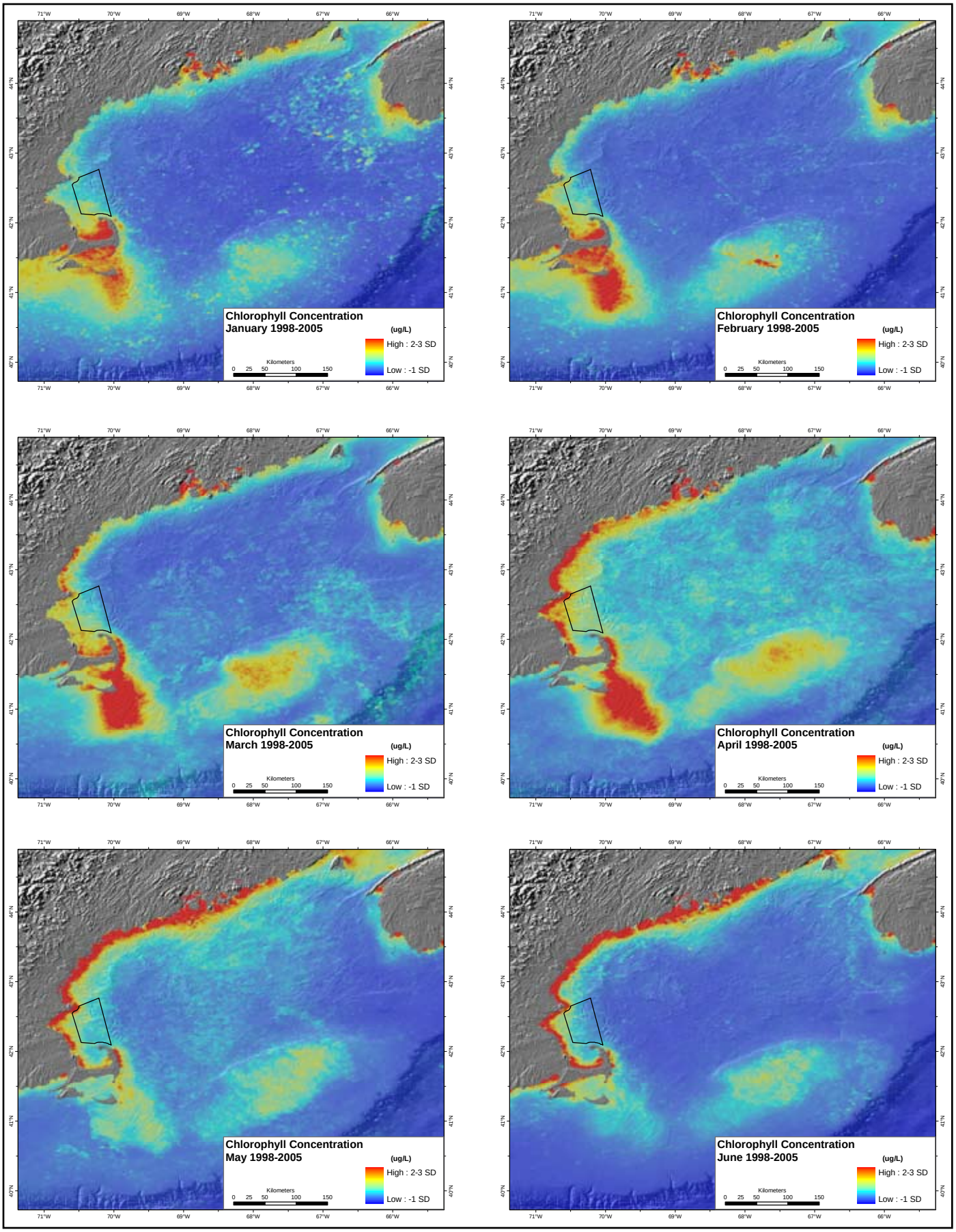


Appendix

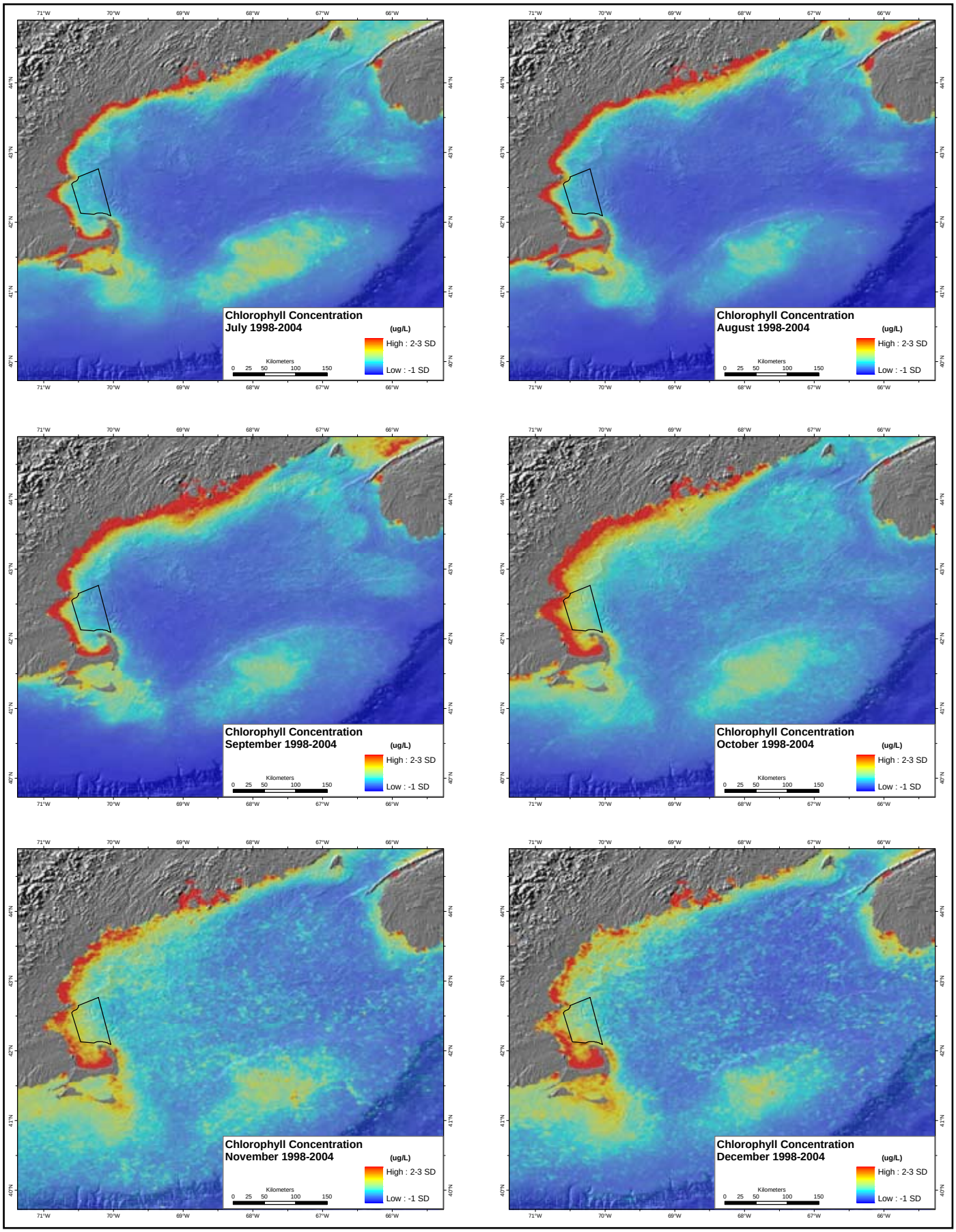
Appendix 5. Summary statistics identifying the presence of internal waves during moon phases.



Appendix 6. Mean monthly chlorophyll concentration within the Gulf of Maine, January-June 1998-2005.



Appendix 6. Continued. Mean monthly chlorophyll concentration within the Gulf of Maine, July-December 1998-2004.



Appendix 7. Benthic community species.

Phylum	Class	Family	Order	Species/Name	Node
Arthropoda	Malacostraca	Idoteidae	Isopoda	*Chiridotea caeca*	coarse sand
Annelida	Polychaeta	Syllidae	Phyllodocida	*Exogone (lpil)*	coarse sand
Annelida	Polychaeta	Paraonidae	Orbiniida	*Aricidea taylori*	coarse sand
Annelida	Polychaeta	Goniadidae	Phyllodocida	*Goniadella gracilis*	coarse sand
Mollusca	Bivalvia	Mactridae	Veneroida	*Spisula solidissima*	coarse sand
Annelida	Polychaeta	Paraonidae	Orbiniida	*Cirrophorus ilvana*	coarse sand
Annelida	Polychaeta	Hesionidae	Phyllodocida	*Microphthalmus (lpil)*	coarse sand
Annelida	Polychaeta	Syllidae	Phyllodocida	*Exogone verugera*	coarse sand
Annelida	Polychaeta	Cirratulidae	Spionida	*Monticellina baptisteae*	coarse sand
Mollusca	Bivalvia	Cardiidae	Veneroida	*Clinocardium ciliatum*	coarse sand
Annelida	Polychaeta	Paraonidae	Orbiniida	*Aricidea catherinae*	coarse sand
Annelida	Polychaeta	Paraonidae	Orbiniida	*Aricidea (lpil)*	coarse sand
Arthropoda	Malacostraca	Phoxocephalidae	Amphipoda	*Phoxocephalus holbolli*	coarse sand
Annelida	Polychaeta	Syllidae	Phyllodocida	*Exogone hebes*	coarse sand
Arthropoda	Malacostraca	Aoridae	Amphipoda	*Unciola irrorata*	coarse sand
Rhynchocoela				*Rhynchocoela (lpil)*	coarse sand
Annelida	Polychaeta	Polygordiidae	Archiannelida	*Polygordius (lpil)*	coarse sand
Echinodermata	Echinoidea			*Echinoidea (lpil)*	coarse sand
Annelida	Oligochaeta	Tubificidae	Tubificida	*Tubificidae (lpil)*	coarse sand
Annelida	Polychaeta	Nephtyidae	Phyllodocida	*Nephtyidae (lpil)*	coarse sand
Annelida	Polychaeta	Maldanidae	Capitellida	*Axiothella mucosa*	coarse sand
Annelida	Polychaeta	Ampharetidae	Terebellida	*Ampharete finmarchica*	coarse sand
Annelida	Polychaeta	Syllidae	Phyllodocida	*Streptosyllis arenae*	coarse sand
Mollusca	Bivalvia	Montacutidae	Veneroida	*Montacutidae (lpil)*	coarse sand
Annelida	Polychaeta	Dorvilleidae	Eunicida	*Parougia caeca*	coarse sand
Annelida	Polychaeta	Cirratulidae	Spionida	*Caulleriella sp. j*	coarse sand
Annelida	Polychaeta	Syllidae	Phyllodocida	*Parapionosyllis longicirrata*	coarse sand
Annelida	Oligochaeta	Enchytraeidae	Tubificida	*Enchytraeidae (lpil)*	coarse sand
Annelida	Polychaeta	Syllidae	Phyllodocida	*Syllides longocirrata*	coarse sand
Annelida	Polychaeta	Dorvilleidae	Eunicida	*Protodorvillea kefersteini*	coarse sand
Annelida	Polychaeta	Syllidae	Phyllodocida	*Sphaerosyllis brevifrons*	coarse sand
Annelida	Polychaeta	Paraonidae	Orbiniida	*Aricidea cerrutii*	coarse sand
Annelida	Polychaeta	Glyceridae	Phyllodocida	*Glyceridae (lpil)*	coarse sand
Mollusca	Bivalvia	Nuculidae	Nuculoida	*Nucula proxima*	harbor
Mollusca	Bivalvia	Astartidae	Veneroida	*Astarte castanea*	harbor
Annelida	Polychaeta	Spionidae	Spionida	*Spiophanes bombyx*	harbor
Mollusca	Bivalvia	Lyonsiidae	Pholadomyoida	*Lyonsia hyalina*	harbor
Annelida	Polychaeta	Spionidae	Spionida	*Dipolydora quadrilobata*	harbor
Annelida	Polychaeta	Nephtyidae	Phyllodocida	*Nephtys ciliata*	harbor
Annelida	Polychaeta	Sabellidae	Sabellida	*Euchone incolor*	harbor
Arthropoda	Malacostraca	Corophiidae	Amphipoda	*Crassicorophium crassicorne*	harbor
Annelida	Polychaeta	Apistobranchidae	Spionida	*Apistobranchus tullbergi*	harbor
Annelida	Polychaeta	Phyllodocidae	Phyllodocida	*Eteone longa*	harbor
Annelida	Polychaeta	Lumbrineridae	Eunicida	*Scoletoma verrilli*	harbor
Annelida	Polychaeta	Spionidae	Spionida	*Polydora cornuta*	harbor
Annelida	Polychaeta	Spionidae	Spionida	*Streblospio benedicti*	harbor
Mollusca	Bivalvia	Mytilidae	Mytiloida	*Mytilus edulis*	harbor
Mollusca	Gastropoda	Nassariidae	Neogastropoda	*Nassariidae (lpil)*	harbor
Mollusca	Bivalvia	Tellinidae	Veneroida	*Tellina agilis*	harbor
Mollusca	Bivalvia	Myidae	Myoida	*Mya arenaria*	harbor

Appendix 7. Continued.

Phylum	Class	Family	Order	Species/Name	Node
Mollusca	Aplacophora			*Aplacophora (lpil)*	fine sand/low TOC
Arthropoda	Malacostraca	Podoceridae	Amphipoda	*Dulichia porrecta*	fine sand/low TOC
Arthropoda	Malacostraca	Lysianassidae	Amphipoda	*Lysianassidae (lpil)*	fine sand/low TOC
Arthropoda	Malacostraca	Pleustidae	Amphipoda	*Pleustidae (lpil)*	fine sand/low TOC
Annelida	Polychaeta	Sabellidae	Sabellida	*Sabellidae (lpil)*	fine sand/low TOC
Arthropoda	Malacostraca	Ischyroceridae	Amphipoda	*Erichthonius difformis*	fine sand/low TOC
Arthropoda	Malacostraca	Stenothoidae	Amphipoda	*Metopella angusta*	fine sand/low TOC
Annelida	Polychaeta	Pholoidae	Phyllodocida	*Pholoe minuta*	fine sand/low TOC
Arthropoda	Malacostraca	Desmosomatidae	Isopoda	*Desmosomatidae (lpil)*	fine sand/low TOC
Arthropoda	Malacostraca	Paramunnidae	Isopoda	*Pleurogonium spinosissimum*	fine sand/low TOC
Annelida	Polychaeta	Terebellidae	Terebellida	*Polycirrus (lpil)*	fine sand/low TOC
Arthropoda	Malacostraca	Anthuridae	Isopoda	*Ptilanthura tenuis*	fine sand/low TOC
Annelida	Polychaeta	Goniadidae	Phyllodocida	*Goniada maculata*	fine sand/low TOC
Mollusca	Bivalvia	Astartidae	Veneroida	*Astarte undata*	fine sand/low TOC
Sipuncula				*Sipuncula (lpil)*	fine sand/low TOC
Arthropoda	Malacostraca	Oedicerotidae	Amphipoda	*Oedicerotidae (lpil)*	fine sand/low TOC
Annelida	Polychaeta	Sphaerodoridae	Phyllodocida	*Sphaerodoropsis minuta*	fine sand/low TOC
Arthropoda	Malacostraca	Aeginellidae	Amphipoda	*Aeginellidae (lpil)*	fine sand/low TOC
Annelida	Polychaeta	Cirratulidae	Spionida	*Tharyx acutus*	fine sand/deep
Annelida	Polychaeta	Terebellidae	Terebellida	*Terebellidae (lpil)*	fine sand/deep
Annelida	Polychaeta	Scalibregmatidae	Opheliida	*Scalibregma inflatum*	fine sand/deep
Annelida	Polychaeta	Capitellidae	Capitellida	*Heteromastus filiformis*	fine sand/deep
Annelida	Polychaeta	Cirratulidae	Spionida	*Chaetozone setosa*	fine sand/deep
Arthropoda	Ostracoda	Cylindroleberididae	Myodocopina	*Synasterope cushmani*	fine sand/deep
Annelida	Polychaeta	Cossuridae	Cossurida	*Cossura delta*	fine sand/deep
Annelida	Polychaeta	Sternaspidae	Sternaspida	*Sternaspis scutata*	fine sand/deep
Rhynchocoela	Anopla	Tubulanidae	Paleonemertea	*Tubulanus (lpil)*	fine sand/deep
Annelida	Polychaeta	Oweniidae	Oweniida	*Galathowenia oculata*	fine sand/deep
Mollusca	Scaphopoda			*Scaphopoda (lpil)*	fine sand/deep
Annelida	Polychaeta	Trochochaetidae	Spionida	*Trochochaeta multisetosa*	fine sand/deep
	Asteroidea			*Asteroidea (lpil)*	fine sand/deep
Mollusca	Gastropoda	Hamineidae	Cephalaspidea	*Haminoea solitaria*	fine sand/deep
Arthropoda	Malacostraca	Ampeliscidae	Amphipoda	*Ampelisca vadorum*	fine sand/deep
Annelida	Polychaeta	Spionidae	Spionida	*Dipolydora socialis*	fine sand/deep
Arthropoda	Malacostraca	Idoteidae	Isopoda	*Edotia montosa*	fine sand/deep
Annelida	Polychaeta	Polynoidae	Phyllodocida	*Polynoidae (lpil)*	fine sand/deep
Annelida	Polychaeta	Cossuridae	Cossurida	*Cossura soyeri*	fine sand/deep
Arthropoda	Malacostraca	Nannastacidae	Cumacea	*Campylaspis rubicunda*	fine sand/deep
Annelida	Polychaeta	Phyllodocidae	Phyllodocida	*Phyllodocidae (lpil)*	fine sand/deep
Annelida	Polychaeta	Orbiniidae	Orbiniida	*Leitoscoloplos (lpil)*	fine sand/deep
Arthropoda	Malacostraca	Ampeliscidae	Amphipoda	*Ampelisca (lpil)*	fine sand/deep
Arthropoda	Malacostraca	Isaeidae	Amphipoda	*Photis (lpil)*	fine sand/deep
Arthropoda	Malacostraca	Phoxocephalidae	Amphipoda	*Harpinia propinqua*	fine sand/deep
Mollusca	Gastropoda	Rissoidae	Mesogastropoda	*Alvania (lpil)*	fine sand/deep
Annelida	Polychaeta	Maldanidae	Capitellida	*Maldane glebifex*	fine sand/deep
Mollusca	Bivalvia	Mytilidae	Mytiloida	*Crenella decussata*	fine sand/deep
Phoronida		Phoronidae		*Phoronis (lpil)*	fine sand/deep
Annelida	Polychaeta	Lumbrineridae	Eunicida	*Scoletoma fragilis*	fine sand/deep

Appendix 7. Continued.

Phylum	Class	Family	Order	Species/Name	Node
Rhynchocoela	Anopla	Lineidae	Heteronemertea	*Lineidae (lpil)*	fine sand/deep
Annelida	Polychaeta	Ampharetidae	Terebellida	*Samythella sp. a*	fine sand/deep
Annelida	Polychaeta	Ampharetidae	Terebellida	*Ampharetidae (lpil)*	fine sand/deep
Annelida	Polychaeta	Maldanidae	Capitellida	*Maldanidae (lpil)*	fine sand/deep
Annelida	Polychaeta	Cirratulidae	Spionida	*Cirratulidae (lpil)*	fine sand/deep
Annelida	Polychaeta	Spionidae	Spionida	*Spio limicola*	fine sand/deep
Annelida	Polychaeta	Trichobranchidae	Terebellida	*Terebellides stroemi*	fine sand/deep
Mollusca	Bivalvia	Periplomatidae	Pholadomyoida	*Periploma margaritaceum*	fine sand/deep
Mollusca	Bivalvia	Nuculidae	Nuculoida	*Nucula delphinodonta*	fine sand/deep
Arthropoda	Malacostraca	Leuconidae	Cumacea	*Eudorella pusilla*	fine sand/deep
Annelida	Polychaeta	Paraonidae	Orbiniida	*Levinsenia gracilis*	fine sand/deep
Annelida	Polychaeta	Paraonidae	Orbiniida	*Aricidea quadrilobata*	fine sand/deep
Annelida	Polychaeta	Cirratulidae	Spionida	*Aphelochaeta (lpil)*	fine sand/deep
Mollusca	Bivalvia	Thyasiridae	Veneroida	*Thyasira trisinuata*	fine sand/deep
Mollusca	Bivalvia	Nuculanidae	Nuculoida	*Yoldia (lpil)*	fine sand/deep
Annelida	Polychaeta	Spionidae	Spionida	*Prionospio steenstrupi*	fine sand/deep
Annelida	Polychaeta	Nephtyidae	Phyllodocida	*Nephtys incisa*	fine sand/deep
Annelida	Polychaeta	Lumbrineridae	Eunicida	*Ninoe nigripes*	fine sand/deep
Annelida	Polychaeta	Capitellidae	Capitellida	*Mediomastus californiensis*	fine sand/deep
Mollusca	Gastropoda	Turridae	Neogastropoda	*Pyrgocythara plicosa*	other
Arthropoda	Malacostraca	Pseudocumatidae	Cumacea	*Petalosarsia declivis*	other
Arthropoda	Malacostraca	Aoridae	Amphipoda	*Leptocheirus pinguis*	other
Annelida	Polychaeta	Oweniidae	Oweniida	*Owenia fusiformis*	other
Annelida	Polychaeta	Nereidae	Phyllodocida	*Nereis grayi*	other
Annelida	Polychaeta	Polynoidae	Phyllodocida	*Harmothoe (lpil)*	other
Annelida	Polychaeta	Phyllodocidae	Phyllodocida	*Phyllodoce maculata*	other
Arthropoda	Malacostraca	Ampeliscidae	Amphipoda	*Byblis (lpil)*	other
Annelida	Polychaeta	Syllidae	Phyllodocida	*Syllis alosae*	other
Annelida	Polychaeta	Opheliidae	Opheliida	*Ophelina acuminata*	other
Annelida	Polychaeta	Capitellidae	Capitellida	*Capitella capitata*	other

Appendix 8. Species list of fishes captured in spring and fall NMFS trawl samples within the Gulf of Maine and Stellwagen Bank National Marine Sanctuary, 1975-2005. Species presence indicated by "x".

		Spring		Fall	
Species	**Common Name**	**SBNMS**	**GOM**	**SBNMS**	**GOM**
Alosa aestivalis	blueback herring	x	x	x	x
Alosa mediocris	hickory shad				x
Alosa pseudoharengus	alewife	x	x	x	x
Alosa sapidissima	American shad	x	x	x	x
Aluterus schoepfi	orange filefish				x
Amblyraja radiata	thorny skate	x	x	x	x
Ammodytes americanus	American sand lance	x	x		
Ammodytes dubius	northern sand lance	x	x	x	x
Anarhichas lupus	Atlantic wolffish	x	x	x	x
Anchoa hepsetus	striped anchovy		x		x
Anchoa mitchilli	bay anchovy				x
Anguilla rostrata	american eel				x
Antennarius radiosus	singlespot frogfish				
Antigonia capros	deepbody boarfish		x		x
Antimora rostrata	blue hake				
Apeltes quadracus	fourspine stickleback	x			
Archosargus probatocephalus	sheepshead				x
Arctozenus rissoi	white barracudina		x		x
Argentina silus	Atlantic argentine		x		x
Argentina striata	striated argentine		x		x
Argyropelecus aculeatus	silver hatchetfish				
Ariomma bondi	silver rag			x	x
Artediellus sp	hookear sculpin			x	x
Aspidophoroides monopterygius	alligatorfish	x	x	x	x
Balistes capriscus	gray triggerfish				x
Brevoortia tyrannus	Atlantic menhaden			x	x
Brosme brosme	cusk	x	x	x	x
Caranx crysos	blue runner				x
Centropristis ocyurus	bank sea bass				x
Centropristis striata	black sea bass		x	x	x
Ceratoscopelus maderensis	horned lanternfish		x		
Chauliodus sloani	viperfish		x		x
Chaunax stigmaeus	redeye gaper		x		x
Chlorophthalmus agassizi	shortnose greeneye		x		x
Citharichthys arctifrons	gulf stream flounder		x	x	x
Clupea harengus	Atlantic herring	x	x	x	x
Coelorhynchus carminatus	long-nosed grenadier		x		
Conger oceanicus	conger eel		x		x
Cookeolus japonicus	bulleye				x
Cryptacanthodes maculatus	wrymouth	x	x	x	x
Cubiceps pauciradiatus	bigeye cigarfish				x
Cyclopterus lumpus	lumpfish	x	x	x	x

Appendix 8. Continued.

		Spring		Fall	
Species	**Common Name**	**SBNMS**	**GOM**	**SBNMS**	**GOM**
Dactylopterus volitans	flying gurnard				x
Decapterus macarellus	mackerel scad				x
Decapterus punctatus	round scad				x
Dipturus laevis	barndoor skate		x		x
Enchelyopus cimbrius	fourbeard rockling	x	x	x	x
Engraulis eurystole	silver anchovy				x
Epigonus pandionis	bigeye		x		
Etropus microstomus	smallmouth flounder		x		x
Etrumeus teres	round herring				x
Eumicrotremus spinosus	Atlantic spiny lumpsucker	x	x		
Fistularia petimba	red cornetfish				x
Fistularia tabacaria	bluespotted cornetfish				x
Foetorepus agassizi	spotfin dragonet		x		x
Gadus morhua	Atlantic cod	x	x	x	x
Gasterosteus aculeatus	threespine stickleback		x	x	x
Glyptocephalus cynoglossus	witch flounder	x	x	x	x
Helicolenus dactylopterus	blackbelly rosefish	x	x		x
Hemitripterus americanus	sea raven	x	x	x	x
Hippoglossoides platessoides	american plaice	x	x	x	x
Hippoglossus hippoglossus	Atlantic halibut	x	x	x	x
Hyperoglyphe perciformis	barrelfish		x		
Hyporhamphus unifasciatus	silverstripe halfbeak				x
Laemonema barbatulum	shortbeard codling				x
Lepophidium profundorum	fawn cusk-eel	x	x	x	x
Leucoraja erinacea	little skate	x	x	x	x
Leucoraja garmani	rosette skate		x		x
Leucoraja ocellata	winter skate	x	x	x	x
Limanda ferruginea	yellowtail flounder	x	x	x	x
Liparis atlanticus	Atlantic seasnail		x		x
Liparis inquilinus	inquiline snailfish		x		
Lophius americanus	goosefish	x	x	x	x
Lopholatilus chamaeleonticeps	blue tilefish		x		
Lumpenus lumpretaeformis	snakeblenny	x	x	x	x
Lumpenus maculatus	daubed shanny	x	x	x	x
Lycenchelys verrilli	wolf eelpout	x	x	x	x
Macrorhamphosus scolopax	longspine snipefish				x
Macrourus berglax	roughhead grenadier		x		
Macrozoarces americanus	ocean pout	x	x	x	x
Malacocephalus occidentalis	western softhead grenadier		x		x
Malacoraja senta	smooth skate	x	x	x	x
Mallotus villosus	capelin		x		
Maurolicus weitzmani	weitzmans pearlsides		x	x	x

Appendix 8. Continued.

		Spring		Fall	
Species	**Common Name**	**SBNMS**	**GOM**	**SBNMS**	**GOM**
Melanogrammus aeglefinus	haddock	x	x	x	x
Melanostigma atlanticum	Atlantic soft pout	x	x	x	x
Menidia menidia	Atlantic silverside		x		x
Merluccius albidus	offshore hake		x	x	x
Merluccius bilinearis	silver hake	x	x	x	x
Monacanthus hispidus	planehead filefish				x
Monolene sessilicauda	deepwater flounder		x		x
Morone saxatilis	striped bass	x			x
Mustelus canis	smooth dogfish		x		x
Myctophum humboldti	humboldts lanternfish				x
Myoxocephalus aenaeus	grubby	x	x		x
Myoxocephalus octodecemspinosus	longhorn sculpin	x	x	x	x
Myoxocephalus scorpius	shorthorn sculpin		x		x
Myxine glutinosa	Atlantic hagfish	x	x	x	x
Naucrates ductor	pilotfish				x
Nemichthys scolopaceus	slender snipe eel		x	x	x
Nezumia bairdi	marlin-spike		x		x
Ogcocephalus corniger	longnose batfish		x		
Ogcocephalus nasutus	shortnose batfish		x		
Ophichthus cruentifer	margined snake eel		x		x
Ophidion selenops	mooneye cusk-eel				x
Opsanus tau	oyster toadfish				x
Orthopristis chrysoptera	pigfish		x		
Osmerus mordax	rainbow smelt		x		x
Paralepis coregonoides	sharpchin barracudina		x		
Paralichthys dentatus	summer flounder		x		x
Paralichthys oblongus	fourspot flounder	x	x	x	x
Parasudis truculenta	longnose greeneye		x		
Peprilus triacanthus	butterfish		x	x	x
Peristedion miniatum	armored searobin		x		x
Petromyzon marinus	sea lamprey		x	x	x
Pholis gunnellus	rock gunnel		x		x
Pollachius virens	pollock	x	x	x	x
Polyipnus clarus	slope hatchetfish		x		x
Polymetme thaeocoryla	lightfish				x
Pomatomus saltatrix	bluefish			x	x
Priacanthus arenatus	bigeye				x
Prionotus carolinus	northern searobin		x	x	x
Pristigenys alta	short bigeye				x
Pseudopleuronectes americanus	winter flounder	x	x	x	x
Reinhardtius hippoglossoides	greenland halibut	x	x		x

Appendix 8. Continued.

		Spring		Fall	
Species	**Common Name**	**SBNMS**	**GOM**	**SBNMS**	**GOM**
Rhomboplites aurorubens	vermilion snapper				x
Sarda sarda	Atlantic bonito				x
Scomber japonicus	chub mackerel				x
Scomber scombrus	Atlantic mackerel	x	x	x	x
Scomberesox saurus	Atlantic saury			x	x
Scophthalmus aquosus	windowpane	x	x	x	x
Scyliorhinus retifer	chain dogfish				x
Sebastes fasciatus	acadian redfish	x	x	x	x
Selar crumenophthalmus	bigeye scad		x		x
Selene setapinnis	Atlantic moonfish				x
Selene vomer	lookdown				x
Seriola zonata	banded rudderfish				x
Simenchelys parasiticus	snubnose eel		x		x
Sphoeroides maculatus	northern puffer				x
Squalus acanthias	spiny dogfish	x	x	x	x
Stenotomus chrysops	scup		x	x	x
Stomias boa	scaly dragonfish		x		
Symphurus civitatus	offshore tonguefish				x
Symphurus diomedianus	spottedfin tonguefish				x
Symphurus plagiusa	blackcheek tonguefish		x		x
Syngnathus fuscus	northern pipefish		x	x	x
Tautoga onitis	tautog		x		x
Tautogolabrus adspersus	cunner	x	x	x	x
Torpedo nobiliana	Atlantic torpedo		x		x
Trachurus lathami	rough scad				x
Trichiurus lepturus	Atlantic cutlassfish		x		
Triglops murrayi	moustache sculpin	x	x	x	x
Ulvaria subbifurcata	radiated shanny	x	x	x	x
Urophycis chesteri	longfin hake		x		x
Urophycis chuss	red hake	x	x	x	x
Urophycis regia	spotted hake		x	x	x
Urophycis tenuis	white hake	x	x	x	x
Zenopsis conchifera	buckler dory		x		x

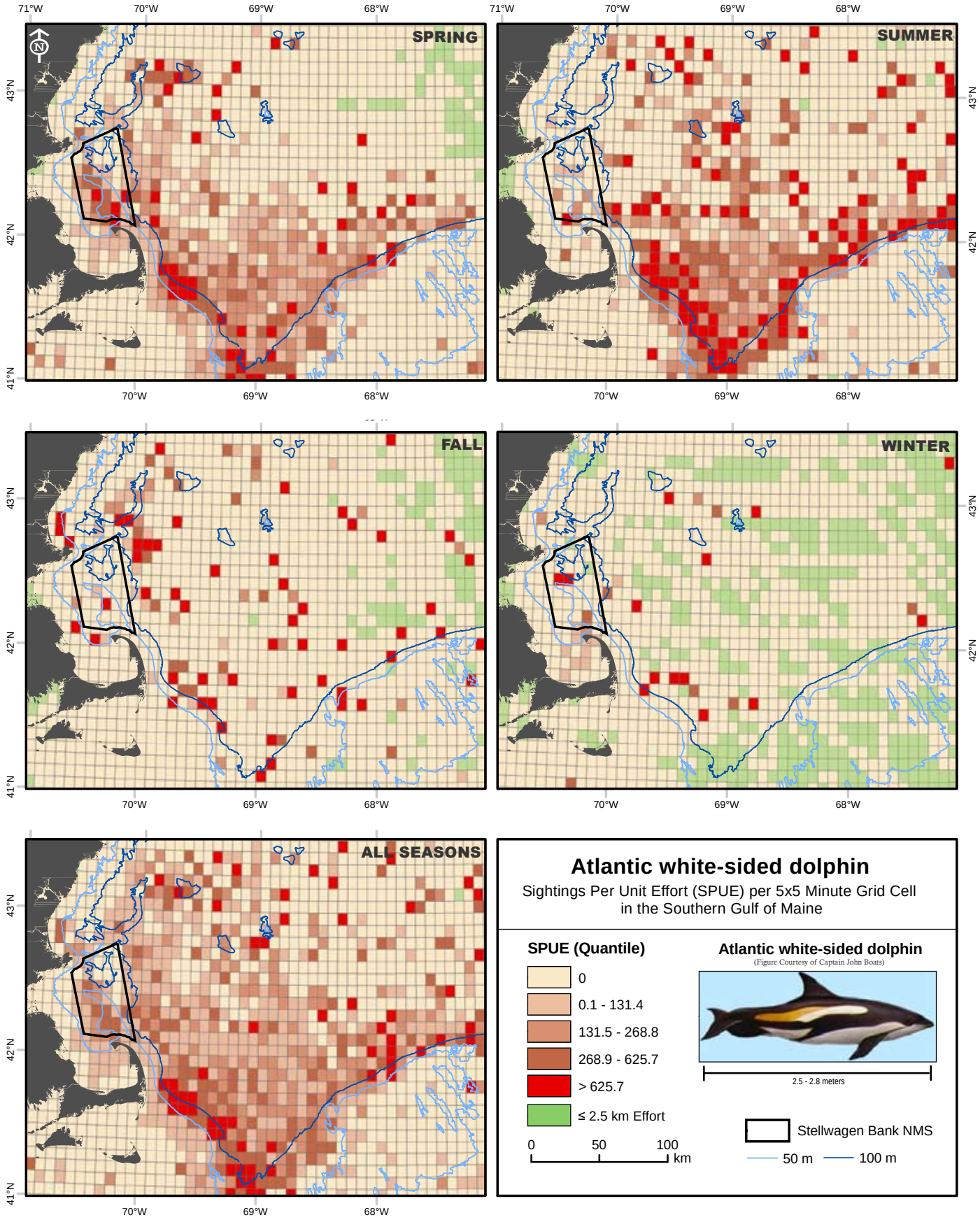
Appendix 9. Species composition along ROV video transects conducted during 2000 within SBNMS. * indicates presence.

Species	Dive 3	Dive 4	Dive 5	Dive 8	Dive 11	Dive 13	Dive 14	Dive 15
Sebastes spp.	*	*	*			*	*	*
Merluccius bilinearis	*	*	*	*	*	*	*	
Plueronectiformes	*	*	*			*	*	
Lumpenus maculatus	*							
Urophycis spp.	*	*	*		*	*	*	*
Myxine glutinosa	*			*				*
Macrozoarces americanus	*	*	*	*	*	*	*	*
Melanogrammus aeglefinus	*		*	*	*	*		*
Pollachius virens	*					*		
Myoxocephalus octodecemspinosus	*	*	*	*	*	*	*	*
Tautogolabrus adspersus	*	*	*	*			*	
Raja spp.	*				*	*	*	*
Lophius spp.	*							
Hemitripterus americanus	*				*		*	
Gadus morhua		*	*	*	*	*		*
Enchelyopus cimbrius		*				*		
Anarhichas lupus		*	*		*			
Brosme brosme			*			*	*	
Lumpenus lumpretaeformis				*		*		
Paralichthys oblongus				*				
Glyptocephalus cynoglossus								*

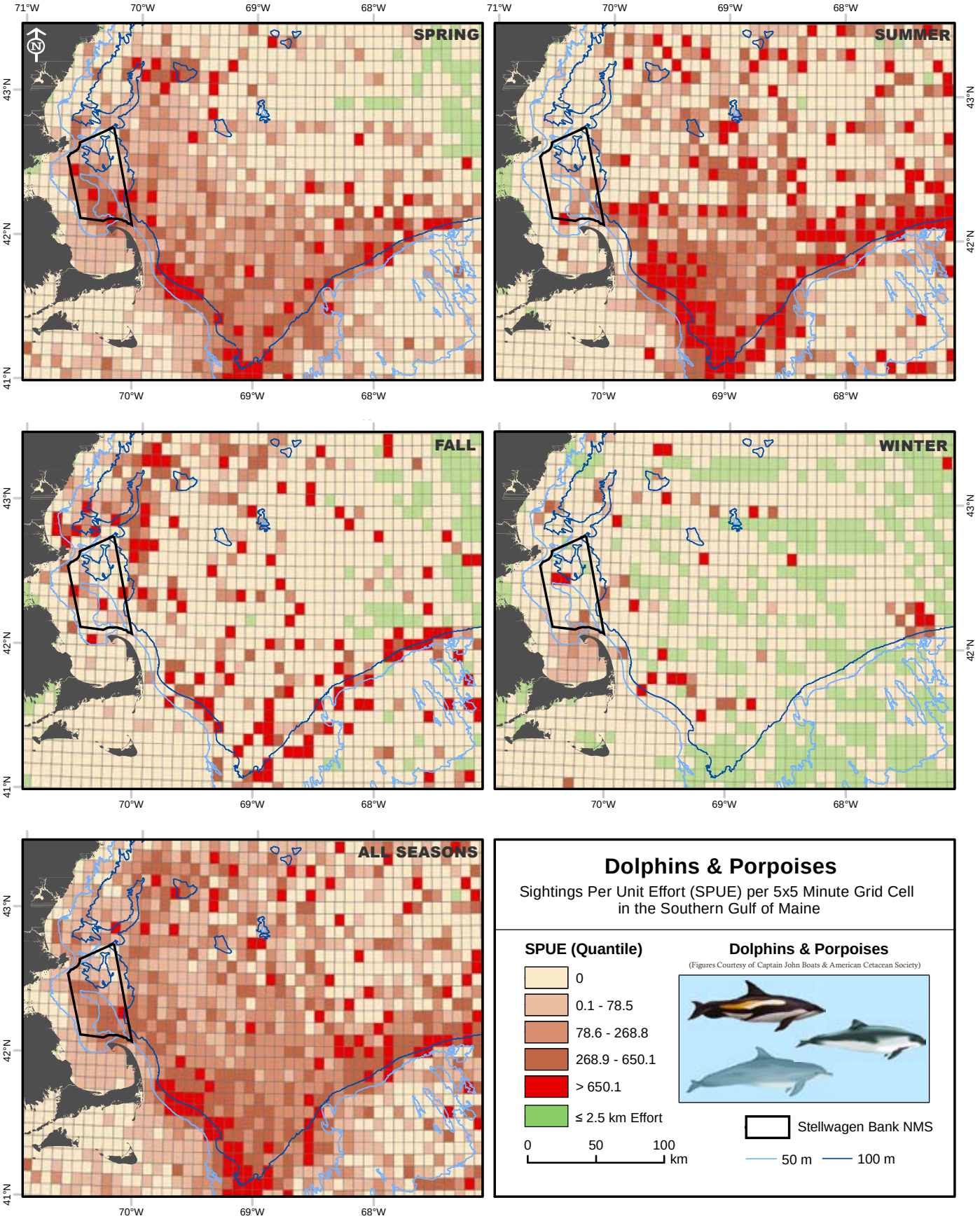
Appendix 10. Species composition along ROV video transects conducted during 2002 within SBNMS. * indicates presence.

Species	Dive 202	Dive 203	Dive 204	Dive 205	Dive 206	Dive 207	Dive 208
Sebastes spp.	*	*	*	*	*	*	*
Tautogolabrus adspersus	*	*	*	*	*	*	*
Gadus morhua	*	*	*	*		*	*
Macrozoarces americanus	*	*	*	*	*		*
Myoxocephalus octodecemspinosus	*	*	*		*	*	*
Plueronectiformes	*		*			*	
Anarhichas lupus				*	*		*
Brosme brosme		*	*	*	*	*	*
Raja spp.	*			*	*		
Pollachius virens			*			*	
Melanogrammus aeglefinus						*	*
Lophius spp.						*	

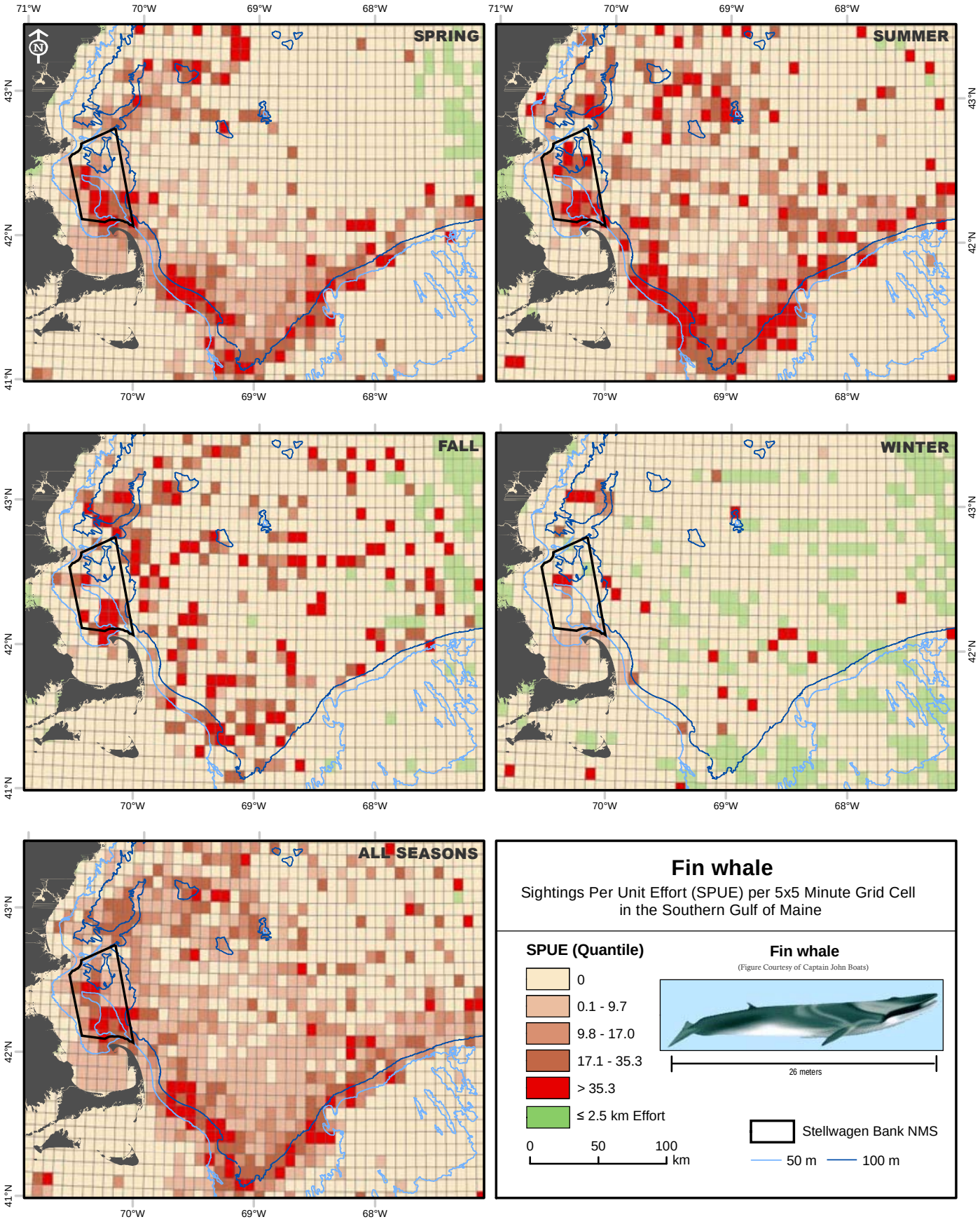
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for Atlantic white-sided dolphins in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



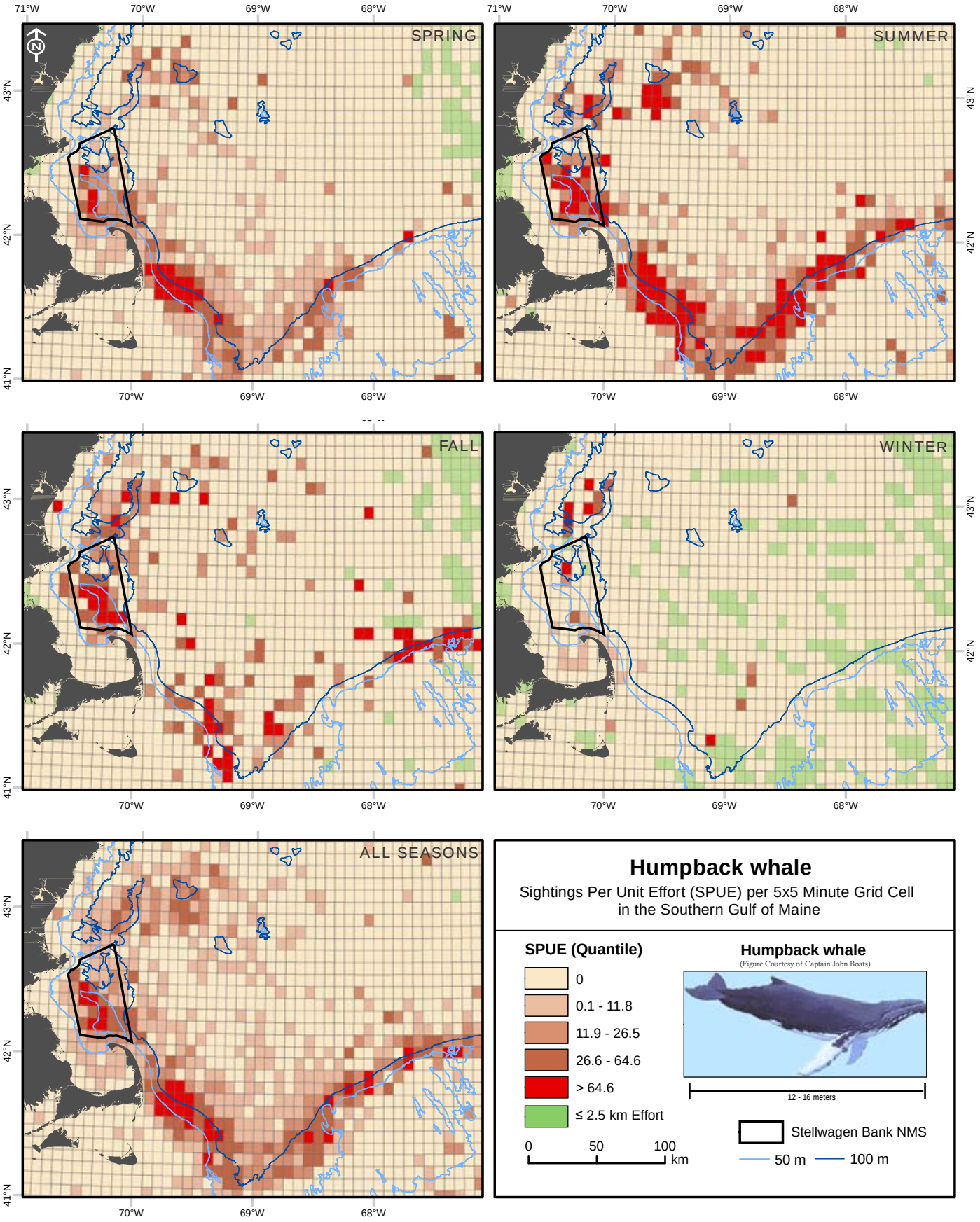
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for dolphins and porpoises in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



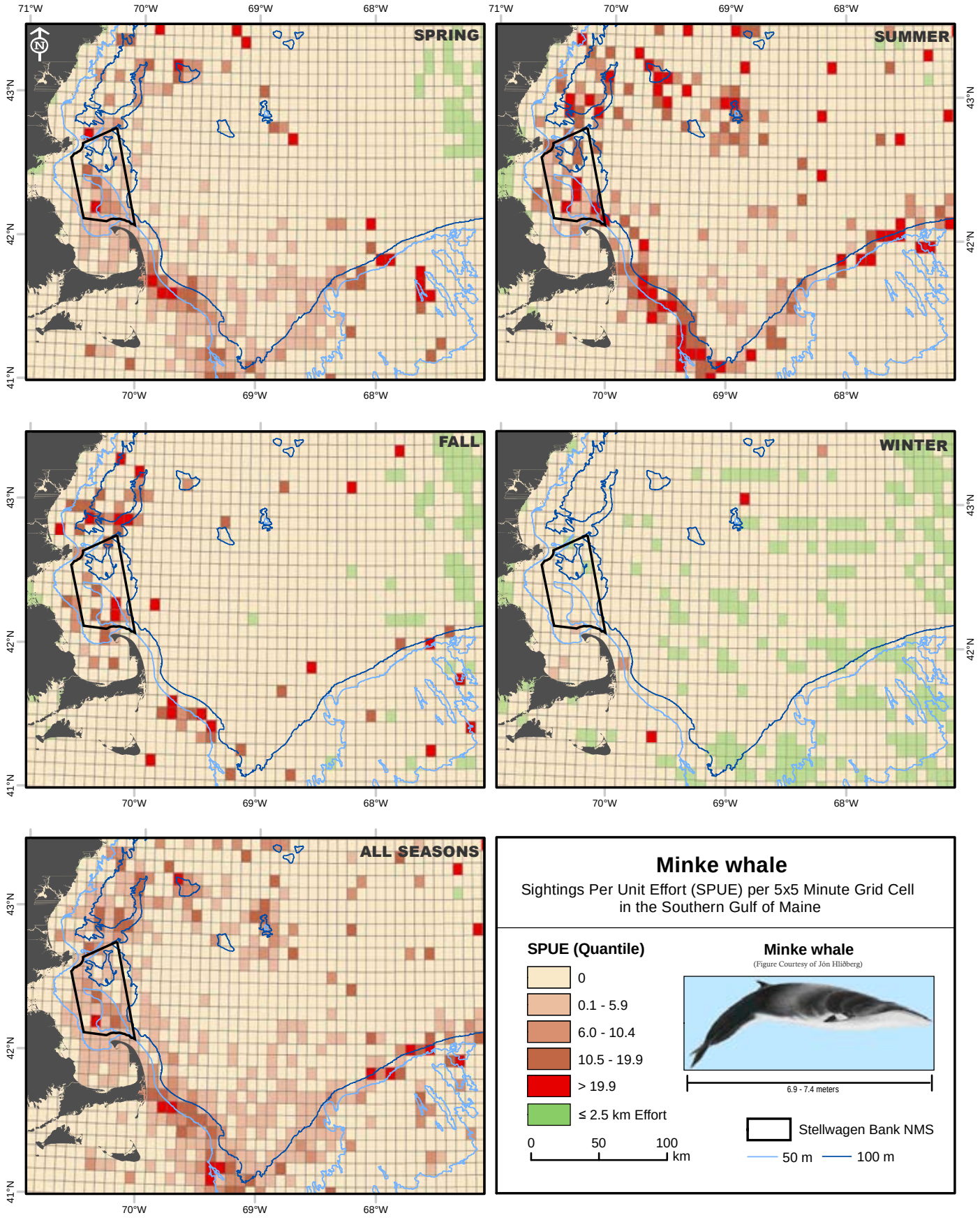
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for Fin whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



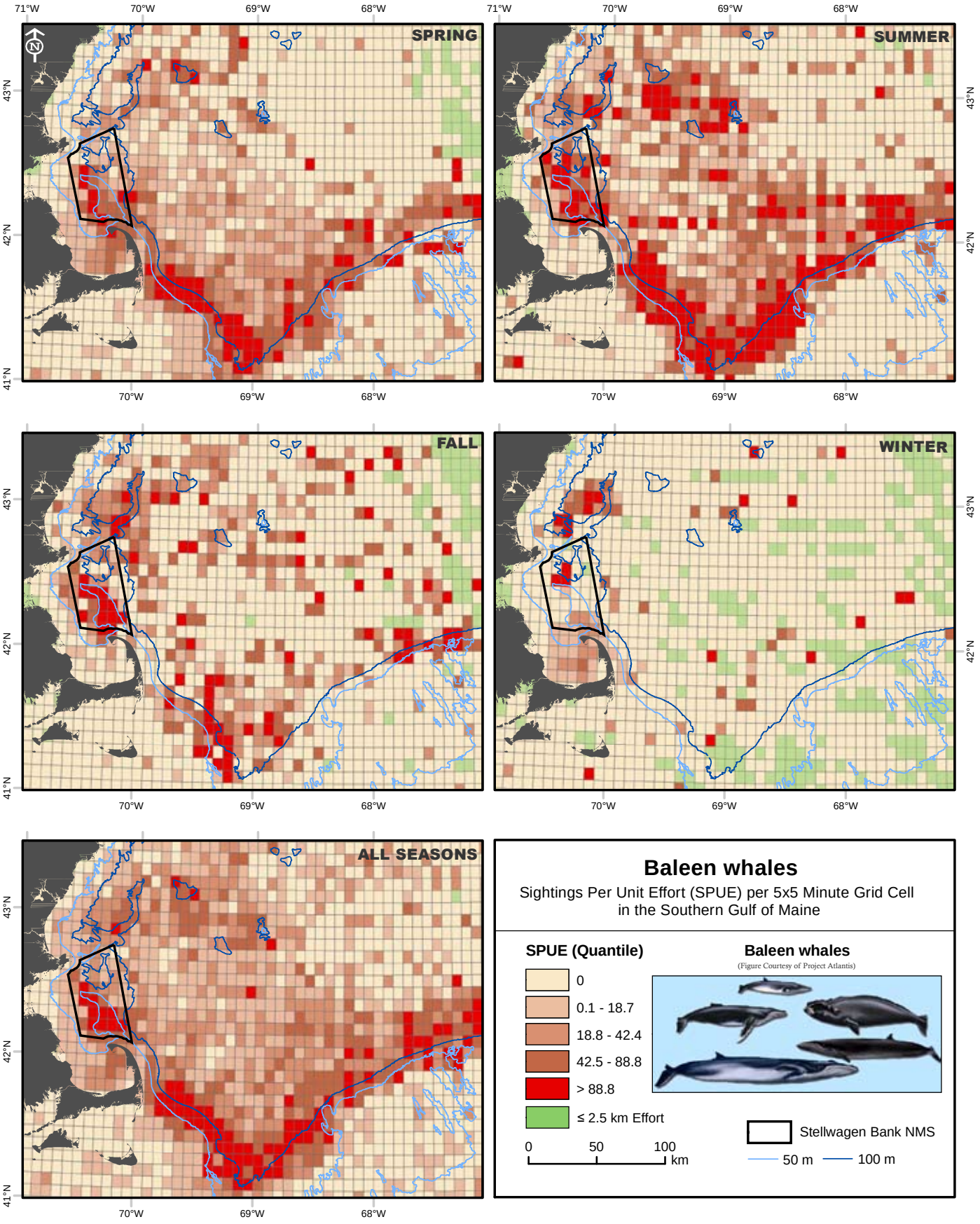
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for Humpback whales in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



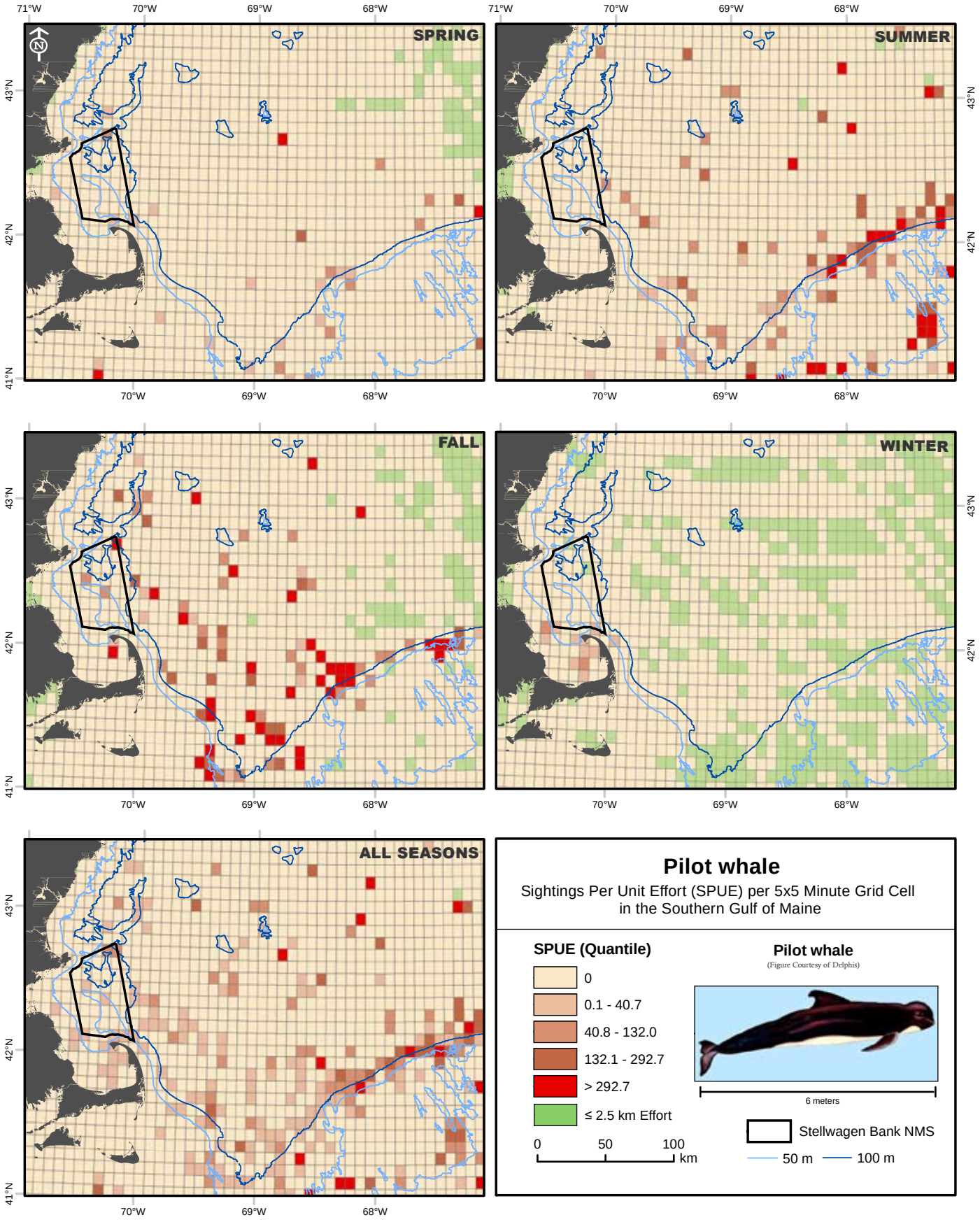
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for Minke whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



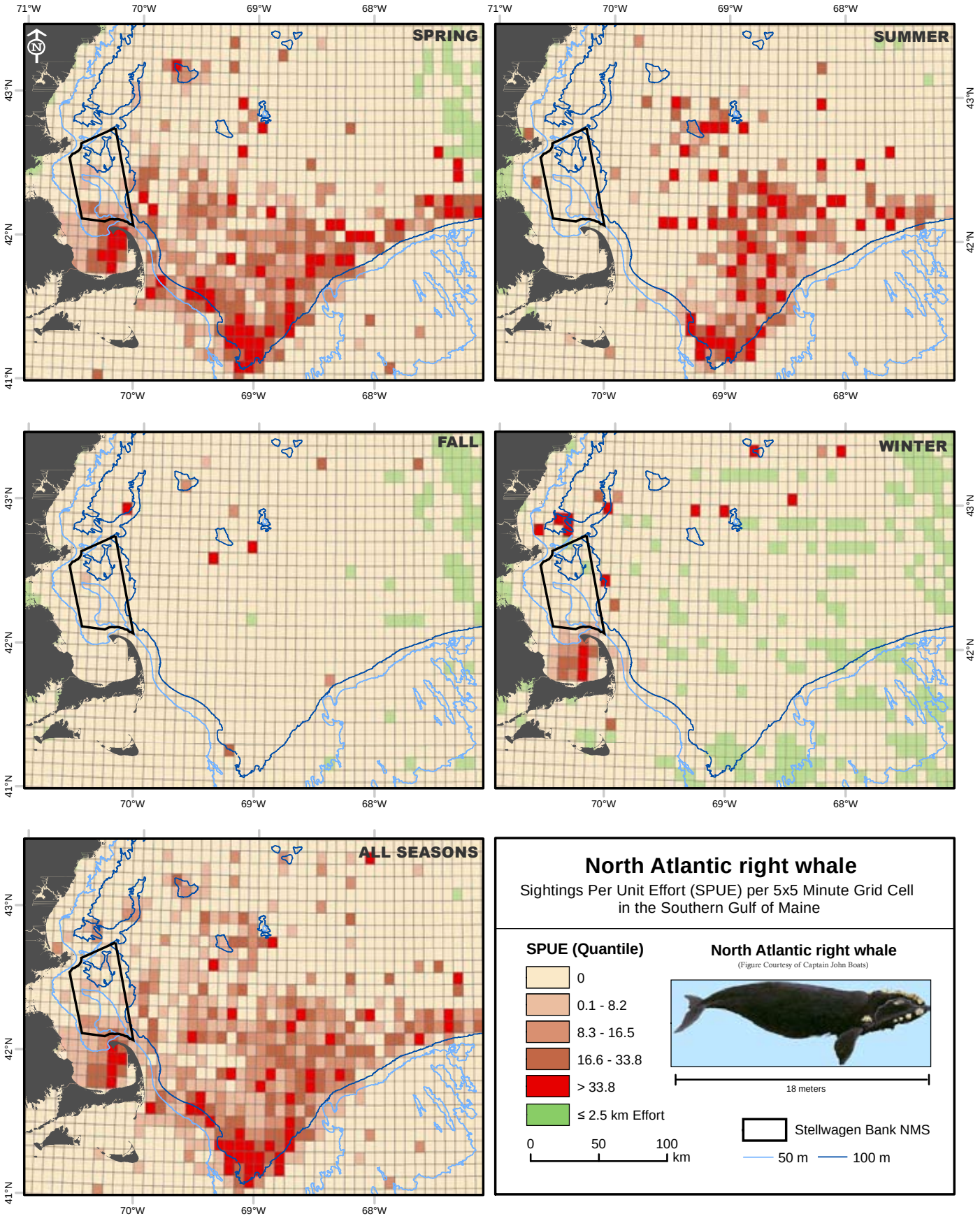
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for Baleen whales in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



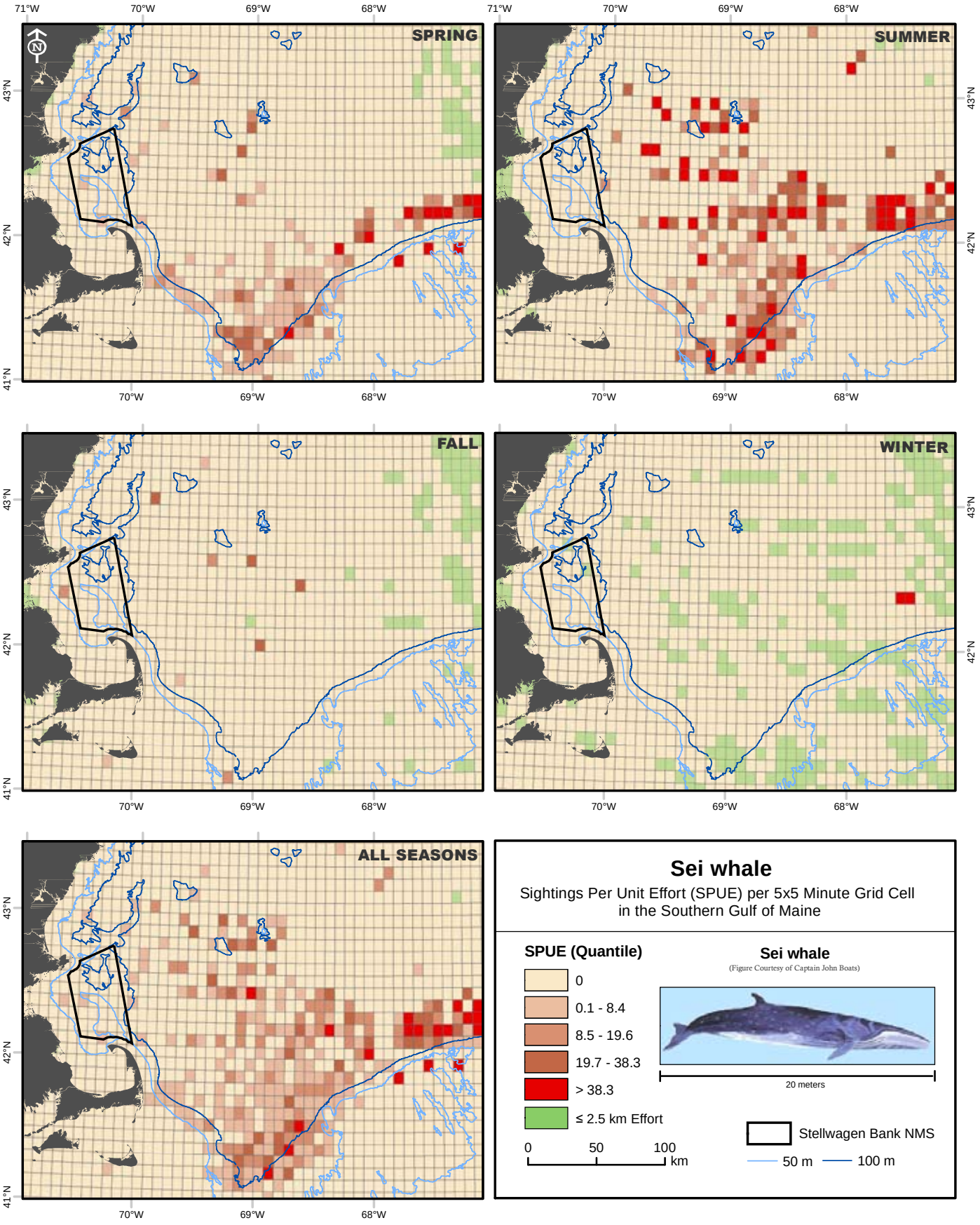
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for Pilot whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



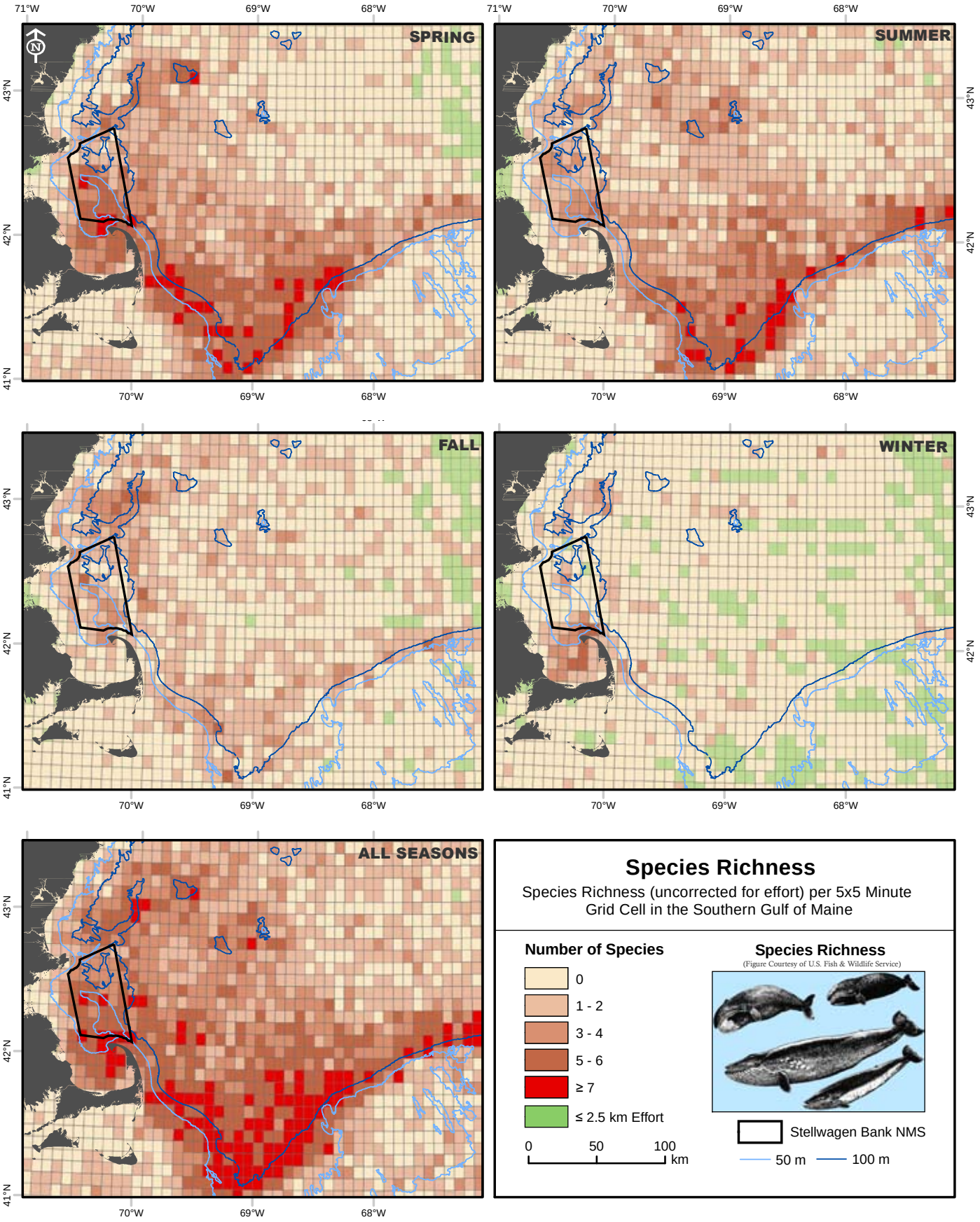
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for North Atlantic right whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



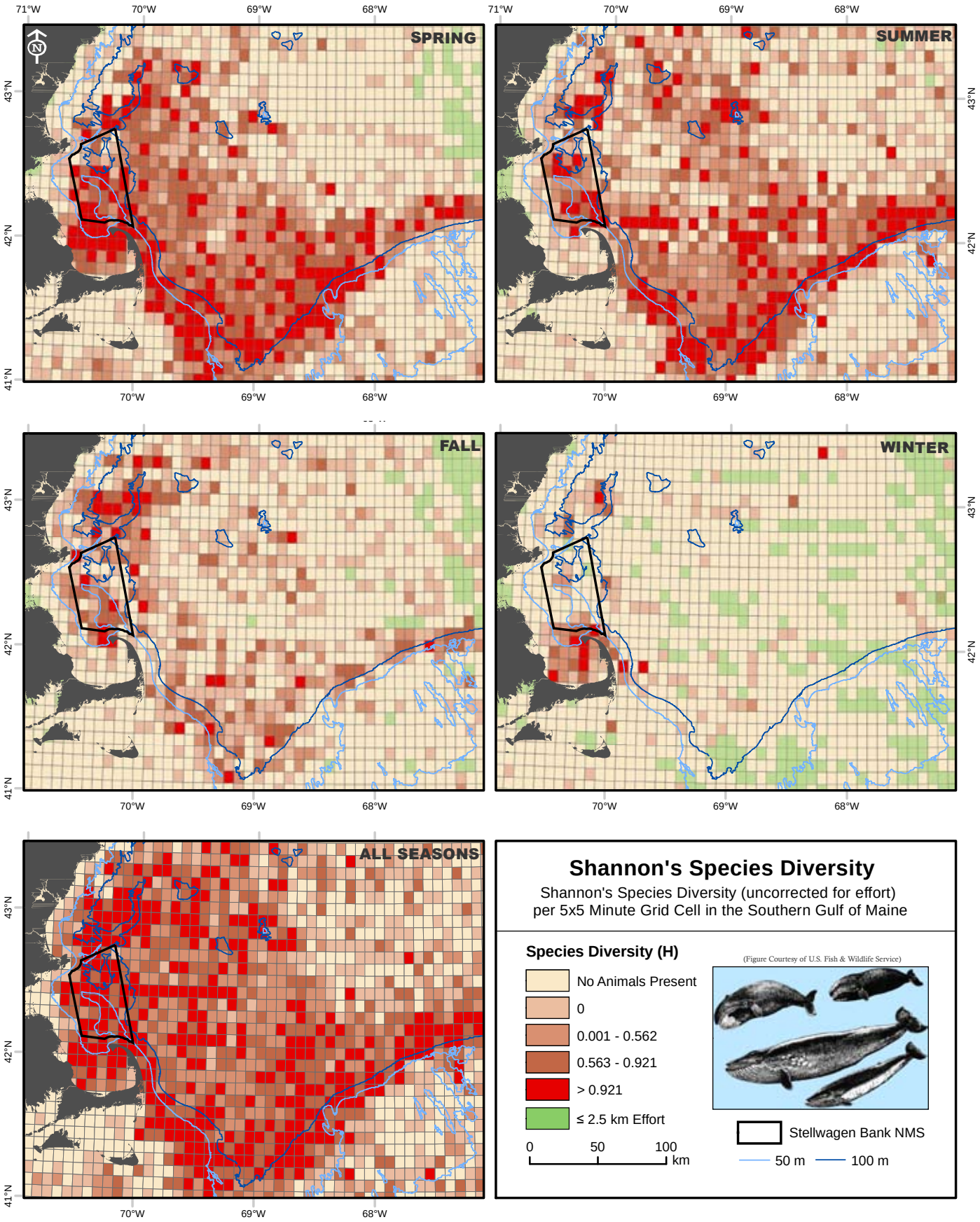
Appendix 10. Seasonal patterns of sightings-per-unit-effort (SPUE) data for Sei whale in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



Appendix 10. Seasonal patterns of cetacean species richness in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



Appendix 10. Seasonal patterns of cetacean diversity (Shannon-Wiener Index) in spring, summer, fall, winter and all seasons combined for the southern Gulf of Maine (1970-2005).



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