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Mesoscale variations of sea surface temperature and ocean color patterns at the Mid-Atlantic Bight shelfbreak

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[1] Concurrent sea surface temperature (SST) and color observations obtained by MODIS (Moderate Resolution Imaging Spectra-radiometer) provide an excellent opportunity to investigate simultaneous mesoscale variations in SST and surface pigment at the Mid-Atlantic Bight (MAB) shelf-break. Cloud-free MODIS images that clearly reveal mesoscale signals are used to estimate the dominant spatial scales of MAB shelfbreak water properties. Along-shelfbreak decorrelation scales for SST and surface pigment are 45 and 40 km, respectively, whereas the across-shelfbreak scales are much shorter, ranging from 19 km for SST to 25 km for pigment. The shelfbreak SST and surface pigment are generally inversely correlated. Cold (warm) SST corresponds to high (low) pigment concentration. Mesoscale variations account for 30% of the total variance in shelfbreak SST. For the shelfbreak surface pigment, the mesoscale variation is much larger, reaching 60–90% of its total variance. **Citation:** He, R., K. Chen, T. Moore, and M. Li (2010), Mesoscale variations of sea surface temperature and ocean color patterns at the Mid-Atlantic Bight shelfbreak, *Geophys. Res. Lett.*, 37, L09607, doi:10.1029/2010GL042658.

1. Introduction

[2] Offshore of the northeastern United States (US) a sharp temperature and salinity front at the Middle Atlantic Bight (MAB) shelfbreak separates the relatively cool and fresh shelf waters from the warm and salty waters of the North Atlantic. Long-term mean states of the MAB shelfbreak front and current are given by *Linder and Gawarkiewicz* [1998], which compiled all available hydrographic observations in the MAB between 1900 and 1990. The resultant mean-fields quantitatively show the seasonal configurations of the shelfbreak front. In winter, the density front extends throughout the entire water column, whereas in summer, a strong pycnocline develops isolating much of the front from the surface. On the shorter time scales, the basic states of the shelfbreak front and current/jet are baroclinically unstable [*Flagg and Beardsley*, 1978; *Gawarkiewicz*, 1991; *Lozier et al.*, 2002]. They respond to both local wind forcing [e.g., *Houghton, et al.* 1988], and upstream source water variations [e.g., *Chapman and Beardsley*, 1989; *Petrie and Drinkwater*,

1993]. The surrounding slope water, particularly the presence of Gulf Stream eddies and rings [e.g., *Gawarkiewicz et al.*, 2001; *Ramp et al.*, 1983] can also exert strong impact on the evolution of the shelfbreak front and jet. So far, it remains an enormous challenge to differentiate dynamical processes controlling variability of shelfbreak front and current. Characterizing the decorrelation scales of MAB shelfbreak water properties is arguably an essential task as they are pertinent to the fundamental question on how to sufficiently observe and model the MAB shelfbreak circulation, so that the cross-front exchanges of mass, heat, salt, nutrient, and other optical properties can be better quantified.

[3] Shipboard sampling of this highly intermittent dynamic system suffers from inherent practical limitations: while providing 3-dimensional snapshot in time, the effort required to conduct these surveys precludes doing so on a frequent basis. Fixed-mooring programs have yielded important clues about the nature of the shelfbreak phenomena. However, one-dimensional observations simply do not fully resolve the fundamentally 3-dimensional circulation process. A future shelfbreak Pioneer Array (the MAB Pioneer Array: http://www.whoi.edu/page.do?pid = 29615), consisting of both fixed moorings and autonomous underwater vehicles cruising around the shelfbreak area will be the most valuable for sampling the fast evolving shelfbreak environment. But before that is fully implemented, satellite observation offers the only observational approach suitable for routine synoptic sampling of physical and biological properties, and therefore the approach we have taken in this research. In particular, concurrent surface temperature and surface pigment observations obtained by MODIS (Moderate Resolution Imaging Spectra-radiometer) provide an excellent opportunity to investigate simultaneous mesoscale variations in SST and ocean color at the MAB shelfbreak. Our objectives of this study are therefore twofold: 1) to determine the nature of the mesoscale signals and decorrelation scales in SST and ocean color distribution at the MAB shelfbreak; 2) to ascertain the degree to which they are linked.

2. Methods and Results

[4] The study domain encompasses the MAB from 37 N° to 42° N and from −75° W to −69° W (Figure 1). To focus on the shelfbreak area, we subsample satellite observations in a shelfbreak centralized curvilinear grid, which has ∼ 1-km spatial resolution with its along-shelf (across-shelf) direction being approximately parallel (perpendicular) to the local shelfbreak isobaths. Because one of our research goals is to estimate the along-shelf and across-shelf correlation scales of shelfbreak water properties, having such a curvilinear grid allows us to simply compute correlation scales in the grid-relative coordinate, thus making our calculation

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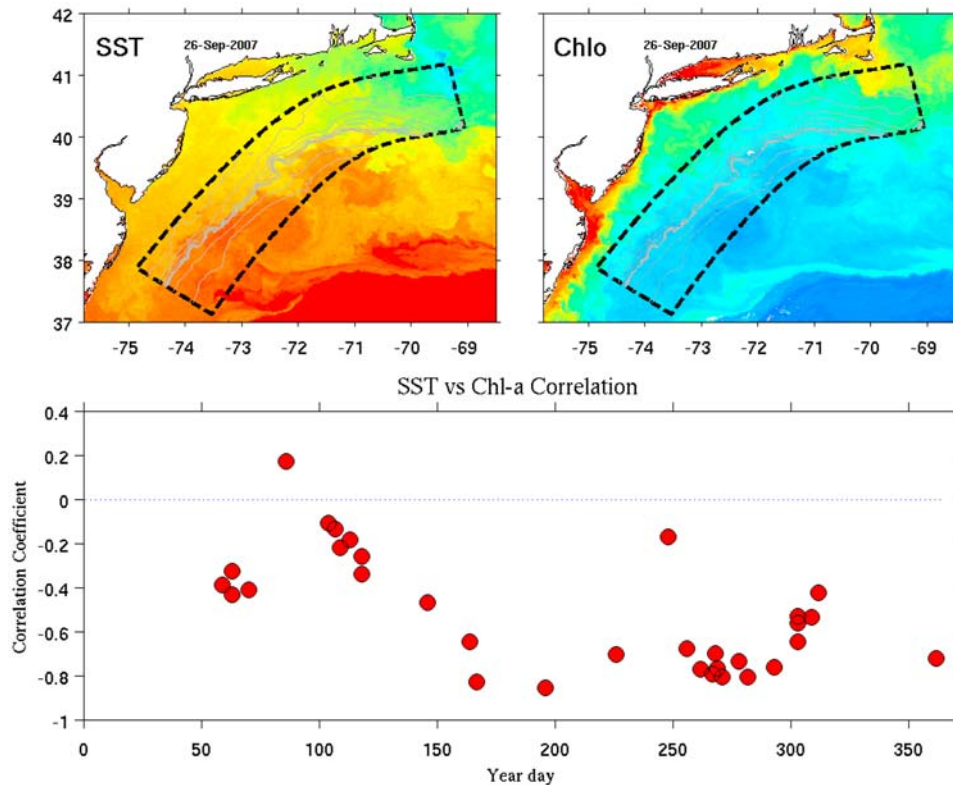
Figure 1. (top) Daily SST and Chl *a* images on September 26, 2007 and (bottom) the correlation between domain-averaged SST and Chl *a* calculated based on 32 daily, cloud-free images. Both SST and Chl *a* data were subsampled in the 1-km resolution shelfbreak curvilinear grid, which is highlighted by the dashed lines.

more robust. While different isobaths at the northern versus the southern end of the alongshelf curvilinear coordinate are included, such a domain is sufficient to resolve ocean surface signatures associated with shelfbreak processes.

[5] Concurrent sea surface temperature and ocean color (Chl *a*) data are measured by the MODIS instrument onboard the NASA Aqua satellite. Launched on May 4, 2002, the Aqua mission is a part of the NASA centered international Earth Observing System (EOS). Aqua flies in a near-polar low-earth orbit, providing once per day observation over the study site. Raw MODIS SST and Ocean Color data are processed by NASA/Goddard Space Flight Center (GSFC) and later sub-sampled and processed for the western North Atlantic Ocean by the Center of Excellence for Coastal Ocean Observation and Analysis (COOA) of the University of New Hampshire. The spatial resolution of COOA MODIS data is 1.25 km, allowing detailed depictions of fine scale variability of the MAB shelfbreak environment. Cloud cover is always a problem in satellite observations. By going through COOA MODIS data archive from 2002 to 2009, we selected 32 cloud-free images that clearly reveal mesoscale signals in both SST and ocean color. For interested readers, these images are available online for examination at (http://omgrhe.meas.ncsu.edu/MODIS/daily.html).

[6] For example, the imagery on Sept 26, 2007 (Figure 1, top) clearly shows the shelfbreak front and two warm-core eddies impinging upon the shelfbreak. One eddy was centered at [−72.5W 38.5N], and the other centered at [–71W, 39.4N]. The SST map also shows a low temperature filament was present between the two eddies, suggesting sig-

nificant offshore entrainment of cold shelf water. Concurrent ocean color image reveals pigment concentrations inside two warm eddies were significantly lower than those in the surrounding waters.

[7] Indeed, the covariation between SST and ocean color is a consistent feature of the entire dataset (Figure 1, bottom). Except just one occasion, correlations between SST and surface pigment are negative, indicating that cold (warm) SST corresponds to high (low) pigment concentration at the MAB shelfbreak. Although the annual cycle is not completely resolved by 32 pairs of color-free images, there does appear to be a significant seasonal variation. In general, the strongest correlation occurs during the fall and winter, and weakens as the time progresses toward the spring.

[8] Both large-scale gradient and mesoscale variability are embedded in both SST and color fields. To focus on mesoscale scale variability, we removed linear trends in both along-shelf and across-shelf directions. *McGillicuddy et al.* [2001] concludes that this is the preferred method for exposing the correlation between mesoscale variations in SST and surface pigment. The procedure was achieved by 2-dimensional linear regression for SST and color field, respectively. The resulting linear planes were then subtracted from the respective raw data to isolate mesoscale signal and variance, which are the focus of this study.

[9] The robust mesoscale content in concurrent surface temperature and color variations presented in these cloud-free images is characteristic of the entire MODIS dataset. In order to provide a quantitative measure of the dominant spatial scales inherent in the data, the autocorrelation functions for both SST and surface pigment were computed for
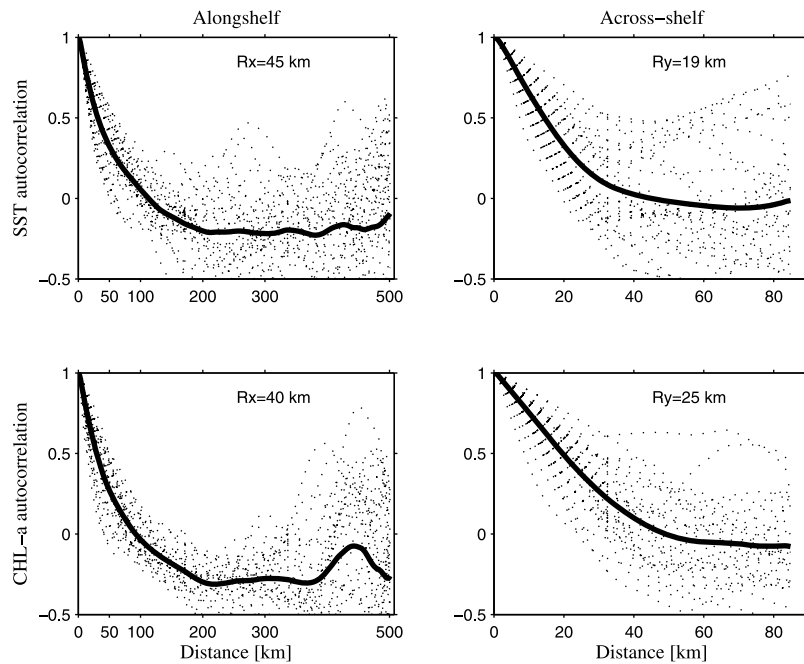
Figure 2. Alongshelf (across-shelf) auto decorrelation functions calculated from 32 daily, cloud-free SST and Chl *a* fields. The thick lines show the mean of respective auto decorrelation functions. 2-D linear trends (thus large scale gradients) were removed prior to the calculation. Exponential (e^{-1}) crossing distances of the mean autocorrelation functions for both SST and ocean color are indicated.

each cloud-free image. Exponential (e^{-1}) crossings of the autocorrelation functions for both SST and ocean color occur at distance lags consistent with mesoscale phenomena (Figure 2). Along-shelf scales of SST and surface pigment are nearly identical (45 and 40 km, respectively). Across-shelf scales are about 50% smaller, ranging from 19 km for SST and 25 km for pigment. We note the value of across-shelf decorrelation scale is roughly the width of the shelf-break jet given by *Linder and Gawarkiewicz* [1998].

[10] Given that only a portion of the annual cycle is resolved by time series of concurrent daily SST and Chl *a* images, we use MODIS Aqua monthly composite SST and pigment (Chl *a*) images (http://omgrhe.meas.ncsu.edu/MODIS/month.html) to help put these daily information into a longer temporal context (Figure 3). Each monthly composite is calculated by arithmetic averaging of all available daily images collected in each month. The area-averaged, monthly mean values of both SST and surface pigment have
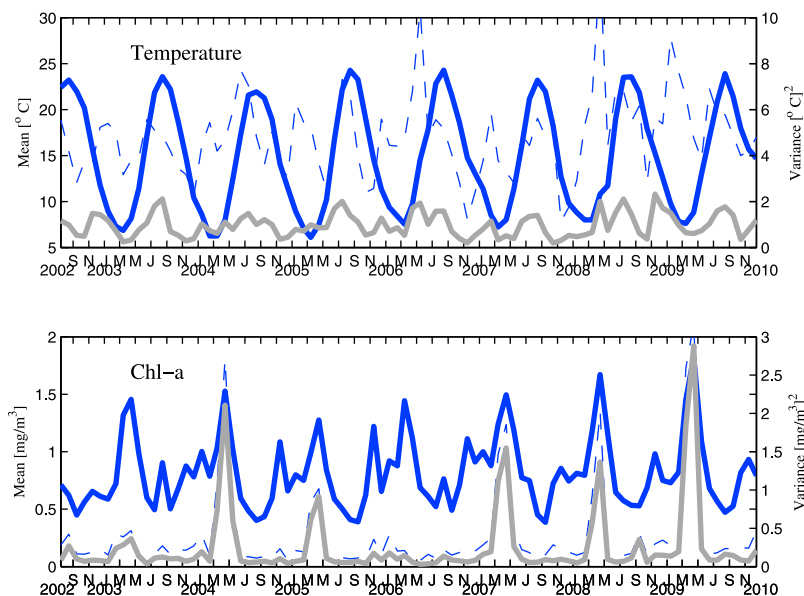
Figure 3. Shelfbreak domain averaged (top) SST and (bottom) Chl *a* concentration from 2002 to 2009: monthly means (thick blue lines), monthly variance (dashed blue lines) and monthly variance after linear trends being removed (thick gray lines).

strong seasonal cycles, as well as significant inter-annual variability. The same is also true for their variance. For SST, bimodal variance peaks are seen, one in winter (Dec–Feb), and the other in summer (May–July). For surface pigment, the highest variance occurs in spring (March – May) when SST is coldest and biomass at its highest. The total variance in Figure 3 contains contributions from both the large-scale trend and mesoscale signal. If we remove linear trends in both along-shelf and across-shelf directions, we retrieve variance residues that relate to the magnitude of the mesoscale signal. Indeed, the fraction of the total variance remaining (i.e., the mesoscale eddy variance) varies considerably after detrending. For surface temperature, such mesoscale eddy variance is about 30% of the total variance. For surface pigment, the mesoscale eddy variance is much larger, reaching 60–90% of the total variance.

3. Discussion and Summary

[11] Based on hydrographic survey data in July 1996, *Gawarkiewicz et al.* [2004] provided decorrelation scale estimations for the MAB shelfbreak subsurface circulation (at 54 m depth). Depending on the state variable being examined, their analysis shows the decorrelation scale can vary from 7 to 20 km. *Chen and He* [2010] performed a high-resolution model hindcast for the MAB shelfbreak circulation in 2006. The model based decorrelation scale estimates (in order to be comparable, also sampled at 54 m below the surface) are similar to those inferred from 1996 observations, ranging from 12 to 22 km. Our analysis was done at the MAB shelfbreak ocean surface, suggesting the along-shelf scale (40–45 km) is larger, but the across-shelf scale (19–25 km) is very consistent with values inferred from earlier studies. Therefore, in order to effectively observe the MAB shelfbreak processes, a sampling grid with a resolution no more than 20 km seems to be necessary.

[12] The preceding analysis also reveals an inverse relationship between shelfbreak SST and surface pigment variation, such that cold (warm) temperature anomalies are associated with high (low) pigment biomass. Shelfbreak upwelling may introduce nutrients into the euphotic zone, which stimulate biomass accumulation [e.g., *Linder and Gawarkiewicz*, 1998; *Chen and He*, 2010]. It is also known that in the MAB, colored dissolved organic matter (CDOM) can be transported from coast to shelfbreak [e.g., *Chant et al.*, 2008], thus it is likely that pigment information derived from MODIS observations reflect some combinations of biomass pigments and CDOM. Without additional in-situ data, it is not possible to determine the partitioning between the two. Moreover, mesoscale variations in SST and ocean color do not necessarily imply a biological response to nutrient supply. High concentration of surface pigment could come from 1) biomass enhancement stimulated by the introduction of nutrient into the euphotic zone, and 2) vertical advection of colored materials from their subsurface maxima [e.g., *McGillicuddy et al.*, 2001]. Without direct biological and nutrient measurements, we are not able to distinguish between the two.

[13] With continuous MODIS SST and color data (Figure 3), we may put them in the context of early studies on regional temperature/stratification and phytoplankton biomass variations. In spring, stratification develops as storm frequency and intensity decrease, solar heating increases. The rede-velopment of stratification promotes classic spring blooms in the MAB [*Gran and Braruud*, 1935; *Sverdrup*, 1953]. The spring development of stratification is often interrupted by wind-driven mixing events. The sensitivies of spring stratification and phytoplankton response to the timing and intensity of these spring mixing events lead to interannual variations of spring blooms. Previous field observations from the MAB generally suggest that nutrient concentrations are depleted in the summertime surface layer when stratification is present [e.g., *Ketchum et al.*, 1958; *Falkowski et al.*, 1983; *Malone et al.*, 1983; *Walsh et al.*, 1987; *Sosik et al.*, 2001]. However, intermittent increases in phytoplankton concentrations are still likely during upwelling-favorable wind events [*Glenn et al.*, 2004]. Upwelling-favorable winds can help to advect vertical flux of nutrients from cold, yet nutrient-rich deeper layers. In the fall, increased mixing due to storms and cooling can often rapidly break down the thermal stratification. The consequent introduction of nutrients into the euphotic zone causes a fall increase in phytoplankton biomass [*O'Reilly et al.*, 1987; *O'Reilly and Zetlin*, 1998; *Yoder et al.*, 2001, 2002]. At present, it is unclear whether the fall breakdown of stratification is primarily the result of local wind-driven vertical mixing, surface cooling, or boundary layer advection [*Lentz et al.*, 2003]. More efforts are needed to identify the factors controlling the timing and extent of stratification and illustrate the corresponding phytoplankton response. In winter, the shelf water in MAB coastal ocean is cold and often vertically well mixed with high nutrient concentrations. While nutrients are available for phytoplankton growth, the seasonal low in incident radiation leads to low light exposure for phytoplankton. However, historical observations of phytoplankton suggest that winter blooms of large-celled phytoplankton are still possible in the research region [*Bigelow et al.*, 1940; *Glibert et al.*, 1985], suggesting that the bloom events may be associated with factors such as the development of intermittent stratification that increases the available light to the phytoplankton [e.g., *Riley*, 1947].

[14] Throughout the entire year, changes in the structure of the shelfbreak front/jet can dramatically influence the stratification, nutrient and phytoplankton distributions at the shelfbreak. Enhanced chlorophyll concentrations in the vicinity of the shelfbreak front indeed have been identified as the result of nutrient fluxes into the upper water column [e.g., *Ryan et al.*, 1999a, 1999b]. These nutrient fluxes however may be related to a variety of processes that have been suggested as potential shelf-slope exchange mechanisms, including wind forcing, instabilities, intrusions, warm-core rings, and upwelling associated with convergence of bottom boundary layer transport at the front [e.g., *Houghton et al.*, 1988; *Barth et al.*, 1998; *Lentz et al.*, 2003; *Chen and He*, 2010]. Piecing together enough synoptic maps from concurrent satellite SST and ocean color data, along with extensive in-situ biophysical measurements from the MAB shelfbreak Pioneer Array that is on the horizon, we will be in a position to better assess synoptic, seasonal, and inter-annual variability in the expression of the controlling mechanism of circulation, water stratification, and phytoplankton biomass at the MAB shelfbreak. The resulting improved understanding will provide critical information for quantifying cross-shelf exchanges of heat, salt, the primary production, and biogeochemical cycling.

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