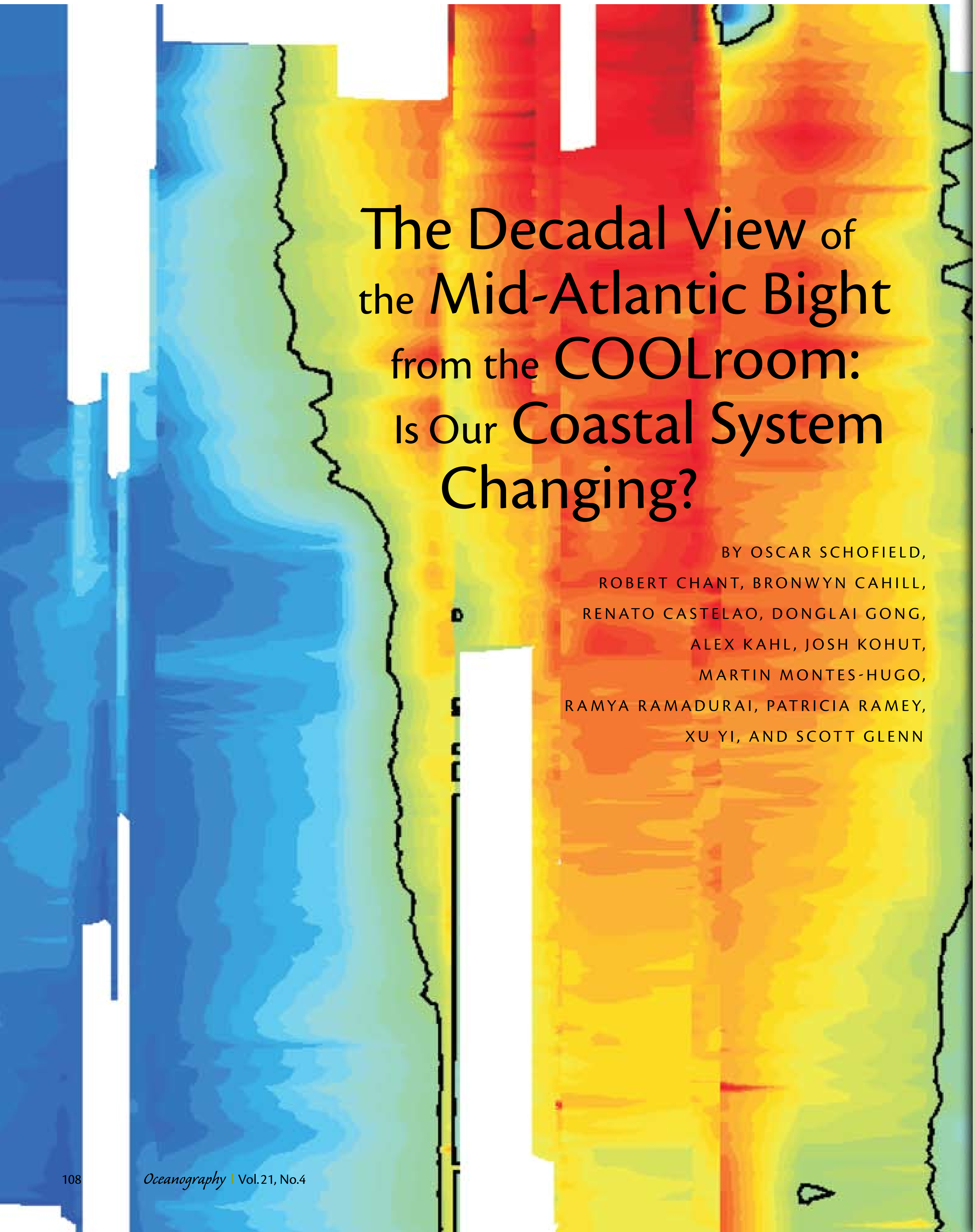

# The Decadal View of the Mid-Atlantic Bight from the COOLroom: Is Our Coastal System Changing?

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**ABSTRACT.** Spatial ocean-observing technologies are permitting researchers to collect data for sustained periods on broad continental shelves. Key technologies used are satellites, high-frequency (HF) radar, and autonomous underwater gliders, which together have allowed study of Mid-Atlantic Bight (MAB) dynamics for the past decade. MAB stratification is the dominant feature regulating annual phytoplankton productivity. Stratification begins in the spring, and by early summer forms one of the world's sharpest thermoclines (temperatures range from ~ 30° to 8°C in just a few meters). Strong stratification deprives the euphotic zone of nutrients until it erodes later in the year. Therefore, it is not surprising that during late autumn and winter, when stratification has eroded, the largest and most recurrent MAB phytoplankton blooms are observed. These fall/winter blooms occur on the inner shelf; the offshore extent of the phytoplankton appears to be limited by light. Comparison of data from the 1970s and 1980s to the last decade suggests phytoplankton bloom size on the MAB has changed, with the magnitude of the fall and winter blooms declining. Declines in the fall are consistent with the hypothesis that erosion of MAB stratification is occurring later in the season. Declines in winter appear to be associated with an increase in winter winds that enhance winter mixing, which in turn increases the light limitation of the phytoplankton. The increase in winter winds occurred during transition to a positive phase of the Atlantic Multidecadal Oscillation. Our experience emphasizes the importance of spatial time series for studying broad continental shelves.

## INTRODUCTION

The coastal ocean reflects a combination of local, regional, and global processes, many of which are impacted by human activity. Currently, close to 1.2 billion of the world's people (23% of the human population) live within 100 m of sea level and 150 km from the coasts (Small and Nicholls, 2003; Small and Cohen, 2004; Figure 1). These coastal communities are disproportionately important to their national economies (NOAA, 1998), and their significance will increase (Vitousek et al., 1997), given current projections that human populations will continue to migrate there (Boesch et al., 2000; Small and Nicholls, 2003). Built infrastructure, pollution, and other pressures associated with large human populations will even more severely impact local coastal ecosystems. Thus, it will be increasingly important to improve coastal management to ensure sustainability of ocean-related economic activity (Boesch et al., 2000). Despite these increasing pressures, current coastal ocean sampling strategies are not sufficient to document, much less manage, human-induced changes, especially when such changes are difficult to discern because they are embedded in long-term secular and cyclical trends in the ocean system.

Many of the most densely populated coastal regions on Earth are found on western continental boundaries, which tend to be characterized by broad continental shelves that experience large seasonal cycles (Figure 1). The inner shelves are often river dominated. They are also recycling shelves characterized by tides, wind-driven flows, and elemental cycling dynamics that are often biologically mediated with long exchange times (greater than a month) (Chen et al., 2003). These regions are extremely productive, and shelf ecology is strongly coupled to shelf seasonality. Climate change is likely to alter the seasonal dynamics of these systems and thus has significant ecological implications. Studying these seasonal dynamics is difficult using traditional sampling techniques, which are prohibitively expensive for use over long time periods. Technical limitations, the interdisciplinary nature of the problems, and the need for sustained time series have made it difficult to fund large interdisciplinary efforts to resolve these issues.

The Coastal Ocean Processes (CoOP) program was unique, as it encouraged large interdisciplinary field campaigns beyond the scale of traditional grants, while simultaneously encouraging development of new technologies that will provide a path forward for the coastal ocean science community for decades to come. This philosophy was particularly rare when the program was initiated, and the program's support has been critical to our team (Rutgers University Coastal Ocean Observation Lab; see http://rucool.marine.rutgers.edu), which has focused on developing a shelf observatory over the last 15 years (Glenn and

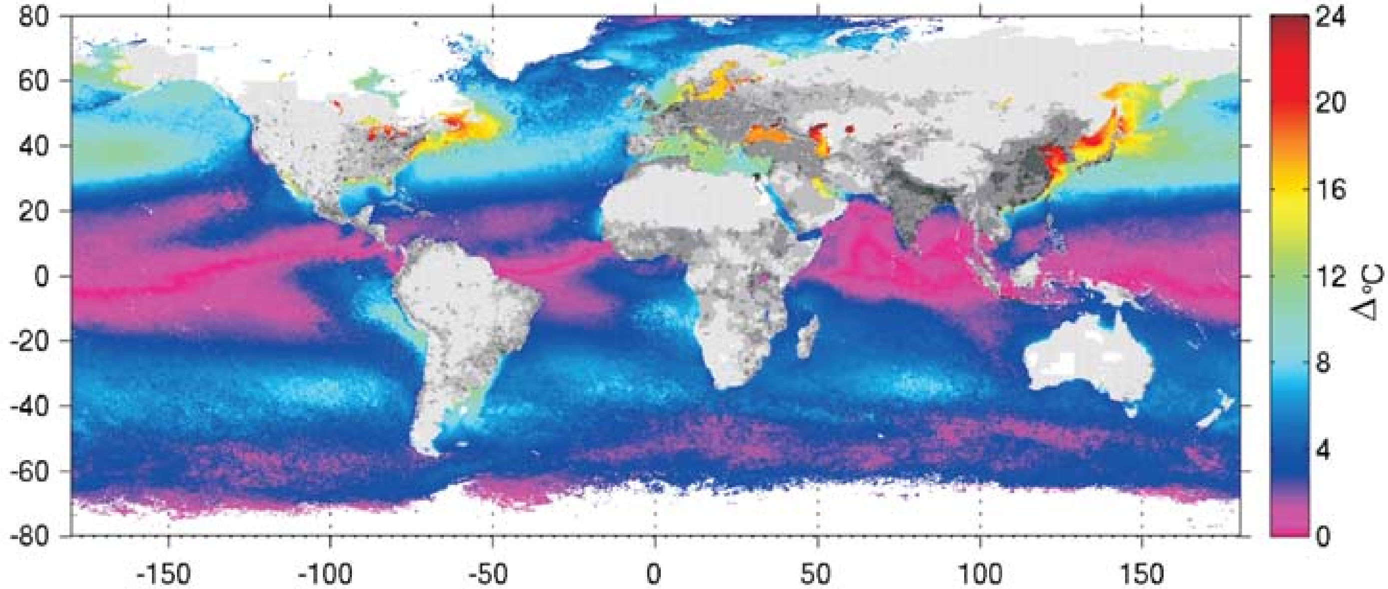


Figure 1. Global ocean temperature contrast between winter and summer months, which were designated based on the mean seasonal temperatures measured with the AVHRR satellite. Data were taken between 1995 and 2005. The grey shades on the land masses indicate human populations (dark grey = high human populations).

Schofield, in review). The scientific community is currently embroiled in rigorous discussion regarding to what degree it should invest in sustained ocean-observing capabilities. We believe these investments will have a large intellectual and societal return. Thus, in this article, we highlight a decade's worth of data collected using our continental shelf observatory (Glenn et al., 1998; Schofield et al., 2002). Based on this experience, we believe observatory approaches will offer the community the ability to study continental shelves in a sustained manner, which is critically important because many continental shelves are exhibiting significant changes now, in our lifetimes.

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## MAB HYDROGRAPHY AND CIRCULATION

We established a cross-shore time series using Webb Slocum gliders in the fall of 2003 (Schofield et al., 2007; Figure 2). The Webb gliders documented the seasonal evolution of shelf stratification, which began in spring and deepened to 30 m by autumn (Figure 2; Castelao et al., 2008). Buoyancy frequency, computed from the difference between the shallowest and deepest density measurements (Figure 3), was used to assess water-column stability. The glider-derived buoyancy frequency confirmed that the water column was vertically homogeneous early in the year. The region close to the coast became stratified first (April/May), soon after the spring freshet. By early June, stratification was strong over the entire shelf. Waters inshore of the 40-m isobath remained more stratified than the offshore region, primarily due to the influence of low-salinity water from the Hudson River, which also helped trap surface heating in a thin surface layer, further increasing its buoyancy. Those conditions persisted until late September/early October, when the increase in the frequency of storms in the MAB rapidly destroyed stratification. This stratification is a dominant physical feature for the MAB ecosystem and determines the nutrient availability, which ultimately sets overall system productivity.

The mean MAB circulation, described by Beardsley and Boicourt (1981), using a few current meter arrays, suggested an annual mean downshelf flow on the order of 5 cm $s^{-1}$ to the southwest. They also noted, however, that the instantaneous alongshelf flow could be an order of magnitude larger and in either direction, depending on wind forcing. Using an extensive HF radar array (Schofield et al., 2002; Glenn and Schofield, 2003), we continuously measured the spatial seasonal surface currents for the entire

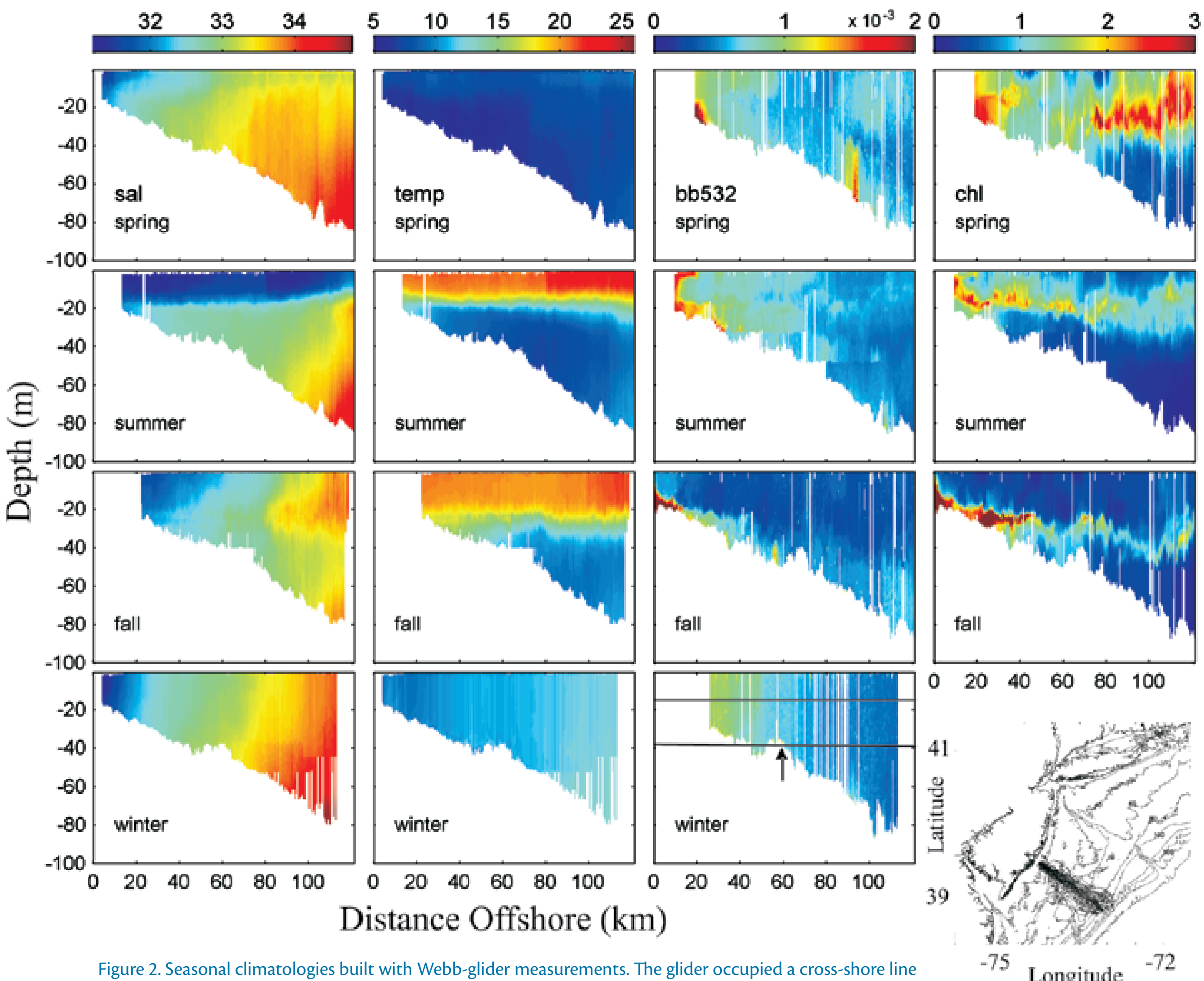


Figure 2. Seasonal climatologies built with Webb-glider measurements. The glider occupied a cross-shore line (lower right panel) across the Mid-Atlantic Bight. The time series was initiated in late October 2003. All gliders are equipped with a conductivity-temperature-depth sensor; however, only some gliders are outfitted with optical sensors. The data presented include salinity (salinity units) in column 1, temperature (°C) in column 2, optical backscatter at 532 nm ($m^{-1}$), and chlorophyll *a* (mg chl *a* $m^{-3}$) measured by in situ fluorescence. Black lines on the winter backscatter panel indicate the range of the 1% light level based on measured chlorophyll values. The arrow indicates the edge of the winter chlorophyll bloom.

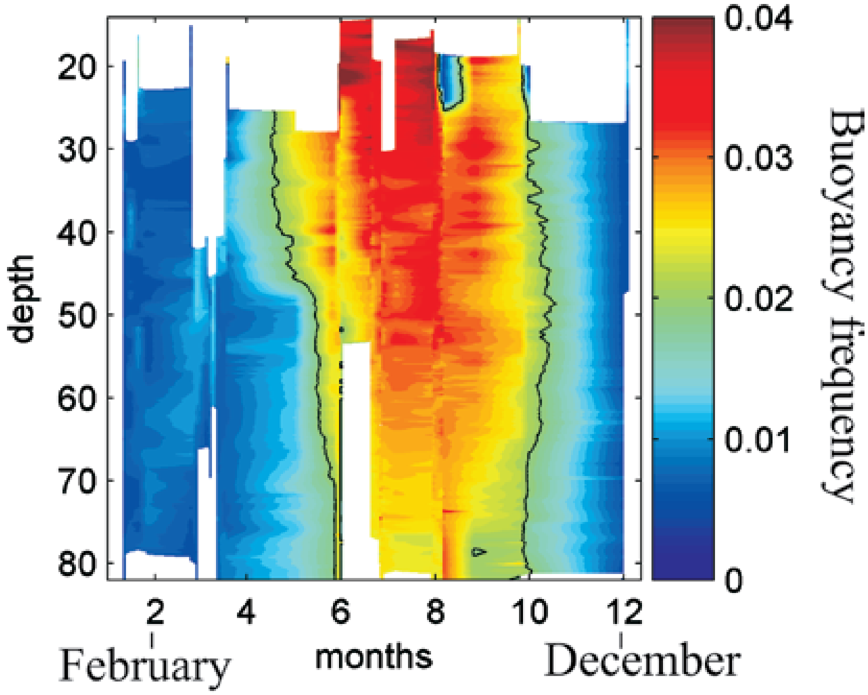


Figure 3. The annual cycle of buoyancy frequency ($s^{-1}$) measured by the Webb gliders. The buoyancy frequency ($N^2 = -[g/\rho]\ \partial\rho_0/\partial z$) was computed based on the difference between the shallowest and deepest density measurement at a site.

shelf for almost a decade. We used this data set to derive surface-current climatologies (Gong et al., in review).

Given the importance of wind-driven shelf circulation, two-dimensional histograms of wind speed and direction (Figure 4a–c) were calculated for the stratified summer (June–September), the well-mixed winter (December–March), and the transitional seasons (April–May, October–November). The dominant wind during the stratified season was alongshore from the southwest (Figure 4a) and associated with the persistent high-atmospheric-pressure system located offshore Bermuda. The winter is dominated by cross-shore winds from the northwest (Figure 4b). The major winds during the transition seasons are split between alongshore winds from the southwest and the northeast (Figure 4c). The corresponding conditionally averaged seasonal surface current responses (Kohut et al., 2004; Gong et al., in review) for the dominant winds are plotted for each season in Figure 4d–f. During the stratified season, the observed response to the dominant alongshelf wind was weak surface currents (< 12 cm $s^{-1}$) that flow to the northeast on the inner shelf and then turn offshore at midshelf. The cross-shelf currents are strongest just south of the Hudson Shelf Valley. In winter, the dominant surface flow is cross shore. During the transition seasons, alongshore winds are equally dominant from the northeast and the southwest. The southwest wind response is again weaker, with typical values in the 8–10 cm $s^{-1}$ range, and it is similar to the stratified response, but with a weaker cross-shelf transport. The averaged current response to the stronger winds from the northeast reaches 20 cm $s^{-1}$ over much of the shelf, and it is predominantly alongshelf over much of the region. The Hudson Shelf Valley again has an influence, with currents to the north being deflected shoreward, and very small currents being observed on the leeward side on the inner to midshelf. Correlations between the cross-shore and alongshore winds and currents (Figure 4g–i) were calculated along a cross-shelf line plotted on the maps in column 2 of Figure 4, which corresponded to the glider time series (Figure 2). This region was not influenced by the complicated flows associated with the Hudson Shelf Valley. During the summer stratified season, the alongshore winds are highly correlated with cross-shelf transport over most of the mid to outer shelf (Figure 4g). During winter, the correlation between cross-shore currents and alongshore winds was very small across the entire shelf. During this period, cross-shore currents were highly correlated with cross-shore winds (Figure 4h). Alongshore currents over the inner half of the shelf are correlated with alongshore winds. During the fall and spring transitions, the high correlation extends over much of the shelf (Figure 4i).

## PHYTOPLANKTON BIOMASS ON THE MAB

The major physical feature regulating overall annual primary productivity of the MAB is the seasonal stratification of the shelf. Phytoplankton biomass on the MAB is low after the shelf has stratified and nutrients are depleted in the euphotic zone (Figure 2). Only the nearshore productivity remains high throughout the summer months due to recurrent coastal summer upwelling

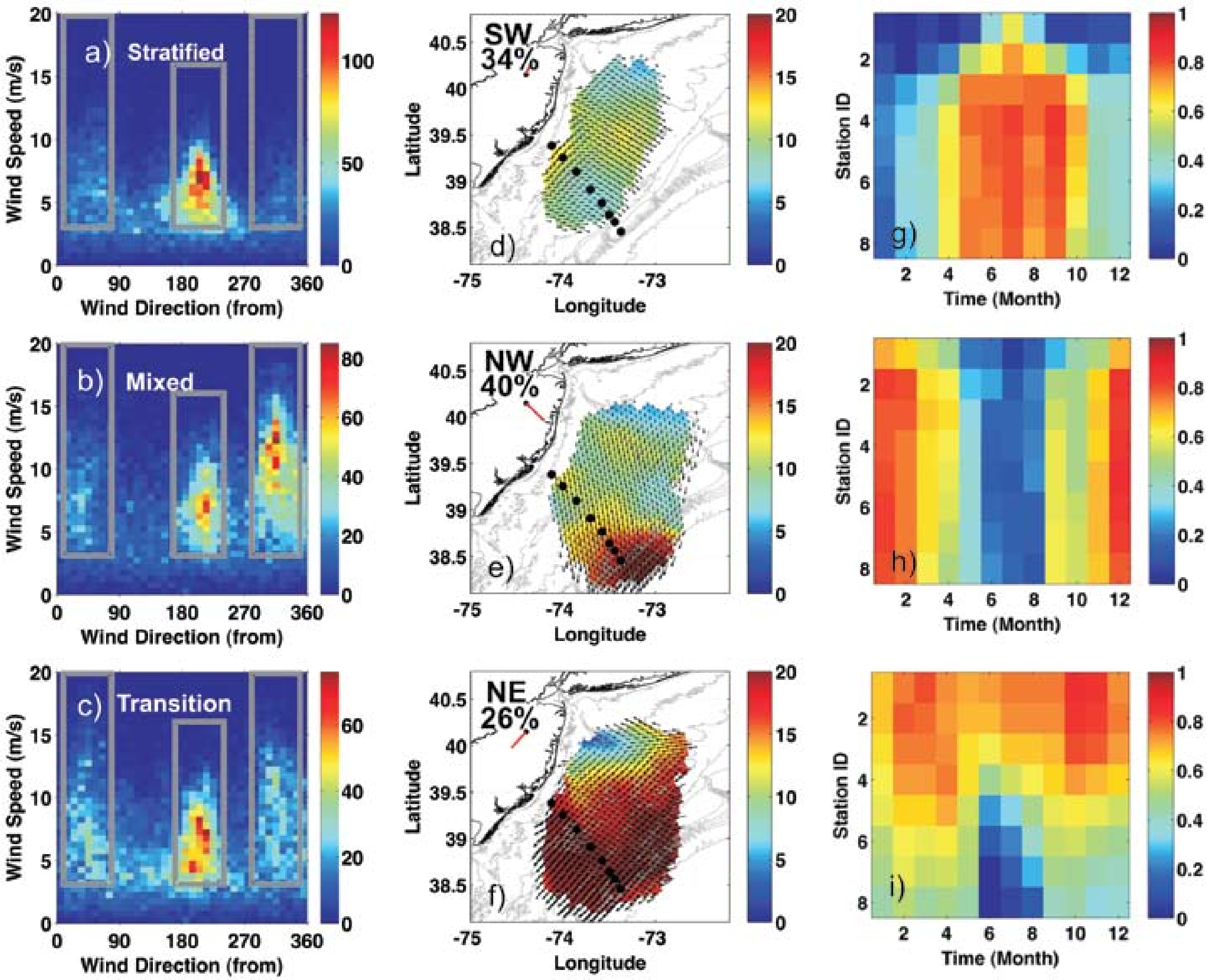


Figure 4. (Column 1) Two-dimensional histogram of wind speed and direction from the Delaware Bay buoy with colors indicating the number of occurrences observed between 2002 and 2007 for (a) stratified, (b) mixed, and (c) transitional seasons. (Column 2) Conditionally averaged 17 CODAR surface current maps for the dominant wind direction for (d) stratified, (e) mixed, and (f) transitional seasons. (Column 3) Correlations between the cross and alongshore components of the buoy winds and the CODAR surface currents along the cross-shelf line shown on the maps in Column 2 for (g) stratified, (h) mixed, and (i) transitional seasons. Station numbers correspond to the dots along the line, with Station 1 on the inner shelf and Station 8 on the outer shelf.

(Glenn et al., 2004; Figure 2). During the stratified season, phytoplankton populations on the outer shelf are confined to the top of the pycnocline as cells rely on the diffusive fluxes of nutrients across this density barrier, given the strong stratification (Figure 3). The MAB pycnocline is sufficiently intense that even tropical storms and hurricanes cannot erode it (see Figure 2 in Glenn et al., 2008). Therefore, it is not surprising that the largest and most recurrent phytoplankton blooms on the MAB occur during the late fall and winter seasons (Ryan et al., 1999; Yoder et al., 2002; Xu et al., in review) when frequent storms and the seasonal convective overturn disrupt shelf stratification, and nutrients in the euphotic zone are replenished.

Spatially, winter blooms are confined to the inner half of the MAB shelf (Figure 5), and the magnitude of the winter bloom appears to be inversely correlated with the number of stormy days on the MAB (Xu et al., in review). We hypothesize that this relationship reflects the increasing light limitation of

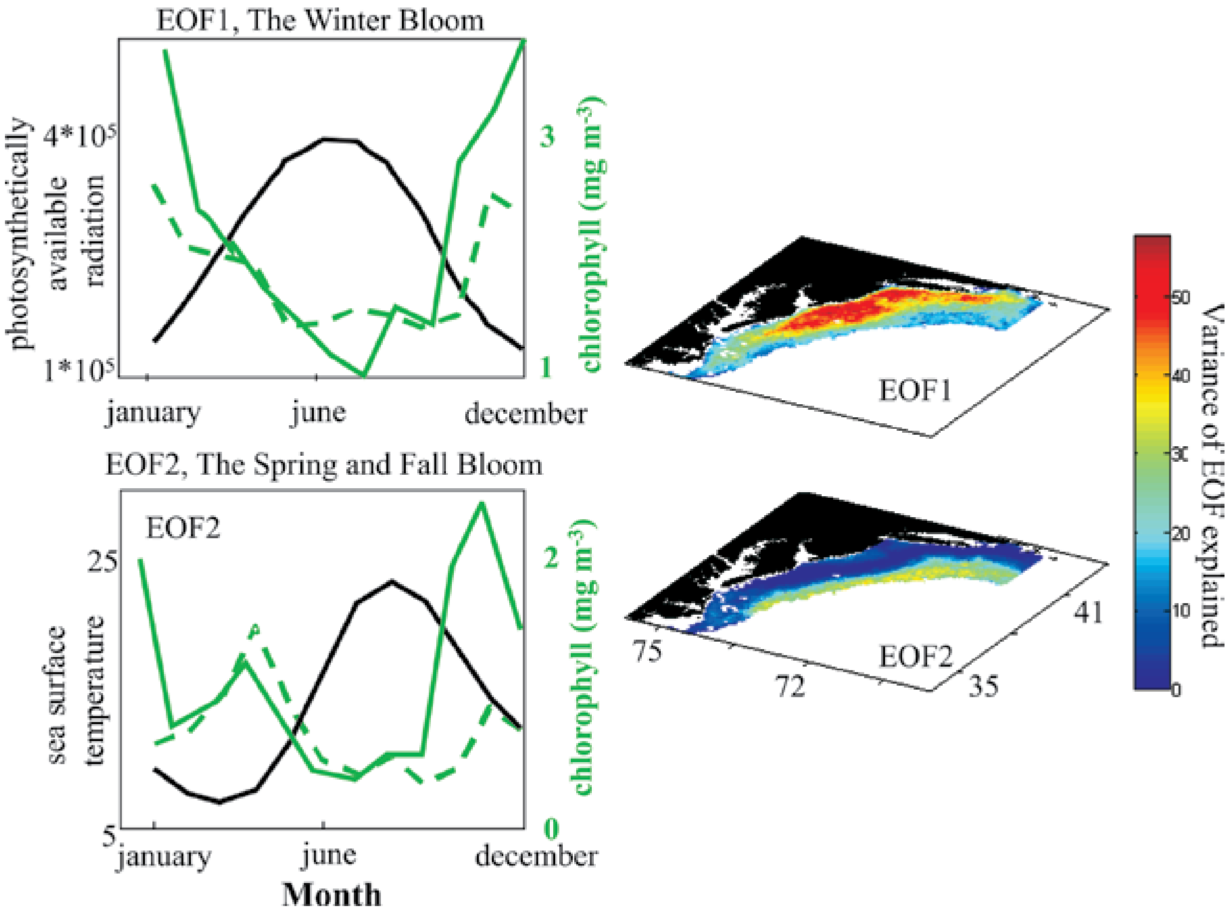


Figure 5. Spatial and temporal dynamics of chlorophyll *a* measured on the MAB. The panels on the left-hand side are the amplitude time series of an empirical orthogonal function (EOF) decomposition for chlorophyll (green lines, mg Chl m$^{-3}$). The EOF consisted of the decomposition of the SeaWiFS and CZCS time-series data set collected for the MAB. Two major EOF modes were identified, associated with the winter and spring/fall blooms. The dotted green line is based on the data collected with the SeaWiFS system, and the solid green line is the decomposition for the CZCS data. Black lines are the mean photosynthetically active radiation (PAR; black line in the upper panel, mW cm$^{-2}$ µm$^{-1}$), and sea surface temperature (black line in the lower panel, °C). The right-hand panels show the spatial modes of the chlorophyll EOFs measured for SeaWiFS. For the spatial maps, the EOFs are expressed as a percentage of the local variance explained by each mode, and the panels show the percentage of the local variance explained by each mode (winter and spring) of the chlorophyll EOF decomposition. There was not a large difference in the spatial maps between the SeaWiFs and CZCS satellite data.

the phytoplankton with storm-induced mixing in the dark winter months (Xu et al., in review). The winter bloom extends from nearshore to a mean depth of 41 m, which, based on the average climatological chlorophyll concentrations, suggests that close to 50% of the water column is above the 1% light level (i.e., sufficient to support photosynthesis; see Xu et al., in review). For deeper waters, the spring bloom is associated with the onset of stratification. This spring bloom is smaller and shorter than the winter bloom and is strongest on the outer shelf, which stratifies in the late spring (Figure 5).

## CHANGES IN THE MAB ECOSYSTEM?

Reports indicate that MAB temperature and salinity have changed over the last decade (Mountain, 2003); however, assessing whether there have been corresponding changes in the MAB ecosystem has been difficult, given the lack of sustained decadal time series. To determine whether any potential changes can be discerned, we calculated the mean seasonal differences in the chlorophyll measured by the Coastal Zone Color Scanner (CZCS; mission span = 1978–1986) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, mission span = 1998–2006). We acknowledge the difficulties in comparing different satellite systems. For example, aerosol parameterization represents only one uncertainty when comparing CZCS versus SeaWiFS; however, given our relatively large temporal and spatial scales, we estimate the bias due to continental aerosols (dust, sulfates) on CZCS-derived chlorophyll is approximately 20%. Overall, terrestrial aerosols result in an overestimate of CZCS chlorophyll values, which would result in smaller values in the winter and larger values in the summer.

Comparing the data, we found that the summer values measured by both satellites were comparable (Figure 5), which suggests that this approach is promising. The MAB chlorophyll biomass changed in the MAB over the last few decades (Figure 6). The fall and winter seasons show declines (43 and 29%, respectively), while the spring and summer months show small increases (8 and 14%, respectively) (Table 1). The annual change in the MAB chlorophyll concentration is close to -14%. This figure is significant given that the fall/winter blooms account for close to 63% of the annual chlorophyll and also represent the most recurrent blooms on the MAB (Ryan et al., 1999; Yoder et al., 2002; Xu et al., in review). Declines in chlorophyll during the fall appear to be distributed over the entire shelf, which implies that any of the underlying processes driving the changes must operate over the entire MAB. A likely candidate is seasonal convective overturn in the autumn, which is associated with ocean cooling and which may have shifted to later in the year.

What climate scale forcing might underlie these changes? The Atlantic Multidecadal Oscillation (AMO) is a measurement of the basin-scale variability of sea surface temperature (SST) in the northern hemisphere (Kerr, 2000). The AMO index for the past 60 years has completed one cycle with temperature oscillations of +/- 0.5°C and a multidecadal low frequency amplitude of +/- 0.3°C (Figure 7). The AMO was in a cool phase from the mid 1960s until the mid 1990s; however, since the mid 1990s,

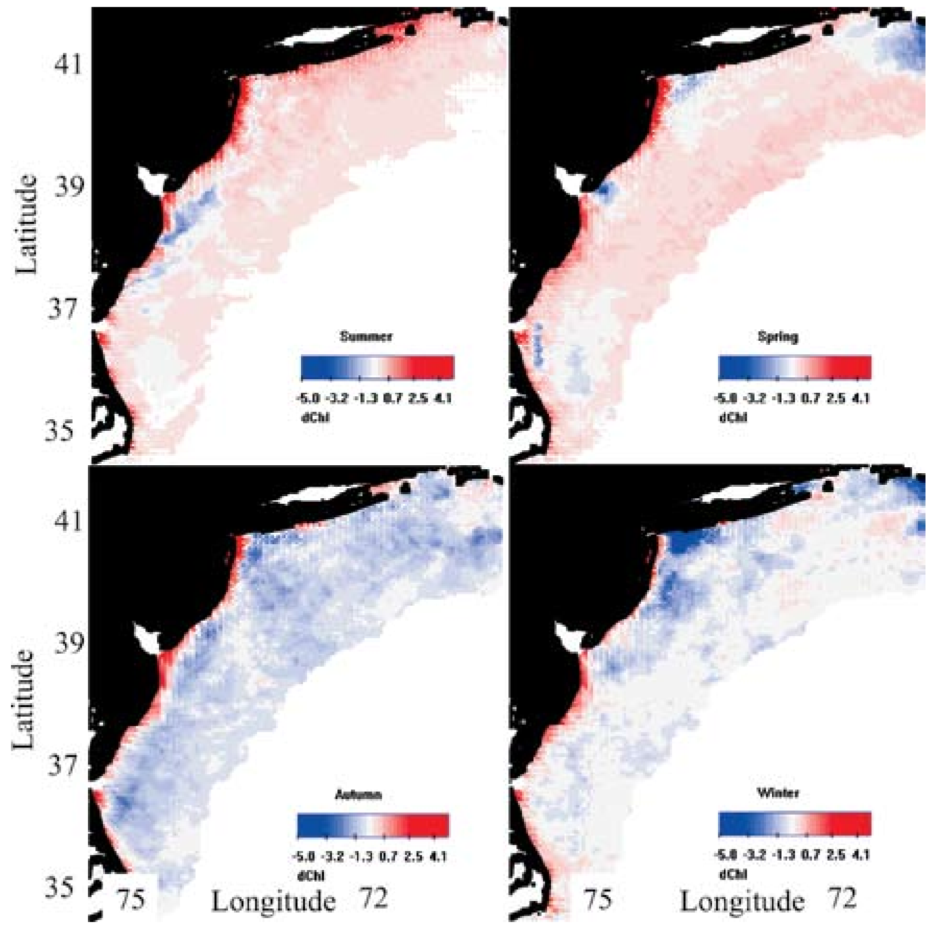


Figure 6. Seasonal chlorophyll differences measured by the CZCS and SeaWIFS satellites. Red colors indicate regions where chlorophyll has increased. The blues indicate where the chlorophyll values have decreased.

Table 1. The integrated change in seasonal chlorophyll over the different seasons (g Chl *a* $m^{-3}$ per season) for the Mid-Atlantic Bight derived from CZCS and SeaWiFS ocean color satellite sensor measurements.

| Season | 1978–1986 | 1998–2006 | Difference | % Change |
|---|---|---|---|---|
| Spring | 2.52 | 2.74 | 0.21 | 8 |
| Summer | 1.73 | 2.02 | 0.29 | 14 |
| Fall | 3.89 | 2.73 | -1.16 | -43 |
| Winter | 3.61 | 2.80 | -0.81 | -29 |
| **Total** | **13.00** | **11.35** | **-1.66** | **-14** |

the AMO has entered a warm phase. The previous warm phase lasted from the mid 1920s to the early 1960s.

The AMO shift from the cool phase to the warm phase in the mid 1990s coincides with a shift in the cross-shelf wind strength measured by NOAA (NDBC Buoy 44009) just outside Delaware Bay. The buoy wind measurement is representative of wind over the MAB. Cross-shelf wind blowing offshore is maximum during winter (Figure 7). During the time period from 1987 to 1995, the two-month low-pass, mean wintertime wind speed was 3.54 m $s^{-1}$. In the years following, from 1996 to 2007, the mean wintertime wind speed was 4.72 m $s^{-1}$. The velocities correspond to wind stress of 0.02 N $m^{-2}$ and 0.035 N $m^{-2}$, respectively (Large and Pond, 1981). The low-frequency cross-shelf wintertime wind stress increased 75% over the period of a decade. Storm intensity is the key variable determining the magnitude of the winter bloom (Xu et al., in review). Therefore, the declines in MAB winter blooms are likely associated with the increase in storminess associated with the positive phase of the AMO.

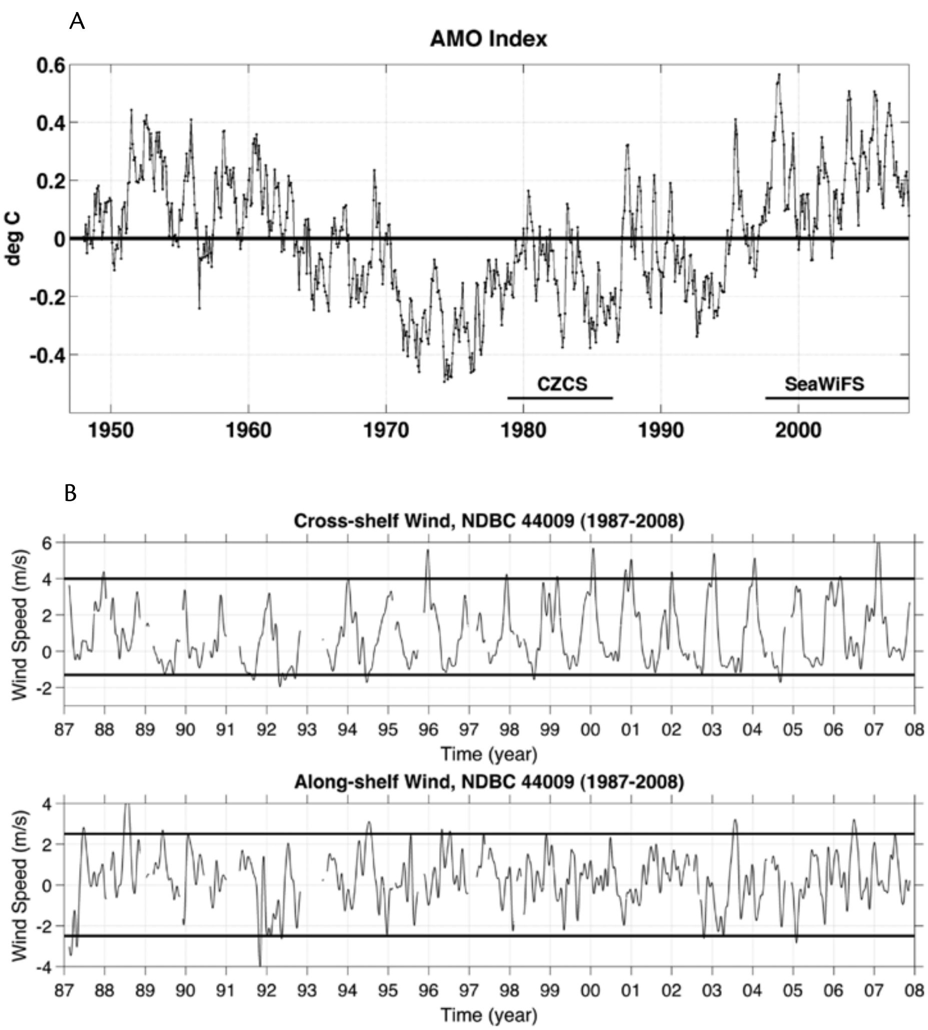


Figure 7. (A) The AMO Index from 1948 to 2008. Periods of CZCS and SeaWiFS satellite operations are highlighted in gray. (B) Cross-shelf (top) and along-shelf (bottom) wind measured at NOAA NDBC Buoy 44009 from 1987 to 2008. Two-month low-pass filtering was applied to the data. The red box indicates the wind levels associated with enhanced winter mixing.

## CONCLUSIONS

The ability to resolve the spatial variability of multiple parameters over seasonal scales is a significant advance for coastal ocean research. On the MAB, spatial time series have documented that there is winter cross-shore transport of large phytoplankton blooms driven by northwest winds. The offshore extent of the winter blooms appears to be constrained by water-column depth. In the spring transition season, the onset of stratification allows for phytoplankton blooms in the deeper waters of the continental shelf. These spring blooms are then advected alongshore by alongshore winds. During the summer months, the shelf is highly stratified and has low primary productivity except for nearshore waters, as southwest winds drive coastal upwelling. The productivity of the autumn transition season largely reflects the timing of the breakdown of shelf stratification. We observed large seasonal changes in primary productivity over the last few decades. Declines are evident in the fall and winter seasons. For winter blooms, the AMO's positive phase is associated with an increase in the number of winter storms that would decrease winter phytoplankton productivity by increasing water-column mixing and decreasing upper water-column light availability. We hypothesize that declines in fall productivity reflect later seasonal breakdowns in MAB stratification. Understanding these factors will require a more complete three-dimensional time series then we presently have; however, autonomous underwater vehicle technology has matured to a point where it will be a critical tool for ocean observing. Measuring the timing of stratification erosion is difficult using traditional ship strategies because this transition appears to happen quickly when seasonal cooling preconditions the shelf, which is then mixed by large storms (Glenn et al., 2008).

Spatial time series will enable new insights into continental shelf processes as researchers will be able to resolve both the mean and fluctuating properties of the system. Fluctuating properties are distinctly different from mean properties; they are energetic and spatially variable. Climate change is altering both the mean and fluctuating properties of the coastal ocean. Many biological responses occur over the temporal and spatial scales of the fluctuating properties. New enabling technologies will allow sampling of these changing fluctuating properties in the coming decade. There is an urgent need for this research, as communities will be increasingly impacted by local ocean changes, and oceanographers will be asked to provide insight and guidance toward managing the changing coastal ocean.


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## REFERENCES

*Editor's Note:* Oceanography *does not usually permit citation of articles that are in review; however, because of the rapidly advancing nature of this issue's topics, we are making an exception. Updates on the status of manuscripts cited as in review here will be posted on the CoOP Web site (http://www.skio.usg.edu/coop).*


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

Boesch, D.F., J.C. Field, and D. Scavia, eds. 2000. *The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources: Report of the Coastal Areas and Marine Resources Sector Team, U.S. National Assessment of 12 of the Potential Consequences of Climate Variability and Change, U.S. Global Change Research Program.* NOAA Coastal Ocean Program Decision Analysis Series No. # 21. NOAA Coastal Ocean Program, Silver Spring, MD, 163 pp.

Castelao, R., S. Glenn, O. Schofield, R. Chant, J. Wilkin, J. Kohut. 2008. Seasonal evolution of hydrographic fields in the central Middle Atlantic Bight from glider observations. *Geophysical Research Letters* 35(L03617), doi:10.1029/2007GL032335

Chen, C.T, K.-K. Liu, and R. MacDonald. 2003. Continental margin exchanges in ocean biogeochemistry. Pp. 53–98 in *The Role of the Ocean Carbon Cycle in Global Change.* M.J.R. Fasham, ed., Springer-Verlag, Berlin.

Glenn, S.M., R. Arnone, T. Bergmann, W.P. Bissett, M. Crowley, J. Cullen, J. Gryzmski, D. Haidvogel, J. Kohut, M.A. Moline, and others. 2004. The biogeochemical impact of summertime coastal upwelling in the Mid-Atlantic Bight. *Journal of Geophysical Research* 109(C12S02), doi:10.1029/2003JC002265.

Glenn, S.M., D.B. Haidvogel, O. Schofield, F.J. Grassle, C.J. von Alt, E.R. Levine, and D.C. Webb. 1998. Coastal predictive skill experiments at the LEO-15 National Littoral Laboratory. *Sea Technology* 39(4):63–69.

Glenn, S., C. Jones, M. Twardowski, L. Bowers, J. Kerfoot, J. Kohut, D. Webb, and O. Schofield. 2008. Glider observations of sediment resuspension in a Middle Atlantic Bight fall transition storm. *Limnology and Oceanography* 53:2,180–2,196.

Glenn, S.M., and O. Schofield. 2003. Observing the oceans from the COOLroom: Our history, experience, and opinions. *Oceanography* 16(4):37–52.

Glenn, S. and O. Schofield. In review. Growing a distributed regional ocean observatory: Our view from the COOLroom.

Gong, D., J.T. Kohut, and S.M. Glenn. In review. Wind driven circulation and seasonal climatology of surface current on the NJ Shelf (2002–2007).

Kerr, R.A. 2000. A North-Atlantic climate pacemaker for the centuries. *Science* 288:1,984–1,986.

Kohut, J.T., S.M. Glenn, and R.J. Chant. 2004. Seasonal current variability on the New Jersey inner shelf. *Journal of Geophysical Research* 109(C07S07), doi: 10.1029/2003JC001963.

Large, W.G., and S. Pond. 1981. Open ocean momentum flux measurements in moderate to strong winds. *Journal of Physical Oceanography* 11:324–336.

Mountain, D.G. 2003. Variability in the properties of shelf water in the Middle Atlantic Bight, 1977-1999. *Journal of Geophysical Research* 108(C1), 3014, doi:10.1029/2001JC001044.

National Oceanic and Atmospheric Administration (NOAA). 1998. *Year of the Ocean. Discussion Papers.* National Oceanic and Atmospheric Administration, Silver Spring, MD.

Ryan, J.P., J.A. Yoder, and P.C. Cornillon. 1999. Enhanced chlorophyll at the shelfbreak of the Mid-Atlantic Bight and Georges Bank during the spring transition. *Limnology and Oceanography* 44:1–11.

Schofield, O., T. Bergmann, W.P. Bissett, F. Grassle, D. Haidvogel, J. Kohut, M. Moline, and S. Glenn. 2002. Linking regional coastal observatories to provide the foundation for a national ocean observation network. *Journal of Oceanic Engineering* 27(2):146–154.

Schofield, O., J. Kohut, D. Aragon, L. Creed, J. Graver, C. Haldeman, J. Kerfoot, H. Roarty, C. Jones, D. Webb, and S.M. Glenn. 2007. Slocum gliders: Robust and ready. *Journal of Field Robotics.* 24(6):473–485, doi:10:1009/rob.20200

Small, C., and J.E. Cohen. 2004. Continental physiography, climate, and the global distribution of human populations. *Current Anthropology* 45(2):269–288.

Small, C., and R.J. Nicholls. 2003. A global analysis of human settlement in coastal zones. *Journal of Coastal Research* 19(3):584–599.

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human domination of Earth's ecosystems. *Science*. 277:494–500.

Xu, Y., R.C. Chant, D.L. Gong, R. Castelao, S.M. Glenn, and O. Schofield. In review. Decadal dynamics in the seasonal phytoplankton dynamics in the Mid-Atlantic Bight.

Yoder, J.A., S.E. Schollaert, and J.E. O'Reilly. 2002. Climatological phytoplankton chlorophyll and sea surface temperature patterns in continental shelf and slope waters off the northeast U.S. coast. *Limnology and Oceanography* 3(47):672–682.