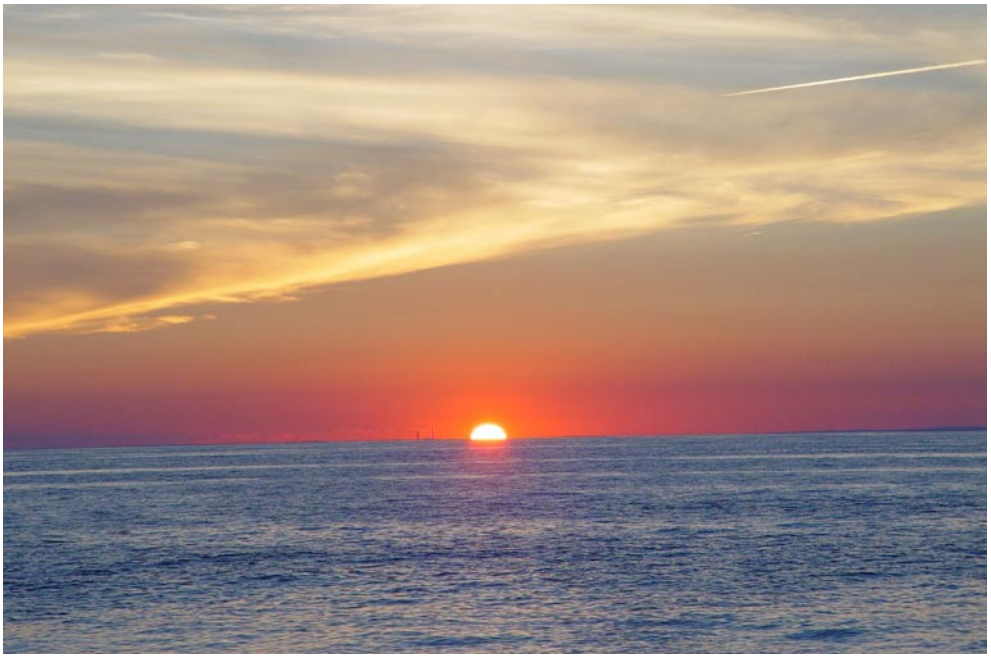
CHAPTER

4

Physical Oceanography

Caroly Shumway, Kevin Ruddock, and Melissa Clark

Introduction



This chapter provides an overview of the large-scale physical processes occurring in the Northwest Atlantic. Oceanographic processes are important predictors of marine species distribution and abundance, from phytoplankton to predatory pelagic fish to whales. For example, variation in seawater density (the combination of temperature and salinity) is one of the major factors governing large scale circulation patterns on the United States East Coast (Epifanio and Garvine 2001). The influence of the Labrador Current and terrestrial freshwater sources along the coast causes water on the Continental Shelf to be generally cooler and fresher than water beyond the Continental Slope, which is more influenced by the Gulf Stream. These two distinct water masses meet at the shelf break front, which can be a barrier to exchange of nutrients and plankton (Townsend et al. 2006). The interrelationship between oceanographic processes and structural features, such as the shelf-slope break or seamounts, leads to distinctive habitats for a range of species (Roff and Evans 2002). Note that the chapter does not address finer-scale current patterns along the coast, which play a role in larval settlement and correspondingly, marine connectivity (Epifanio and Garvine 2001). We recommend that such patterns be examined in the future.

Technical Team Members

Kathryn Jessen-Eller, Ph.D, University of Rhode Island
Grant Law, Ph. D, Oregon Health and Science University
Dan Morse, The Nature Conservancy, Eastern Division
Anna Pfeiffer-Herbert, University of Rhode Island
Kevin Ruddock, The Nature Conservancy, Rhode Island
Caroly Shumway, Ph.D, Boston University

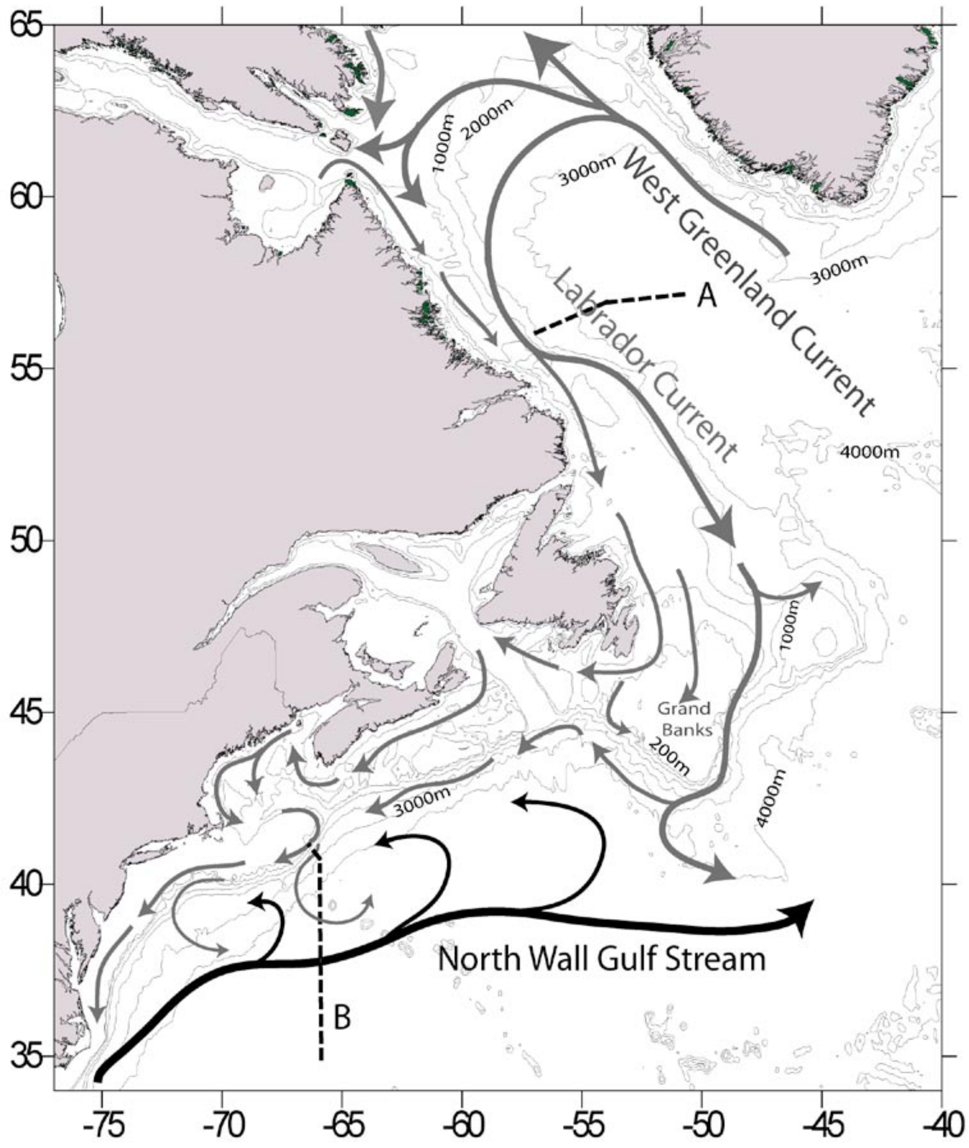


Figure 4-1. Currents in the Northwest Atlantic region (reprinted with permission from Townsend et al. 2006).

Circulation Patterns

Large-scale currents transport larvae of numerous oceanic species and determine habitat connectivity at a broad scale (Shanks 1995). The broad, non-tidal circulation of the western Atlantic (Figure 4-1; Townsend et al. 2006) is dominated by two major current systems, the Gulf Stream and the Labrador Current. The Gulf Stream, characterized by relatively warm temperatures and high salinities, flows northward past Cape Hatteras and turns to the east below the southern New England shelf. This current switches between two modes of circulation that are related to its position relative to the Continental Slope (Townsend et al. 2006). When the Gulf Stream is positioned farther offshore, it has more active meanders that can split from the current as warm water eddies, known as warm core rings or filaments, which are transported onto the shelf (Townsend et al. 2006). The Labrador Current originates in the Arctic, where it is fed by Greenland ice melt and continental fresh water sources, giving it a cold, low salinity signature (Townsend et al. 2006). It diverges around the Grand Banks, and part of it becomes Labrador slope water that flows into the Gulf of Maine and further south to the Mid-Atlantic Bight (Longhurst 2007).

The Gulf of Maine is isolated from the broader scale North Atlantic circulation by Browns and Georges Banks (Townsend et al. 2006). Water enters the Gulf of Maine primarily through the Northeast Channel that divides the two banks, and average circulation is counter-clockwise around the Gulf (Townsend et al. 2006). The inner shelf region of southern New England from Buzzards Bay to Long Island Sound is also semi-isolated by the presence of land. Long Island Sound has an estuarine circulation pattern due to freshwater input (Townsend et al. 2006). Circulation on the inner shelf of the Mid-Atlantic Bight is also influenced by low density water from Delaware and Chesapeake bays (Townsend et al. 2006). At the southern end of the region, very little water is exchanged past Cape

Hatteras, between the Mid-Atlantic and South-Atlantic bights (Townsend et al. 2006).

The circulation patterns of this region are influenced by the North Atlantic Oscillation (NAO), an atmospheric phenomenon that changes the strength of major wind patterns (Longhurst 2007). During periods of negative NAO, the Gulf Stream shifts to the south and the Labrador Current increases in volume, penetrating farther down the coast (Townsend et al. 2006; Longhurst 2007). In contrast, during periods of positive NAO, the Gulf Stream shifts to the north and the Labrador Current weakens (Townsend et al. 2006; Longhurst 2007). The shifting balance between these two currents has significant implications for biological communities because it can expose those communities to very different temperature and salinity regimes (Townsend et al. 2006).

Wind forcing on seasonal and shorter time scales also affects circulation of the northwestern Atlantic shelf. Winds from the north, which are common in winter, push the colder shelf water to the inner shelf (Longhurst 2007). Winds from the south push surface water out away from the coast, which in some places causes upwelling of deep water near the coast (Longhurst 2007). The Mid-Atlantic Bight is frequently in the path of cyclones, which cause vertical mixing and thus resupply nutrients to the surface layer (Townsend et al. 2006).

Tidal Influence

Tides have an obvious effect at the shoreline, where marine organisms must adapt to exposure to air, but they also influence ecosystem processes further offshore. For example, tides can prevent stratification (i.e., layering of different water masses). Strong tidal mixing in the Gulf of Maine prevents stratification over shallow areas such as Georges Bank (Longhurst 2007). Such areas often serve as spawning and nursery grounds for fish because they tend to be characterized by high biological productivity and have recirculating currents that retain larvae (Mann and Lazier 2006). When stratification persists over the shelf, the tide interacts with the sharp change in topography at the shelf break to generate internal waves which help mix nutrients through the water column and are one mechanism for transporting larvae across the shelf (Mann and Lazier 2006).

Tides can also play a major role in sediment mobility, which affects bottom communities. If energy from tides exceeds a certain threshold, it disturbs sediments on the sea floor. Tidal energy varies with the range in tidal height and the amount of constriction by bottom topography. The energy needed to move sediment depends on the sediment grain size and density, seabed roughness, and how well the sediment grains are cemented together (Porter-Smith et al. 2004).

It is important to note that tides are just one process for mobilizing sediment. Storm waves, for example, also can cause rapid sediment transport that exceeds the amount of transport caused by normal wave and tidal energy over the course of months (Porter-Smith et al. 2004). Sediment mobility has implications for the types of benthic communities found in a given area and the persistence or stability of these communities over time. Mobile sediments tend to be dominated by a single opportunistic species that can quickly recolonize following a disturbance, while stable sediments, such as gravel, tend to support greater species diversity (Newell et al. 1998).

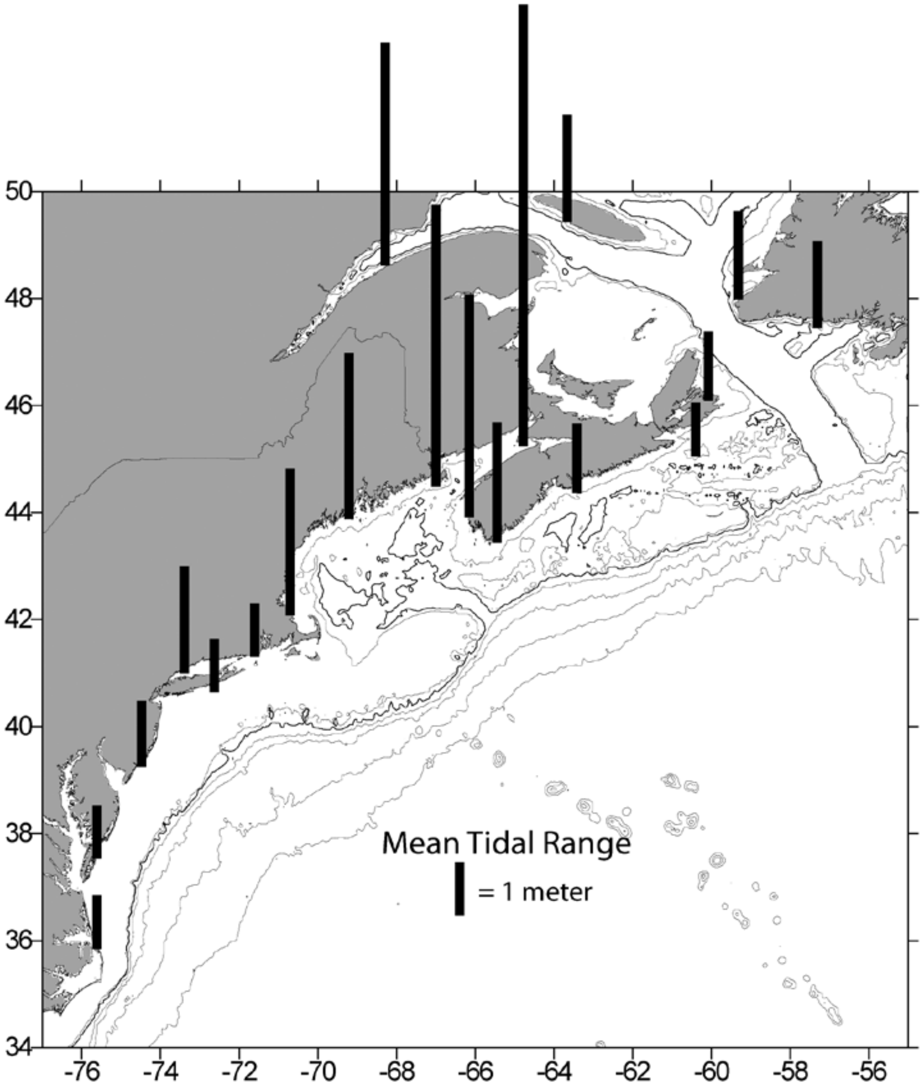


Figure 4-2. Mean tidal range in the Northwest Atlantic region (reprinted with permission from Townsend et al. 2006).

Figure 4-2 (from Townsend et al. 2006) shows the strength of tides within the Northwest Atlantic region. The height of the black bar indicates the strength of the tide at that point. The strongest tides are in the Gulf of Maine, particularly on the northern (Canadian) end by the Bay of Fundy. Penobscot Bay and Cape Cod Bay also have a strong tidal influence, as does the western end of Long Island Sound.

Oceanographic Analysis: An Overview of Methods

For all of the temperature-related analyses described below, source data was obtained from Dr. Grant Law, Center for Coastal Margin Observation and Prediction, Oregon Health and Science University. The dataset included temperature values plotted on a standard grid of three-dimensional point locations that has finer detail toward the shore and surface, where there is greater need for higher resolution. The data comprised seasonal climatologies (Jan-Mar, Apr-Jun, Jul-Sep, Oct-Nov) to a depth of 2,500 m, from 1980-2007. Hydrographic observations were compiled from several sources, including Hydrobase, National Marine Fisheries Service (NMFS), and Department of Fisheries and Oceans Canada (DFO). An archive of South Atlantic Bight hydrographic data assembled by Brian Blanton at UNC was also included in the archive. All hydrographic data were quality checked, then archived into yearly files. While hydrographic data varied in spatial and temporal coverage, an interval of three months appeared to produce consistently useable climatologies. Climatologies were created by interpolating three months of observed hydrography to the standard grid using the OAX5 optimal-analysis application. OAX5 alters the weighting factors of nearest neighbors relative to the shape of the bathymetry, producing more physically reasonable solutions.

The specific methods for each set of analyses are provided in the sections below.

Sea Surface Temperature

Water temperature is an important predictor of species distribution. Sea surface temperature (SST) means are useful for understanding patterns of species assemblages and predicted ecosystem changes. Ectothermic organisms (i.e., cold-blooded species such as marine invertebrates and fish) have both physiological and behavioral preferences for certain temperatures. If temperatures become too warm, species can become physiologically stressed, influencing such processes as reproduction and feeding. Previous research has shown that mean SST is correlated with diversity of zooplankton (Rutherford et al. 1999) and distribution patterns of apex predators (tuna/billfish: Worm et al. 2005).

Methods

To display seasonal average sea surface temperature, data points of questionable accuracy were removed from the dataset and averages over all years were calculated for each season. The resulting surface temperature values were then interpolated using ordinary kriging in ArcGIS 9.1, creating a smooth data grid representing the average sea surface temperature for 1980 – 2007 for each season.

Results

Mean SST generally decreases with latitude, and varies seasonally. The warmest mean SST found in the Northwest Atlantic region is associated with the Gulf Stream, which carries warm subtropical water north along the Continental Slope. From the winter to spring months, cooler water spreads over the shelf, with a slight north-south temperature gradient (Figure 4-3a and 4-3b). In the summer, warmer water spread over the shelf and to the Georges Bank Gyre (Figure 4-3c). Fall showed little difference from summer, except for more extensive warming in the Mid-Atlantic Bight (Figure 4-3d).

The annual range in SST on the Continental Shelf has increased from the mid-20th century to the present as a result of increasing summer maximum SST and constant or decreasing winter minimum SST (Friedland and Hare 2008). However, temperature changes are still within the range of past temperatures (Friedland and Hare 2008). Worldwide, 11 of the last 12 years (1995 to 2006) were among the 12 warmest years of record (IPCC 2007). For the Northwest Atlantic region, warming trends are more pronounced in shallow coastal ponds or estuaries (not mapped in this analysis, but see Chesapeake: Preston 2004; Great Harbor, Woods Hole, MA: Nixon et al. 2004). Narragansett Bay, RI, has warmed over 1.1°C since 1970 (Nixon et al. 2003; Smith 2007).

Sea Surface Temperature Gradients

Maps of sea surface temperature gradients display the rate of change in surface temperature or 'fronts.' These maps show the locations of persistent, large scale gradients in surface temperature for the given decades, and also show how these patterns have changed over the time scale of the data. Sharp gradients in SST suggest the presence of a front between distinct water masses with different temperatures. Fronts are areas of particularly high biological activity due to cross-frontal mixing of nutrients, which stimulates high primary productivity (Mann and Lazier 2006). Fronts are the location of high densities of phytoplankton (Munk et al. 1995; Mann and Lazier 2006), zooplankton (Munk et al. 1995; Wishner et al. 2006), fish larvae (Munk et al. 1995), marine mammals (Etnoyer et al. 2004), and seabirds (Haney 1986). Worm et al. (2005) also showed that SST gradients are positively correlated with tuna and billfish diversity.

Methods

To calculate the gradient, SST was interpolated for each season of each year from 1980 through 2007. This was done at a relatively coarse scale of 10 km cell size and smoothed to eliminate small scale fluctuations and to focus on the larger scale patterns. To identify areas of relatively high gradient, a slope grid was calculated from each surface temperature grid. This captured the rate of temperature change for each 10 km cell. The resulting data were inspected to determine a reasonable division value to characterize each cell as either high gradient or low gradient. Any cell with a slope change greater than 0.0009 degrees was classified as high gradient. Each decade was then

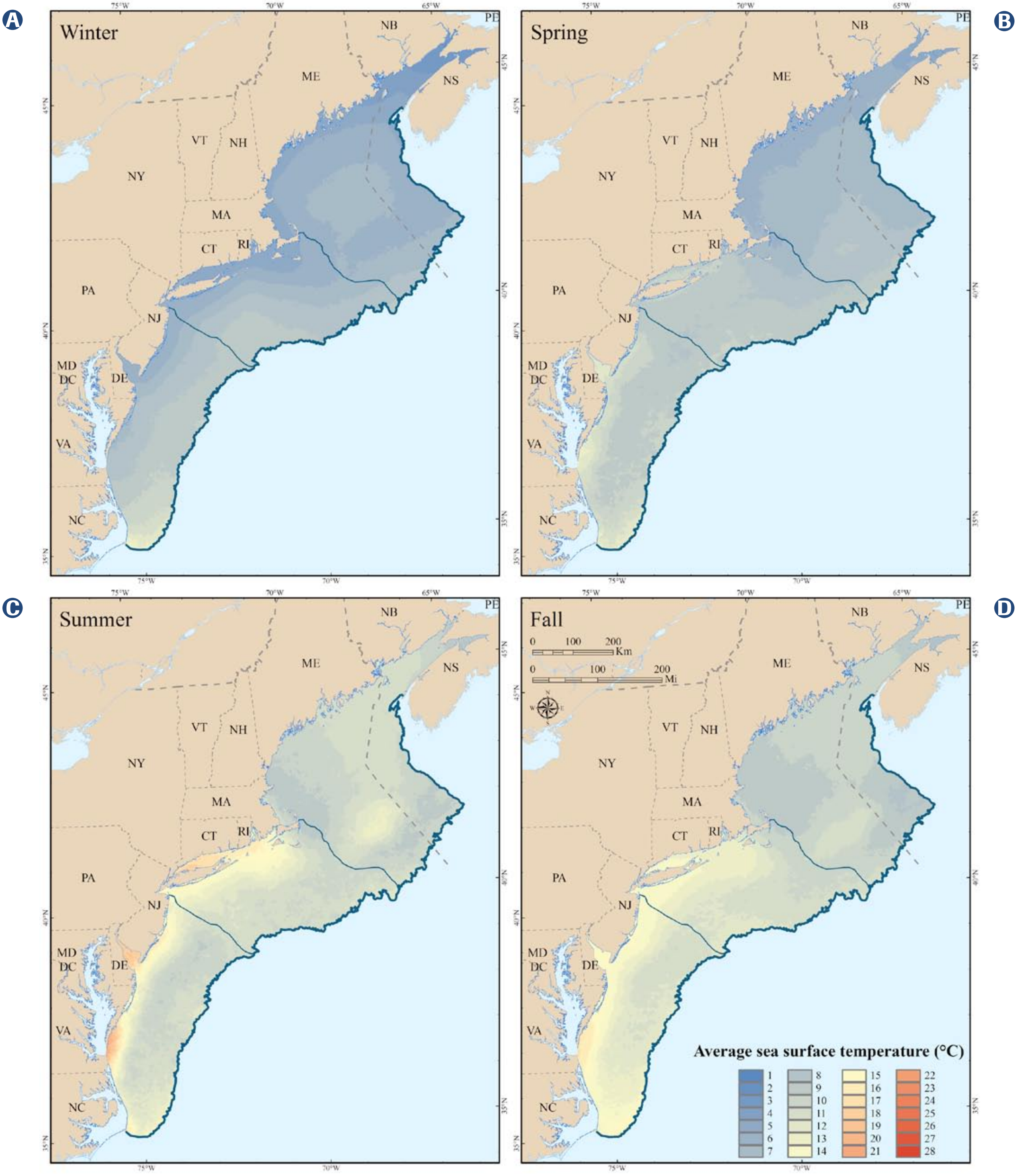


Figure 4-3. Average sea surface temperature by season.

classified by summing the number of years with a high gradient in each cell. Finally, the values from the earliest decade were subtracted from the values for the most recent decade to illustrate patterns of change between 1980 and 2007.

Results

Differences in the spatial and seasonal patterns of SST gradients are apparent (Figures 4-4, 4-5, 4-6 and 4-7). A shelf break front (red-brown area) located between the Southern New England subregion and Georges Bank was compact in the winter, extends northward to a larger area in the spring, shifts further northward in the summer, and was weak and patchy in the fall. Persistent SST gradients extended onto the Nantucket Shoals in the summer and fall. In the Mid-Atlantic Bight subregion, a mid-shelf front was a persistent feature in the winter, but disappeared in the spring. The mid-shelf front was replaced by persistent SST gradients over the inner shelf and shelf break in the summer, which disappeared again in the fall. A patch of high SST gradients began next to Cape Hatteras and extended to the north off of the shelf. This signature occured from winter to summer, but was absent in the fall.

A sharp front between cooler shelf water and warmer slope water is a common feature of the shelf break of eastern North America (Beardsley and Boicourt 1981; Mann and Lazier 2006). The water column above Georges Bank is well-mixed by tidal currents, while the water around the bank stratifies in the spring and summer, causing the development of a front between the cooler well-mixed water and warmer stratified water (Mann and Lazier 2006). This feature was apparent in the greater persistence of SST gradients around Georges Bank in the spring and summer, and the greater extent in the summer. The water column above Nantucket Shoals was also well-mixed by tides (Townsend et al. 2006), which explains the seasonally present SST gradients in that area. Wintertime fronts over the mid-shelf are a consistent feature south of Long Island (Ullman and Cornillon 2001; Townsend et al. 2006). In the Mid-Atlantic Bight subregion, the persistent SST gradients that extended offshore from Cape Hatteras likely demarcate the edge of the Gulf Stream. The Gulf Stream is closest to shore at Cape Hatteras and varies in offshore position to the north, as well as over time (Townsend et al. 2006).

Because fronts are associated with concentrated primary production and foraging by zooplankton and fish, changes in the persistence of thermal fronts may impact both secondary production and the life history cycles of fish (Roman et al. 2005). Figure 4-4d, 4-5d, 4-6d and 4-6d showed the change in SST gradient patterns over the past few decades. These figures compared the 2000-2007 period and the 1980-1989 period. Differences between these two decades may indicate changes in environmental forcing from climate oscillations (i.e. the North Atlantic Oscillation) and/or longer-term climatic warming trends. The SST gradient at the shelf break weakened over time in all seasons from 1980-1989 to 2000-2007. In winter, SST gradients over the mid-shelf also weakened. SST gradients over the Continental Slope strengthened over time, especially in the winter. The SST gradients associated with the Gulf Stream wall strengthened in the spring-fall. SST gradients also strengthened on the Nantucket Shoals and Block Island Delta of Southern New England in spring-fall. SST gradients in the Georges Bank area strengthened in the fall and summer, but weakened in the winter.

Stratification

Stratification is the layering of different water masses, with warmer water at the top. Measures of stratification tell us how well-mixed the water is. In the Northwest Atlantic region, like other temperate regions, stratification is greatest during the warmer months. Stratification traps phytoplankton in the warm surface waters, enabling them to utilize the nutrients. Winter winds can cause stratification to break down and mixing to occur, which brings more nutrients from deeper water to the surface to replenish those being used in the upper layers.

Why is stratification biologically important? The degree of stratification of the water column affects three important ecosystem processes:

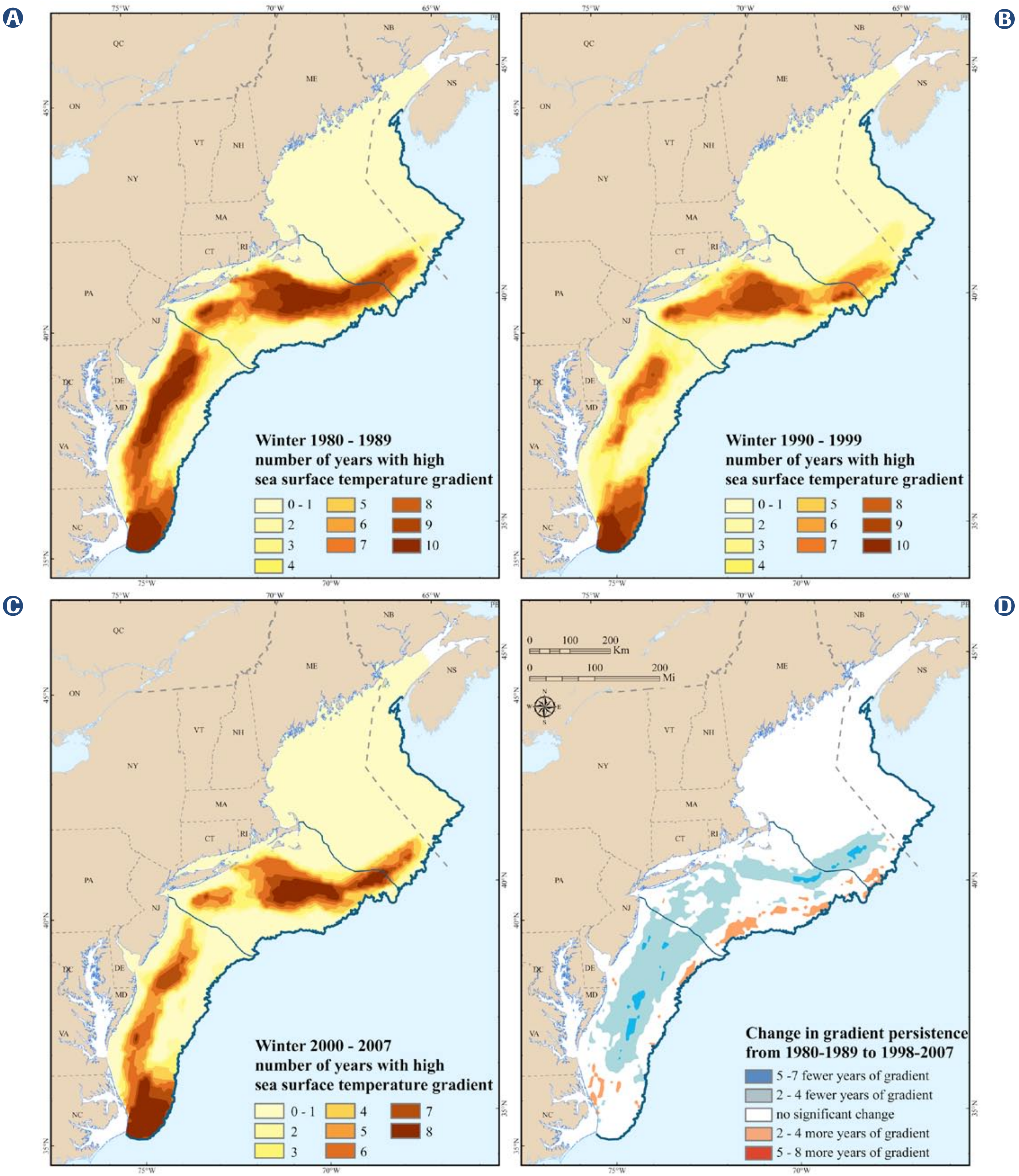


Figure 4-4. Winter sea surface temperature gradients by decade (a, b, c); Change in gradient persistence from 1980-1989 to 1999-2007 (d).

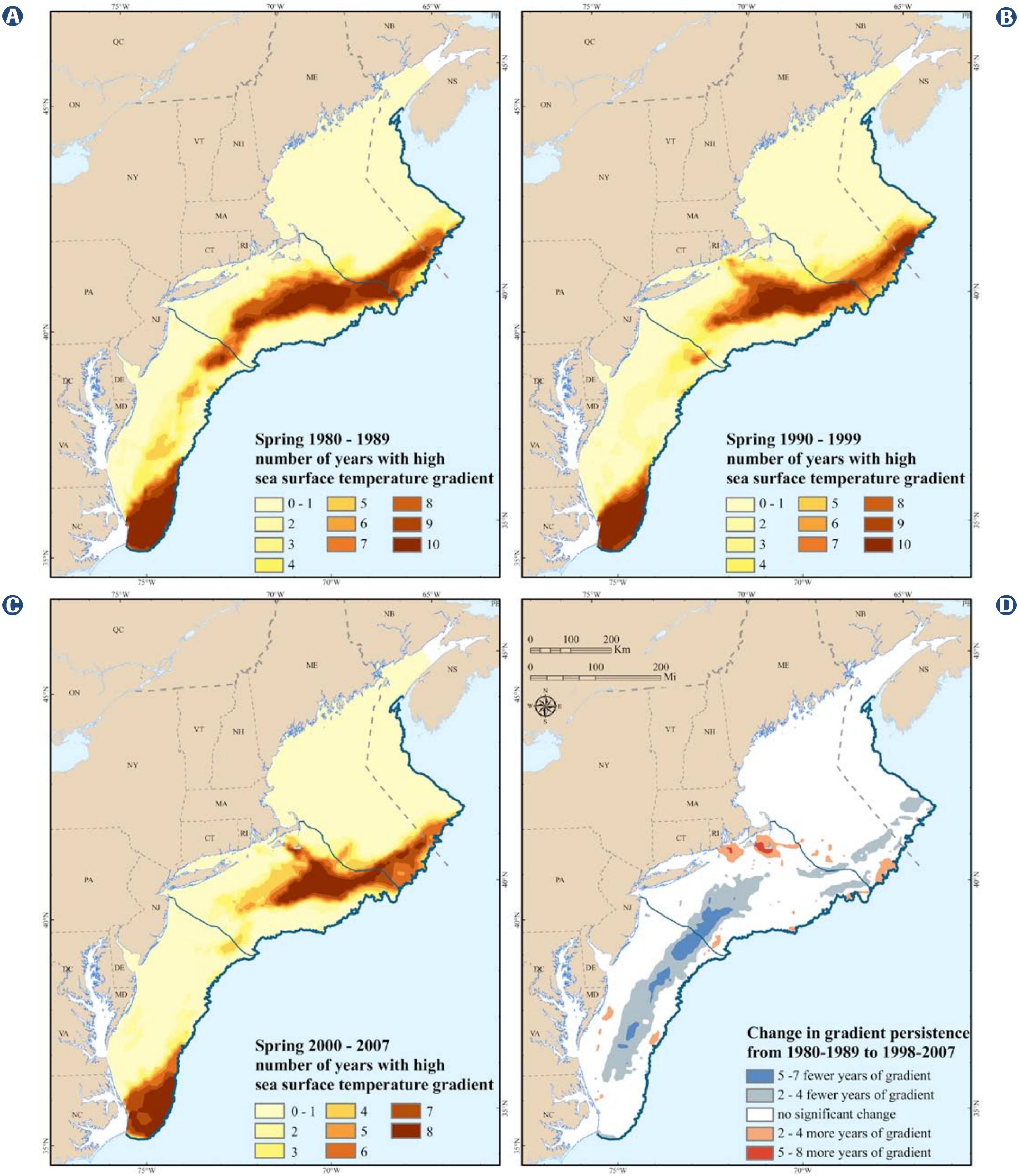


Figure 4-5. Spring sea surface temperature gradients by decade (a, b, c); Change in gradient persistence from 1980-1989 to 1999-2007 (d).

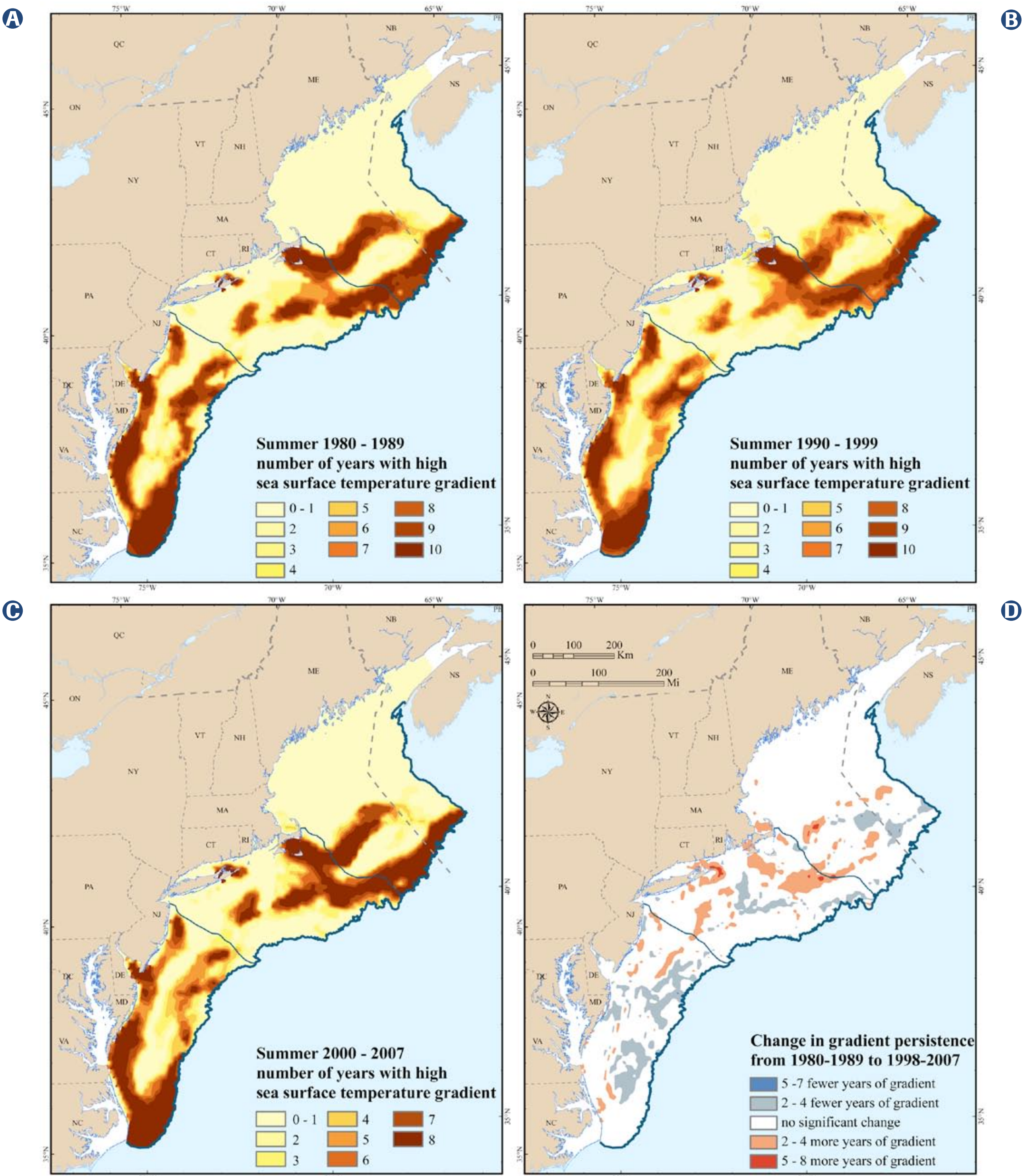


Figure 4-6. Summer sea surface temperature gradients by decade (a, b, c); Change in gradient persistence from 1980-1989 to 1999-2007 (d).

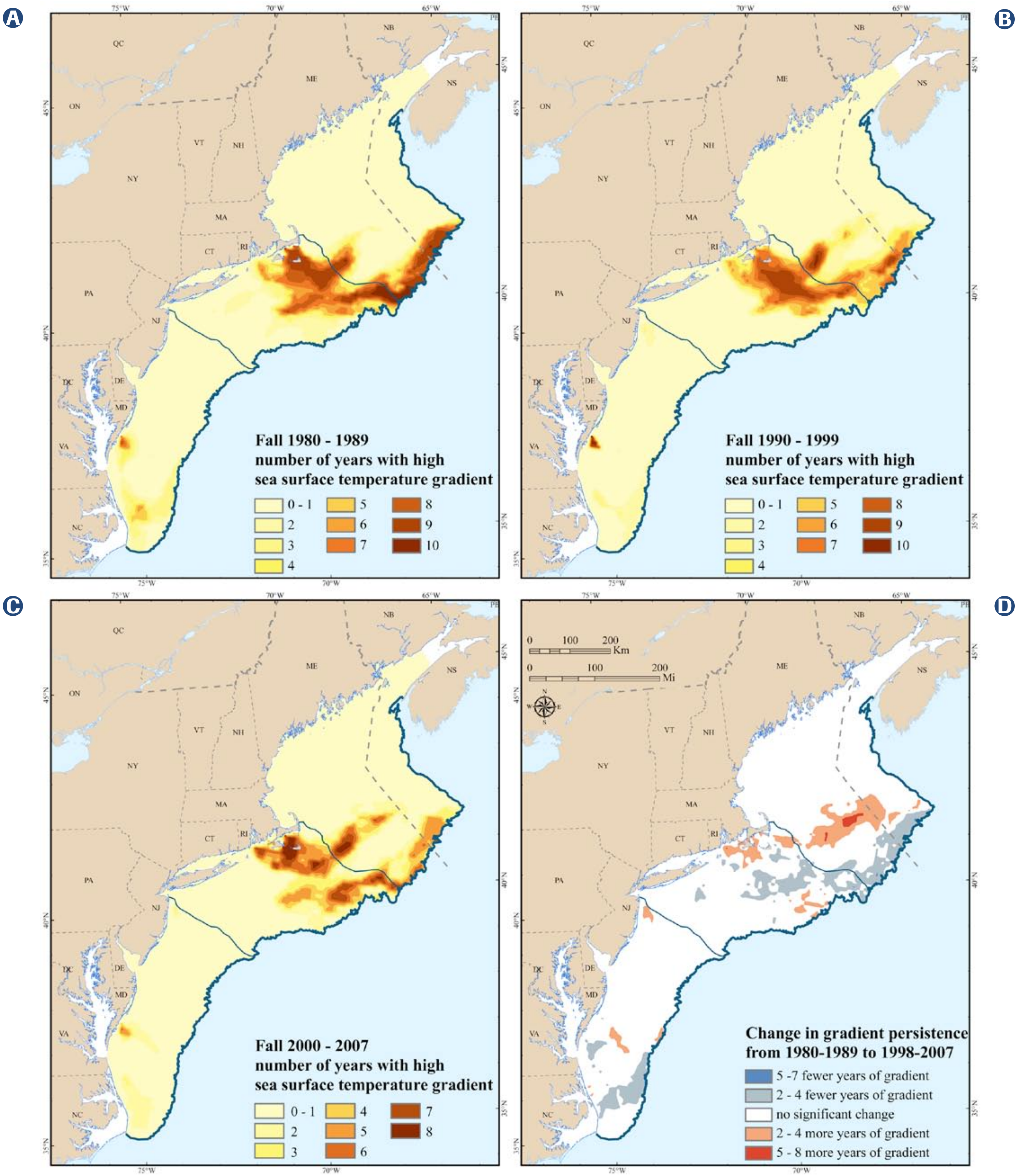


Figure 4-7. Fall sea surface temperature gradients by decade (a, b, c); Change in gradient persistence from 1980-1989 to 1999-2007 (d).

- Stratification increases the stability of the water column, providing conditions for seasonal accumulation of high density patches of phyto plankton, which may provide a rich food source for higher trophic levels (McManus et al. 2003). However, if stratification extends too long, the water masses become depleted of nutrients. Fortunately, winter winds cause stratification to break down. This has the advantage of enabling nutrients from deeper, colder waters to come to the surface.
- Stratification controls the development of phytoplankton blooms. Because the surface layer is well mixed down to the pycnocline (the depth of maximum change in density), phytoplankton are physically mixed throughout the layer (Mann and Lazier 2006). If the surface layer is much thicker than the euphotic zone (the vertical zone where light intensity is high enough for photosynthesis to occur), phytoplankton populations cannot grow. Conversely, if the surface layer is thin enough relative to the euphotic zone, phytoplankton populations can grow rapidly, forming a bloom. This is the mechanism responsible for the spring phytoplankton bloom in the North Atlantic Ocean (Mann and Lazier 2006).
- Stratification also increases the potential for hypoxia by preventing deep water from exchanging with the atmosphere (Rabalais et al. 2002). Hypoxia causes the exclusion of fish and other mobile organisms and mortality of many benthic organisms (Rabalais et al. 2002).

Methods

Stratification was calculated by subtracting the density at 50 m from the surface density. Where the seafloor is shallower than 50 m, stratification was calculated as the density difference between the seafloor and the surface. The resulting stratification values were then interpolated using ordinary kriging in ArcGIS 9.1, creating a smooth data grid representing the average degree of density stratification for 1980 – 2007 for each season.

Results

The maps produced by this analysis agree with observed seasonal patterns of stratification. In the winter (Figure 4-8a), the water column was mixed by winds from the surface down to 50-100 m (Longhurst 2007). The water over the shelf was nearly completely mixed, except for a narrow band of stratification near the coast. The highest stratification during these months (dark red) occurred at the Hudson outflow, in Delaware Bay, and between Chesapeake Bay and Cape Hatteras. In the spring (Figure 4-8b), the water column becomes stratified and formed a thinner surface layer due to solar heating and increased freshwater inputs (Longhurst 2007). The map of spring stratification showed stratified conditions throughout the ecoregion, except north of Penobscot Bay in the Gulf of Maine. The broadest extent of stratification occurred in the Mid-Atlantic Bight, extending to the 50 m isobath throughout.

In the summer (Figure 4-8c), stratification greatly intensified and extended throughout the Gulf of Maine, but not on Georges Bank or Bay of Fundy. In the Southern New England subregion, only parts of the Great South Channel remained mixed. All of the Mid-Atlantic Bight subregion was very stratified, with the exception of the southeastern end of the region. As water over the shelf stratifies in the summer, a pool of cold, higher nutrient deep water remained isolated (Townsend et al. 2006). This cold pool is distinctly colder and fresher than the water mass over the Continental Slope. The cold pool flows to the south, bringing a supply of nutrients to the southern end of the Mid-Atlantic Bight (Townsend et al. 2006).

In the fall (Figure 4-8d), increased wind events cause mixing throughout the Gulf of Maine, Georges Bank, by the Block Island Delta (Southern New England subregion) and the outer shelf. The inner shelf of the Southern New England subregion from Narragansett Bay south and the Mid-Atlantic Bight remained moderately stratified (yellow); the coast just south of Chesapeake Bay showed a small patch of increased stratification (red).

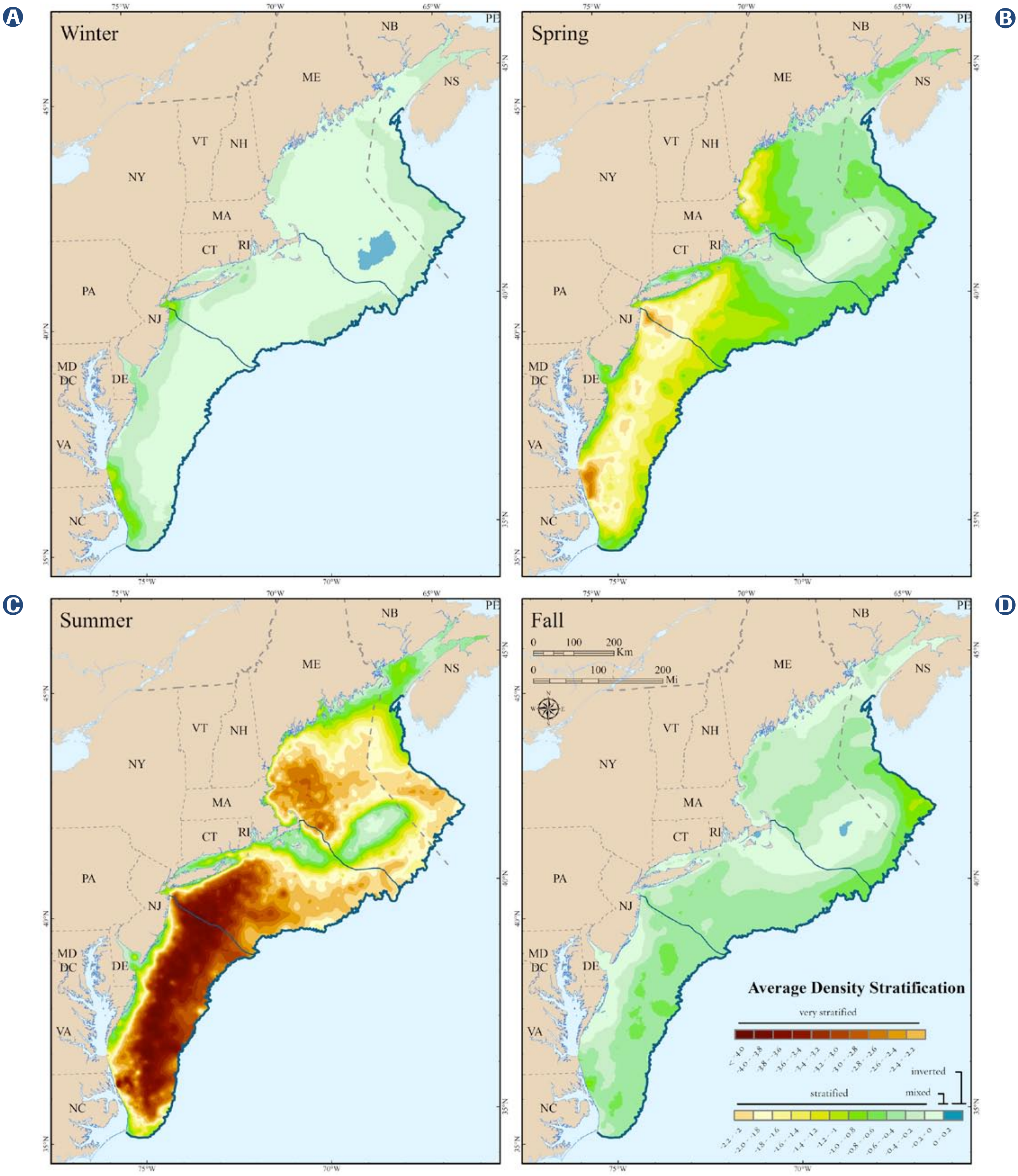


Figure 4-8. Average sea surface temperature stratification by season.

Marine Plankton

Plankton are free-floating aquatic organisms which drift or swim with the movement of water. This group includes microscopic single-celled organisms from the kingdoms Archaea, Bacteria, Plantae and Protista, as well as multicellular larval and adult forms of animals. Phytoplankton are primary producers in both coastal and open-ocean marine ecosystems. Zooplankton feed on phytoplankton, and are secondary consumers. The third broad category of plankton are bacterioplankton, which decompose organic matter and help recycle carbon and essential nutrients.

Plankton are important for many reasons:

- Phytoplankton and zooplankton support commercially and ecologically important fisheries (including shellfish);
- Increases in phytoplankton abundance is a good indicator of commercially productive waters;
- Plankton play a critical role in global biogeo chemical cycles, including those of essential nutrients and carbon;
- Artificially-introduced nutrients (nutrient loading), particularly nitrate in marine systems, cause phytoplankton blooms (eutrophication) that can reduce bottom oxygen levels to hypoxic or anoxic levels in stratified water, causing fish kills if anoxic for periods of time;
- Species composition and abundance can be used as a) historic or current indicators or predictors of ecosystem or fishery health and b) to assess changes in climate, sea level, and biogeochemistry; and
- Blooms of toxic algae can harm both marine life and people.

Climate change can dramatically influence both coastal and offshore plankton biomass. Subsequent changes in currents, sea level, and storm frequency can alter nutrient availability.
In the Southern New England region, for example, increased invasions of boreal phytoplankton (from the north) along with those from the south (Greene et al. 2008) have been documented.

Phytoplankton

Methods

Phytoplankton concentration was determined by measuring chlorophyll a, which can be detected using remote sensing techniques. To measure chlorophyll by satellite, images from the Sea Viewing Wide Field-of-View Sensor (SeaWiFS) obtained from NASA were used. These images have a 1.1 km^2 nominal resolution. These data were processed by Dr. Tim Moore at the Ocean Process Analysis Laboratory, University of New Hampshire in order to improve the estimation of chlorophyll in the coastal zone. The chlorophyll data were derived from a regionally-parameterized empirical algorithm which follows the functional form:

$$X=\log(\max(Rrs443,Rrs490,Rrs510)/Rrs555)$$

$$\text{Log}(\text{Chl})=a0+a1^{*}X+a2^{*}X^{2}+a3^{*}X^{3}+a4X^{4}$$

where the exponential coefficients were fitted to a regional subset of the NASA bio-Optical Marine Algorithm Data (NOMAD) set. The data were processed in MATLAB and delivered in .HDF format. The data were converted from .HDF to MATLAB using Marine Geospatial Ecology tools (Roberts et al. 2009). In each image, land and clouds were removed, so as to not skew the calculation.

Seasonally averaged chlorophyll images were created for the time period January 1998 – December 2006. The data time series ranges are monthly for January 1997 – February 2007. Years with inconsistent monthly data were eliminated (1997 and 2007). The seasons are defined to be consistent with other target data: winter, January – March; spring, April – June; summer, July – September; fall, October – December.

Results

Throughout the Northwest Atlantic region, large-scale spatial patterns in plankton biomass are driven by local currents and topography, seasonal nutrient loading. In general, in all seasons the highest levels of chlorophyll a were found in the coastal areas, with the highest concentrations at the tips of the Bay of Fundy, various harbors within the Gulf of Maine, Long Island Sound, New York Bight, Delaware Bay, Albemarle Sound and Pamlico Sound. Overall, high concentrations of plankton were observed within inshore bays and sounds fed by freshwater rivers and mixed by tides (e.g. Bay of Fundy, Long Island Sound, Chesapeake Bay, etc.) and where currents cause upwelling over the Continental Shelf (e.g. Georges Bank and Nantucket Shoals). The lowest levels of chlorophyll a were found seaward of the shelf-slope break and the deep waters of the Gulf of Maine.

In the Bay of Fundy, the northern edges remain highly productive throughout the year. The almost continuous productivity within the bay is due to the extremely high tidal action (tides in the Bay of Fundy are the highest in the world) and the presence of submerged ledges, islands, and channels which cause upwelling. This upwelling brings deep water nutrients to the surface, even during the summer when other shelf areas are experiencing stratification.

Figure 4-9a shows productivity in the winter months. For the two northerly subregions, less productivity was observed compared to the other seasons. Reduced productivity was also observed along the coast and on Georges Bank, Nantucket Shoals, and Long Island Sound. In the Gulf of Maine/Georges Bank subregion, this difference was most noticeable between Penobscot Bay and Cape Cod Bay as well as on Georges Bank. In the Southern New England subregion, Nantucket Shoals continued to exhibit medium-high concentrations because the water is shallow, but close to cooler southern-flowing waters from the Labrador Current, causing blooms to persist into winter.

Figure 4-9b shows spring productivity when phytoplankton biomass is expected to be highest for the Northwest Atlantic Ocean. At this time of year, levels of phytoplankton were high in coastal bays and sounds because of increased nutrient availability from rain and subsequent river run-off and increased light availability. Phytoplankton hot spots were also evident over Georges Bank within the Gulf of Maine and Nantucket Shoals within the Southern New England subregion.

During the summer months, many of the bays and sounds throughout the region showed high to very high levels of productivity (orange to red) (Figure 4-9c). Enclosed coastal areas were more prone to summer eutrophication when water is stratified, because they mix less with open water and are constantly receiving nutrients from land runoff. In the Gulf of Maine, areas that retained high productivity well into the summer include the Bay of Fundy (discussed above) and coastal areas (about equal to fall levels). The eutrophication in the Gulf of Maine is thought to be due to coastal upwelling-induced nutrient enhancement, not human causes. Elsewhere in the Northwest Atlantic region, eutrophication was observed during the summer months in Long Island Sound, Delaware Bay and Chesapeake Bay, where anthropogenic nutrient loading and subsequent hypoxia are well documented. While Albemarle and Pamlico Sounds in the Mid-Atlantic Bight showed high levels of productivity year-round, eutrophication conditions are currently considered “unknown” by NOAA (Bricker et al. 2007). Offshore, productivity was lowest in the summer. Along the shelf-slope break, the lowest levels of primary productivity were observed. In both the Gulf of Maine and Southern New England subregions, the fall bloom was smaller than that which occurs in the spring (Figure 4-9d).

Zooplankton

Methods

Zooplankton biomass data were obtained from the COPEPOD database (NOAA) for 1977-2007. The sampling stations are indicated as black points on Figure 4-10. Data were grouped into 1977-1979, 1980s, 1990s, and 2000-2001. The samples did not include inshore bays or sounds. Voronoi polygons were constructed around the location of each sample point and the value of each point was assigned to each polygon. Voronoi polygons are created so that every location within a polygon is closer to the sample point in that polygon than any other sample point, so that the data were accurately represented. Zooplankton counts were displayed as follows: very high (>1 ml/m³; red), high (0.5-1 ml/m³; pink); moderate (0.2-0.5 ml/m³; yellow), low (0.1-0.2 ml/m³; light blue) or very low (<0.1 ml/m³; dark blue). Note that limited winter sampling took place in the Gulf of Maine and Southern New England subregions in 2000-2001.

Results

Figures 4-10, 4-11, 4-12, and 4-13 shows zooplankton concentrations for the four time groups, separated by season. Compared to the chlorophyll maps, zooplankton exhibited much greater variability both by season and by decade. In addition to being affected by seasonally-changing variables influencing phytoplankton growth (e.g., nutrient availability, temperature, light intensity), zooplankton populations can be altered by predators feeding upon them. Shellfish, fish, jellyfish, ctenophores, and baleen whales use zooplankton as a food source.

In general, zooplankton densities were generally highest inshore to the 50 m isobath. The densities decreased as one moves offshore. Hot spots of zooplankton biomass included Georges Bank, Cape Cod Bay, Nantucket Shoals, the New York Bight (Hudson outflow), and along the Delaware coast and offshore from Chesapeake Bay.

In the winter, zooplankton levels were at moderate to low levels in the Gulf of Maine (Figure 4-10a–4-13a). In the Southern New England subregion, a high-density patch was observed south of the Nantucket Shoals. In recent years, in the Mid-Atlantic Bight, zooplankton levels were obviously higher, as evidenced by the very thin strip of high (red) levels appearing in the area just south of the New York Bight (Hudson outflow), Delaware Bay, and Virginia's eastern shore.

Zooplankton levels were highest in the spring, following the phytoplankton bloom (Figure 4-10b–4-13b). In the Gulf of Maine/Georges Bank subregion, the broadest spatial extent of high to very high zooplankton occurred over Georges Bank. High levels were also observed from Jeffreys Ledge to Stellwagen Bank. In the Southern New England subregion, zooplankton density was high across Nantucket Shoals, Block Island Sound, and the New York Bight. In the Mid-Atlantic Bight subregion, high to very high levels of zooplankton biomass were consistently observed at the New York Bight (Hudson outflow) extending south to Delaware Bay.

During the summer, zooplankton biomass was noticeably reduced across most of the Gulf of Maine and Southern New England (Figure 4-10c–4-13c). However, high regions remained over Georges Bank, inshore, and within the New York Bight. In the Mid-Atlantic Bight, very high levels were observed around Delaware and Chesapeake Bays.

In the fall, zooplankton levels are reduced to moderate levels across most of the Gulf of Maine. Moderate levels of zooplankton remain in Cape Cod Bay, and from Narragansett Bay south to the end of the Northwest Atlantic region (Figure 4-10d–4-13d). In the Mid-Atlantic Bight, small hot spots remained south of Chesapeake Bay. During this time, high zooplankton levels were observed throughout the region from the coast to approximately the 50 m isobaths.

Comparing the maps across decades, a striking difference was observed in winter levels of zooplankton across the Northwest Atlantic region. In the 1970s, primarily low to medium levels were observed. In the 1980s and 1990s, slightly higher patterns were observed, particularly in Georges Bank and Nantucket Shoals in the Southern New England subregion, Delaware and Chesapeake Bays, and the Virginia eastern shore. The spring bloom showed an increasing trend in some areas. The offshore hot spots on Georges Bank, Nantucket Shoals, and the Virginia coast were visible throughout the time period, and the spatial extent of high concentrations has increased.

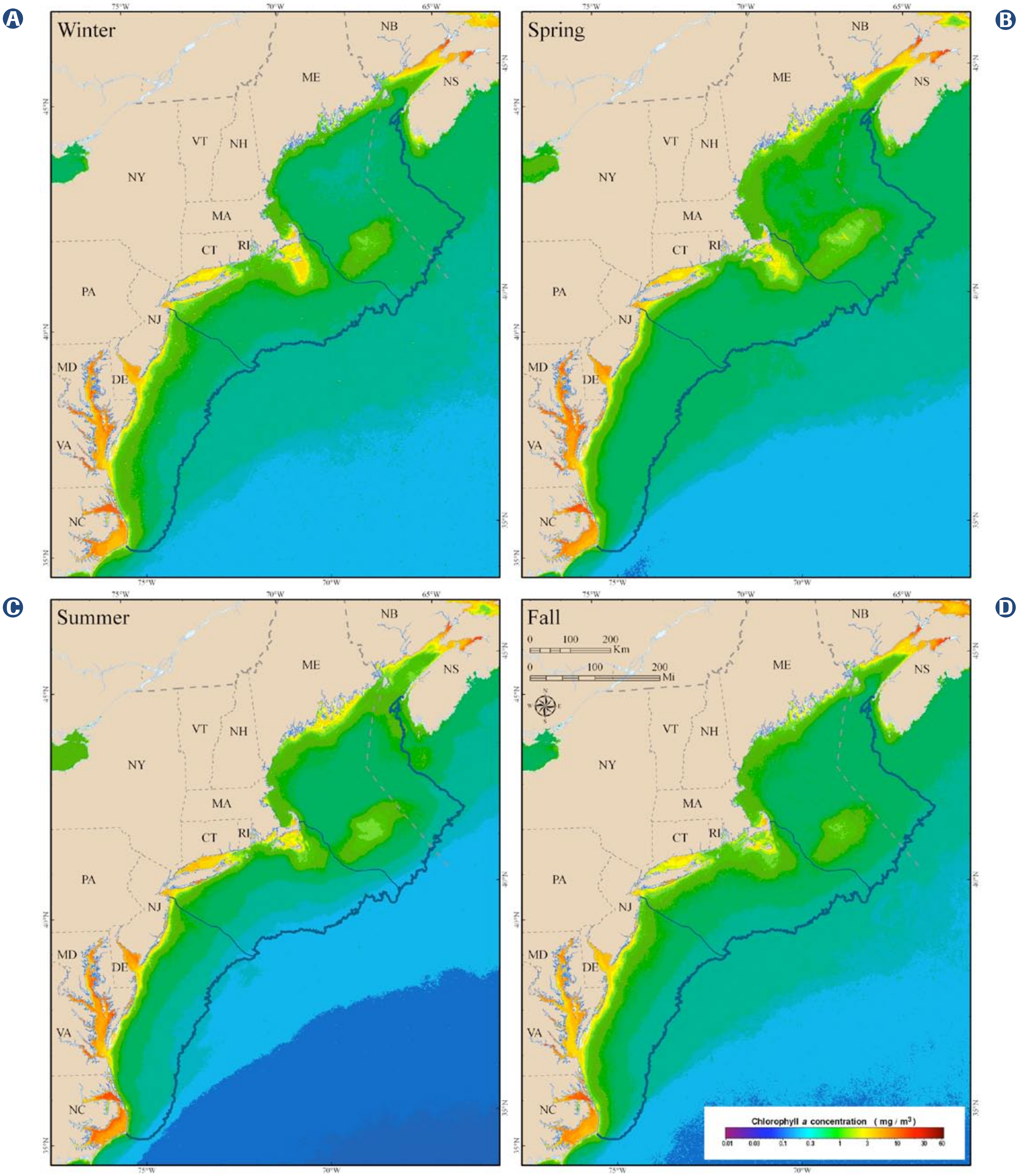


Figure 4-9. Average phytoplankton concentration (chlorophyll a) by season.

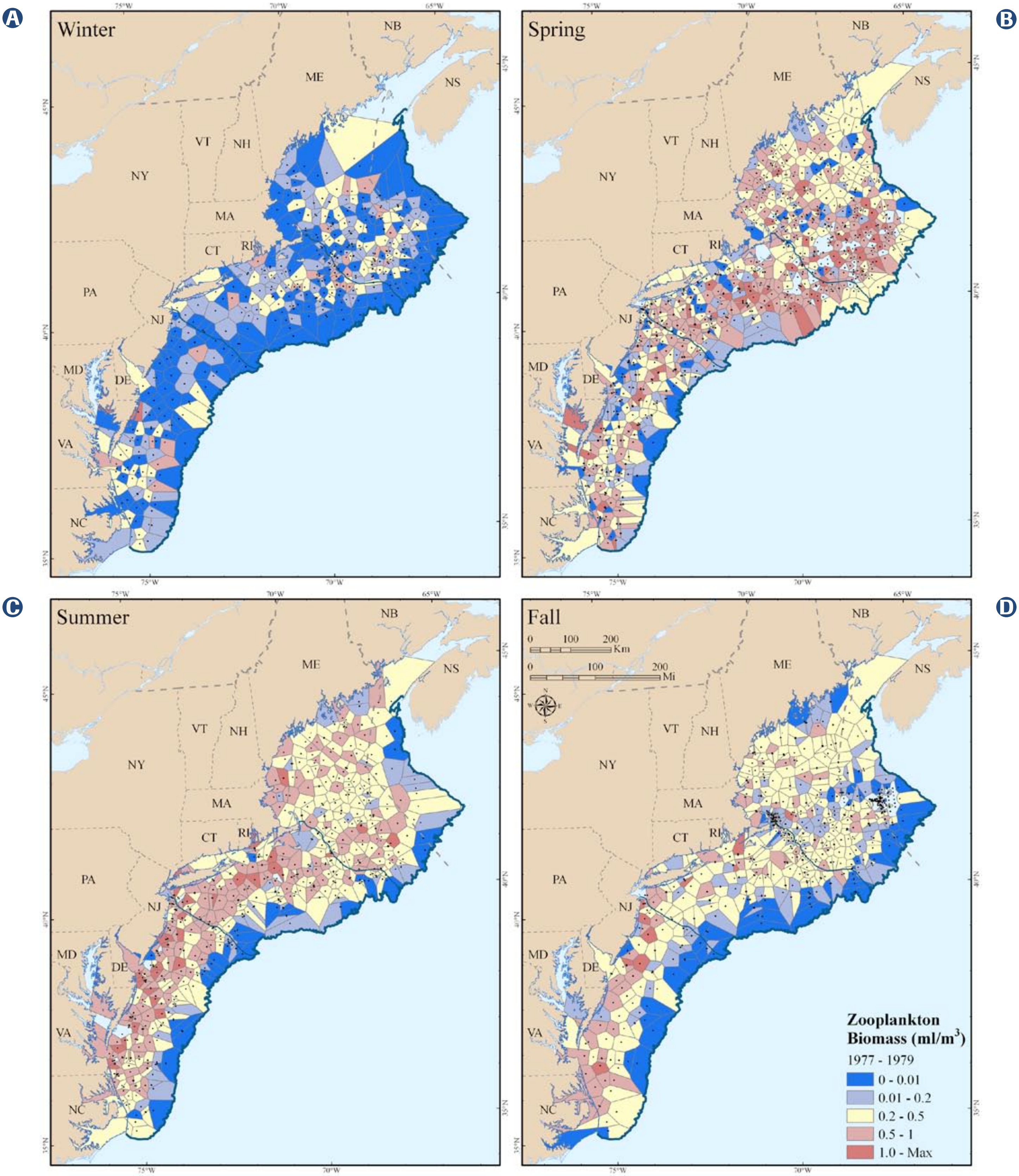


Figure 4-10. Mean zooplankton biomass from 1977-1979 (shown as Voronoi polygons). Black points represent sample locations.

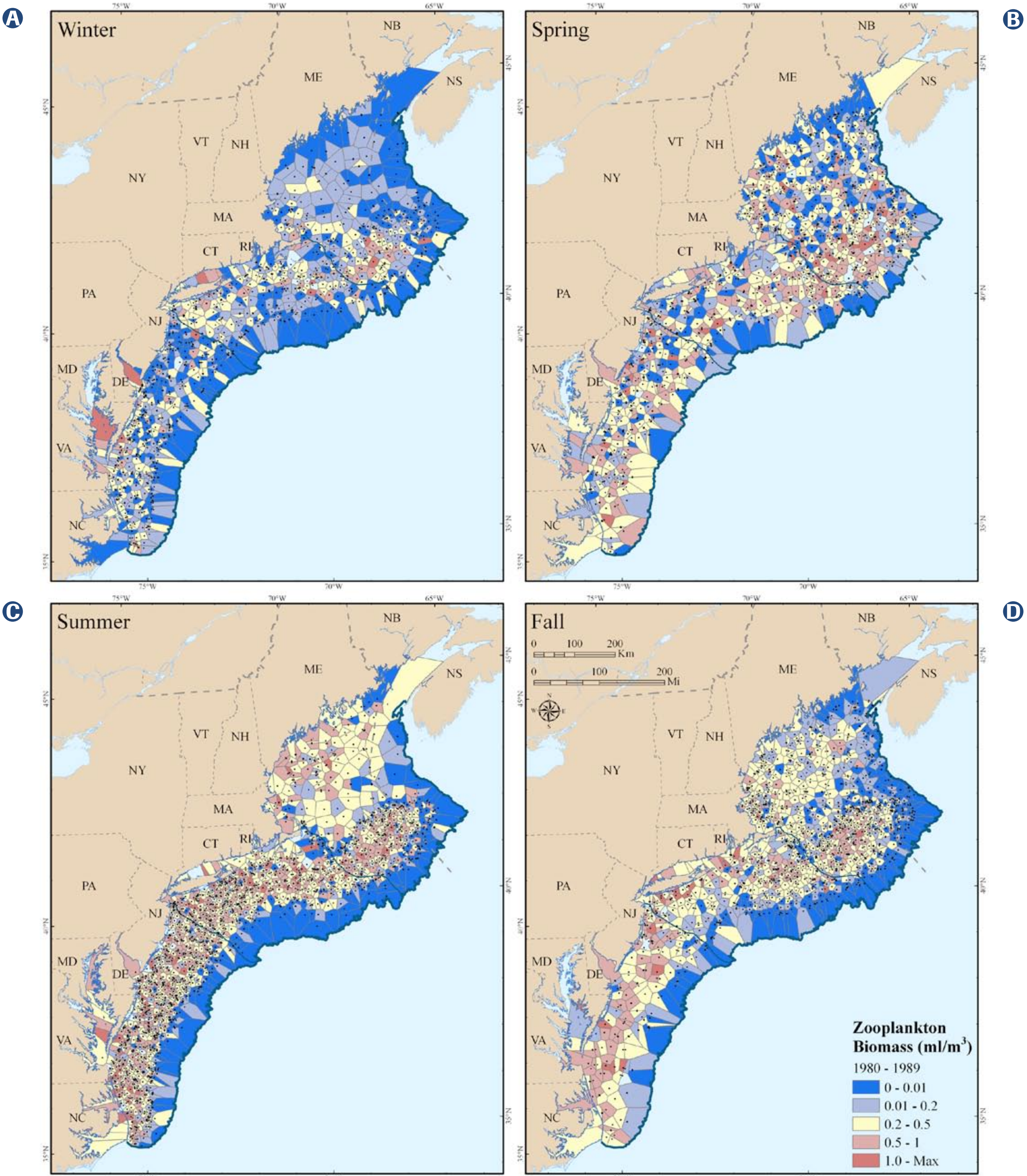


Figure 4-11. Mean zooplankton biomass from 1980-1989 (shown as Voronoi polygons). Black points represent sample locations.

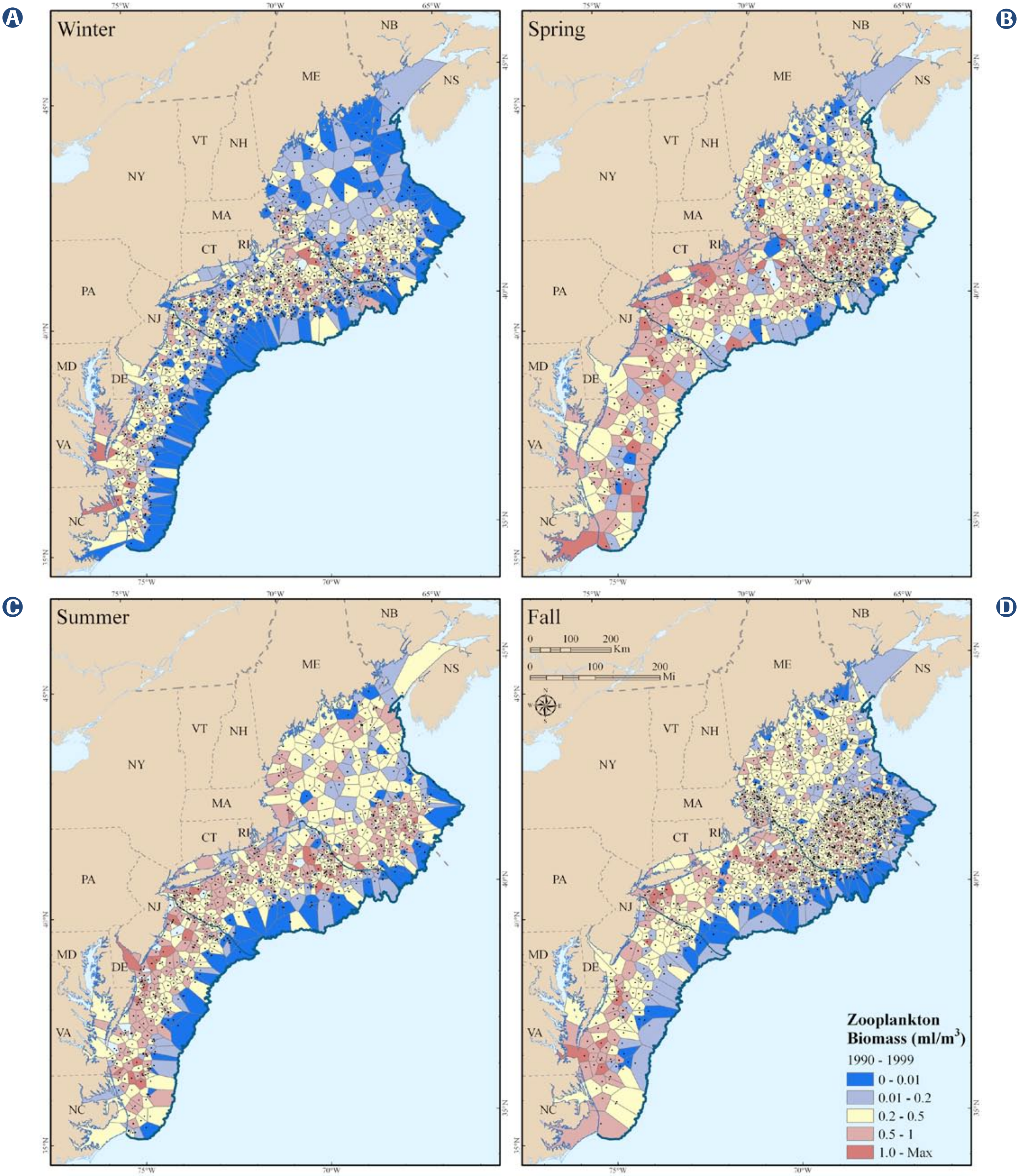


Figure 4-12. Mean zooplankton biomass from 1990-1999 (shown as Voronoi polygons). Black points represent sample locations.

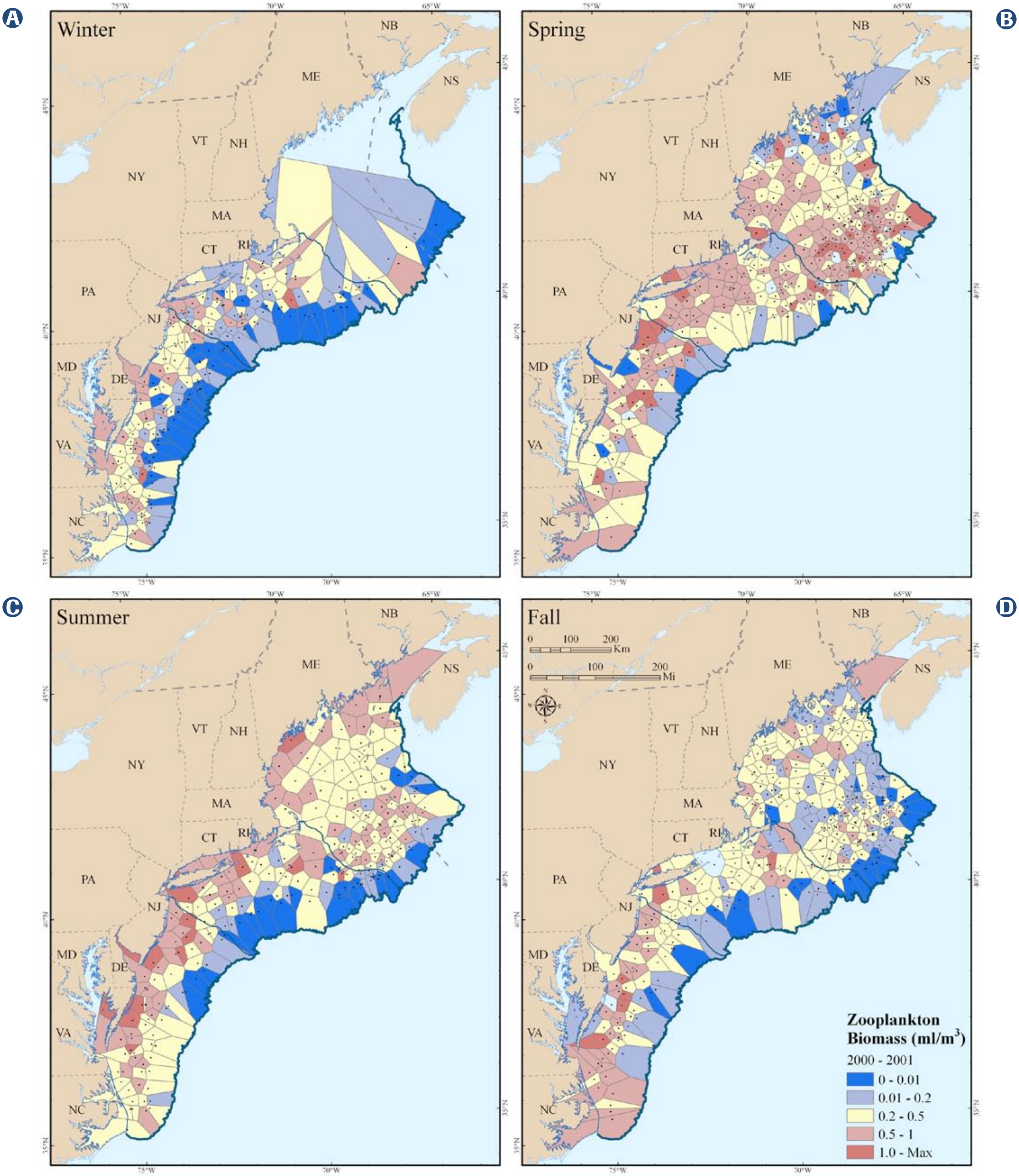


Figure 4-13. Mean zooplankton biomass from 2000-2001 (shown as Voronoi polygons). Black points represent sample locations.

Literature Cited

Beardsley, R. C., and W. C. Boicourt. 1981. On estuarine and continental-shelf circulation in the Middle Atlantic Bight. Pages 198-233 in B. A. Warren and C. Wunsch, eds. Evolution of Physical Oceanography. MIT Press, Cambridge, Massachusetts.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. Effects of nutrient enrichment in the nation's estuaries: A decade of change. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. 328 pp.

CCSP (Climate Change Science Program). 2008. Scientific assessment of the effects of global change on the United States. Report of the Committee on Environment and Natural Resources National Science and Technology Council. Available from http://www.climatescience.gov/Library/scientific-assessment (accessed October 2008).

Epifanio, C. E., and R. W. Garvine. 2001. Larval transport on the Atlantic continental shelf of North America: a review. Estuarine, Coastal and Shelf Science 52: 51-77.

Etnoyer, P., D. Canny, B. Mate, and L. Morgan. 2004. Persistent pelagic habitats in the Baja California to Bering Sea (B2B) Ecoregion. Oceanography 17: 90-101.

Friedland, K. D., and J. A. Hare. 2008. Long-term trends and regime shifts in sea surface temperature on the continental shelf of the northeast United States. Continental Shelf Research 27: 2313-2328.

Greene, C. H., A. J. Pershing, T. M. Cronin, and N. Ceci. 2008. Arctic climate change and its impacts on the ecology of the North Atlantic. Ecology 89(11) Supplement: S24–S38.

Haney, J. C. 1986. Seabird segregation at Gulf Stream frontal eddies. Marine Ecology Progress Series 28: 279-285.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: The physical science basis. Contribution of Working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M.
Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY.

Longhurst, A. 2007. Ecological Geography of the Sea. 2nd edition. Academic Press, Amsterdam.

Mann, K. H., and J. R. N. Lazier. 2006. Dynamics of Marine Ecosystems. 3rd edition. Blackwell, Malden, Massachusetts, USA.

McManus, M.A., A.L. Alldredge, A.H. Barnard, E. Boss, J. F. Case, T.J. Cowles, P.L. Donaghay, L.B. Eisner, D.J. Gifford, C.F. Greenlaw, C.M. Herren, D.V. Holliday, D. Johnson, S. MacIntyre, D.M. McGehee, T.R. Osborn, M.J. Perry, R.E. Pieper, J.E.B. Rines, D.C. Smith, J.M. Sullivan, M.K. Talbot, M.S. Twardowski, A. Weidemann, J.R. Zaneveld. 2003. Characteristics, distribution and persistence of thin layers over a 48 hour period. Marine Ecology Progress Series. 261: 1-19.

Munk, P., P. O. Larsson, D. Danielsen, and E. Moksness. 1995. Larval and small juvenile cod Gadus morhua concentrated in the highly productive areas of a shelf break front. Marine Ecology Progress Series 125: 21-30.

Newell, R. C., L. J. Seiderer, and D. R. Hitchcock. 1998. The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. Oceanography and Marine Biology: an Annual Review 36: 127-178.

Nixon, S. W., S. Granger and B. Buckley. 2003. The warming of Narragansett Bay. 41°N A Publication of Rhode Island Sea Grant and Land Grant Programs 2:18-20.

Nixon, S. W., S. Granger, B. A. Buckley, M. Lamont, and B. Rowell. 2004. A one hundred and seventeen year coastal temperature record from Woods Hole, Massachusetts. Estuaries 27: 397-404.

Porter-Smith, R., P. T. Harris, O. B. Andersen, R. Coleman, D. Greenslade, and C. J. Jenkins. 2004. Classification of the Australian continental shelf based on predicted sediment threshold exceedance from tidal currents and swell waves. Marine Geology 211: 1-20.

Preston, B. L. 2004. Observed winter warming of the Chesapeake Bay estuary (1949-2002): implications for ecosystem management. Environmental Management 34: 125-139.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman Jr. 2002. Gulf of Mexico hypoxia, a.k.a. “the dead zone.” Annual Review of Ecology and Systematics 33: 235-263.

Roberts, J. J., B. D. Best, D. C. Dunn, E. A. Treml, and P. N. Halpin. (in review). Marine Geospatial Ecology Tools: An integrated framework for ecological geoprocessing with ArcGIS, Python, R, MATLAB, and C++. Environmental Modeling & Software. http://mgel.env.duke.edu/tools.

Roff, J. C. and S. M. J. Evans. 2002. Frameworks for marine conservation – non-hierarchical approaches and distinctive habitats. Aquatic Conservation Marine Freshwater Ecosystems 12: 635-648.

Roman, M., X. Zhang, C. McGilliard, and W. Boicourt. 2005. Seasonal and annual variability in the spatial patterns of plankton biomass in Chesapeake Bay. Limnology and Oceanography 50: 480-492.

Rutherford, S., S. D’Hondt, and W. Prell. 1999. Environmental controls on the geographic distribution of zooplankton diversity. Nature. 400: 749-753.

Shanks, A.L. 1995. Mechanisms of cross-shelf dispersal of larval invertebrates and fish. pp. 323–368 in: Ecology of Marine Invertebrate Larvae, L.R. McEdward (ed). CRC Press, Boca Raton, Florida.

Smith, L. 2007. The Effects of Global Climate Change on the Coastal Ecosystems of Rhode Island. URI IGERT white paper.

Townsend, D.W., A.C. Thomas, L.M. Mayer, M.A. Thomas, J.A. Quinlan. 2006. Oceanography of the Northwest Atlantic continental shelf. Chapter 5 in A.R. Robinson and K.H. Brink, eds. The Sea: the Global Coastal Ocean: Interdisciplinary Regional Studies and Syntheses. Harvard University Press, Cambridge, Massachusetts.

Ullman, D. S., and P. C. Cornillon. 2001. Continental shelf surface thermal fronts in winter off the northeast US coast. Continental Shelf Research 21: 1139-1156.

Wishner, K. F., D. M. Outram., and D. S. Ullman. 2006. Zooplankton distributions and transport across the northeastern tidal front of Georges Bank. Deep-Sea Research II 53: 2570-2596.

Worm, B., M. Sandow, A. Oschlies, H. K. Lotze, and R. A. Myers. 2005. Global patterns of predator diversity in the open oceans. Science 309: 1365-1369.