Diagnosing the warming of the Northeastern U.S. Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response

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Received 30 August 2013; revised 3 December 2013; accepted 4 December 2013; published 13 January 2014.

[1] The temperature in the coastal ocean off the northeastern U.S. during the first half of 2012 was anomalously warm, and this resulted in major impacts on the marine ecosystem and commercial fisheries. Understanding the spatiotemporal characteristics of the warming and its underlying dynamical processes is important for improving ecosystem management. Here, we show that the warming in the first half of 2012 was systematic from the Gulf of Maine to Cape Hatteras. Moreover, the warm anomalies extended through the water column, and the local temperature change of shelf water in the Middle Atlantic Bight was largely balanced by the atmospheric heat flux. The anomalous atmospheric jet stream position induced smaller heat loss from the ocean and caused a much slower cooling rate in late autumn and early winter of 2011–2012. Strong jet stream intraseasonal oscillations in the first half of 2012 systematically increased the warm anomalies over the continental shelf. Despite the importance of advection in prior northeastern U.S. continental shelf interannual temperature anomalies, our analyses show that much of the 2012 warming event was attributed to local warming from the atmosphere.

Citation: Chen, K., G. G. Gawarkiewicz, S. J. Lentz, and J. M. Bane (2014), Diagnosing the warming of the Northeastern U.S. Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response, *J. Geophys. Res. Oceans*, *119*, 218–227, doi:10.1002/2013JC009393.

1. Introduction

[2] The coastal ocean off the northeastern U.S. (Figure 1), which encompasses the Gulf of Maine (GoM) and the Middle Atlantic Bight (MAB), lies in the confluent zone of the North Atlantic's subtropical and subpolar gyres and thus is subject to influences from both the Gulf Stream and the Labrador Current. The general circulation over the continental shelf is equatorward flow with complex shelf-deep ocean exchanges across the shelf break [*Loder et al*., 1998]. The MAB shelf break and Georges Bank are also distinguished by high biological productivity with economically important commercial fisheries [e.g., *Marra et al*., 1990; *Ryan et al*., 1999; *O'Reilly et al*., 1987]. Therefore, understanding the ecosystem dynamics and its response to the physical environment in this region have long been recognized as important [e.g., *Fogarty and Murawski*, 1998; *He et al*., 2011; *Ji et al*., 2008].

[3] The coastal ocean in the MAB and GoM was anomalously warm in the first half of 2012, which led to major impacts on the northeastern U.S. coastal ecosystem and commercial fisheries. According to a National Oceanic and Atmospheric Administration (NOAA) Northeast Fishery Science Center ecosystem advisory (issued in August 2012) [*Friedland*, 2012], the surface temperature of the northeastern continental shelf during the first half of 2012 was the highest on record based on both contemporary satellite remote sensing data and long-term ship-board measurements from the past 150 years; The spring bloom in 2012 started as early as February, and phytoplankton biomass was higher than average; The distribution of Atlantic Cod had a northward shift consistent with the response to the warming over the continental shelf. From the CINAR (Cooperative Institute for the North Atlantic Region) Shelf break Ecosystem Workshop in January 2013 [*Gawarkiewicz et al*., 2013], commercial fishermen reported an abundance of squid in the summer of 2012 as well as the appearance of warm water species not previously seen off southern New England. Implications of this dramatic warming for management of living marine resources are discussed in *Mills et al*. [2013]. Thus, it is of great importance to understand the spatial and temporal characteristics of the warming and its underlying dynamical processes.

[4] Long-term sea surface temperature (SST) changes in the coastal ocean off the northeastern U.S. are mainly controlled by along-shelf transport originating in the Labrador Sea [*Shearman and Lentz*, 2010]. On the U.S. west coast, the atmospheric jet stream has also been reported to have major impacts on the temperature as well as ecosystem changes in the coastal ocean on an intraseasonal scale (~20 day)

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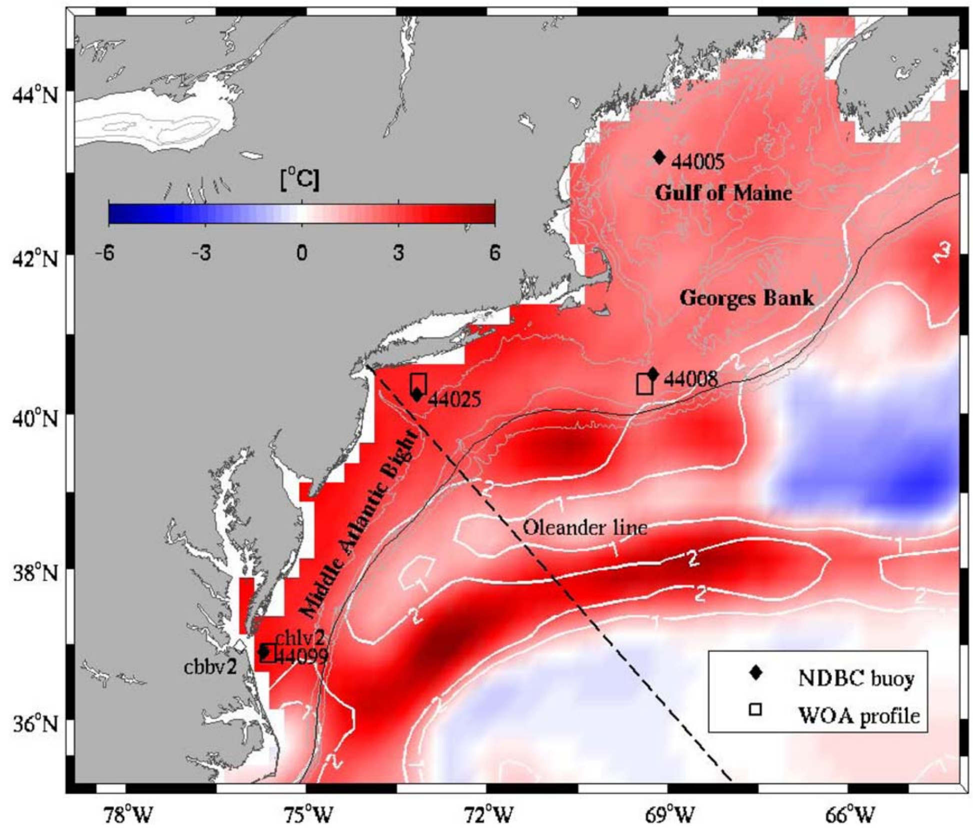

Figure 1. Map of the Middle Atlantic Bight (MAB) and Gulf of Maine (GoM) showing locations of NDBC buoys (diamonds) and the Oleander line (black dashed line). Shown in the background is the mean SST anomaly in March 2012 referenced to the March average SST during 2000–2010. White contours represent 1 and 2 standard deviations. Square boxes ($\sim$0.25°) demonstrate the location of WOA profiles which are used to estimate the relationship between SST and depth-averaged temperature for nearby buoys. The 50, 100, 200, and 1000 m isobaths (ETOPO-1) are also shown. The thin black line is the smoothed 200 m isobath that is used to define along-shelf and cross-shelf directions.

[*Bane et al*., 2007]. On a seasonal time scale, the shift of the jet stream's latitude is also associated with the timing of initiation of upwelling favorable wind patterns on the west coast of the U.S. [*Barth et al*., 2007].The processes which determine the temperature anomalies in the coastal ocean off the northeastern U.S. on a seasonal scale are not well known at present. Here, we aim to understand the spatiotemporal characteristics of the warm anomalies and characterize the relative importance of ocean advection and atmospheric forcing to the temperature budget in the coastal ocean in the MAB during the 2012 warming event. However, the lack of depth-dependent measurements during this event inhibits our effort to fully close the temperature budget. Therefore, we examine the contribution of atmospheric heat flux and attribute the residual to ocean advective flux. Improved understanding of the dynamical processes controlling the continental shelf warming will lead to better ecosystem management and forecasting.

2. Method and Data

[5] We examined surface air and water temperature data from National Data Buoy Center (NDBC) buoys within the MAB and GoM. We chose four buoys (Figure 1) that are located in the GoM (44005), and on the continental shelf near Nantucket (44008), Long Island (44025), and Virginia Beach (44099). For comparison with recent seasonal averages, water temperature records from 2000 to 2010 serve as temporal means to compare against temperature in 2011 and 2012 at each buoy. At buoy 44099, water temperature measurements are only available from 2008 to present. To construct a continuous time series, water temperature data from nearby buoy cbbv2 (near the Chesapeake Bay Bridge Tunnel) and chlv2 (Chesapeake Light, the same location as 44099) are used. The temperature record during 2000–2004 at buoy chlv2 was used in place of 44099. Water temperature data during 2005–2007 was projected for buoy 44099 based on linear regression between temperature records during 2008–2011 at buoy 44099 and cbbv2. All time series in this study were 8 day low-pass filtered to remove weather-band signals.

[6] To extend the analysis from the SST to the water column over the continental shelf, expendable bathythermograph (XBT) data collected off New Jersey along the Oleander line (from New York Harbor to Bermuda) were examined. The XBT transects are available on a monthly basis since 1977 (po.msrc.sunysb.edu/Oleander/XBT/NOAA_XBT.html). We used the vertical profile closest to

the 100 m isobath for each month, which was representative of the thermal structure over the middle and outer continental shelf.

[7] Atmospheric data are available from the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR). The NARR data set has temporal and spatial resolution of 3 h and 30 km, respectively, and it spans from 1979 to the present. Shortwave radiation, longwave radiation, latent heat flux, and sensible heat flux components are used to calculate net downward heat flux into the ocean. To determine the latitude of the atmospheric jet stream, the maximum meridional gradient of geopotential height at 200 hPa along 70°W was used [*Bane et al*., 2007]. Wind speed and specific humidity at 10 m above the sea surface are also available in the NARR data set.

[8] At the three buoy locations in the MAB, the depth-averaged temperature was estimated based on the closest grid point (square boxes, Figure 1) of the World Ocean Atlas (WOA) 2009 climatology (www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html). The climatological data were used to develop a linear relationship between the climatological surface temperature and climatological depth-averaged temperature. The linear relationship was then used to estimate depth-averaged temperature at buoy locations from the surface temperatures during 2011–2012. At each location, we further produced two more profiles, i.e., ±1 standard deviation (from WOA09) of the original profile, to account for the interannual variability of the thermal structures. Thus two more linear coefficients were calculated at each location and were used to estimate depth-averaged temperature in order to provide the range of uncertainties.

[9] Daily Optimal Interpolated (OI) Advanced Very High Resolution Radiometer (AVHRR) SST fields from the National Climate Data Center (NCDC) were used to compute the SST anomaly for March 2012 (Figure 1). The data are available from September 1981 to the present with a spatial resolution of 0.25°. The SST anomaly in March 2012 was computed relative to the mean SST in March during 2000–2010.

3. Results

3.1. Buoy Temperatures

[10] SST records at four NDBC buoys during 2011–2012 are compared to the mean values from 2000 to 2010 in Figure 2. The shelf-wide warm anomalies observed in the first half of 2012 began in fall 2011. Systematic anomalous SST was observed from November 2011 to at least June 2012. The warm anomalies in the western GoM (44005) and on the continental shelf near Nantucket (44008), Long Island (44025), and Virginia Beach (44099) varied from 0 to 6°C, with the maximum anomaly of 6°C near Virginia Beach in March 2012. The average SST anomalies during the first half of 2012 (January to June) are 1.7°C, 1.9°C, 2.4°C, and 2.2°C, respectively, from the Gulf of Maine to Virginia Beach. While the average magnitudes of the warm anomalies are not extremely large, the much larger short-term fluctuations (up to 6°C), the large area of the anomalies (Figure 1), and the long duration of the shelf-wide warm anomalies (at least 8 months) are significant and affected a large number of marine organisms.

[11] The timing of the seasonal-scale warm anomalies (November 2011 to June 2012) is largely consistent from the GoM to the MAB. The short-term anomalies at 44008 (Nantucket) during early October and late November of 2011 are the results of a northward diversion of the Gulf Stream [*Gawarkiewicz et al*., 2012]. On an intraseasonal time scale, warm anomalies are in-phase from north to south, particularly during March to May 2012. Calculation of cross correlation between buoys (Table 1) reveals that SST anomalies are highly correlated with maximum correlation at zero lag. Further comparison also shows that correlations in 2012 are higher than other years during 2000–2010. The consistent timing of warm anomalies suggests that the warming is related to large-scale atmospheric forcing as opposed to along-shelf advection.

3.2. Vertical Structure of the Thermal Anomalies

[12] To determine the vertical extent of the warm anomalies, we examine Oleander XBT temperature profiles near the shelf break off New Jersey (Figure 3). The mean profiles from 2000 to 2010 for each month are representative of the mean thermal structure on the continental shelf. In comparison, monthly profiles in the first half of 2012 show that the warm anomalies extended from the surface through the water column to at least 50 m depth near the shelf break. During January to April when the upper water column was well mixed, warm anomalies ranged from 1 to 3°C from the surface to 50 m. In May 2012, the temperature in the upper 15 m was ~5°C warmer than the mean, and the warm anomaly decreased with depth and reached zero below 30 m. In June 2012, although the thermal stratification remained similar to the mean condition, the temperature was about 2–3°C warmer over the upper 50 m of the water column. The magnitudes of the XBT temperature anomalies at the surface are comparable to those of the Long Island buoy measurements, despite the spatial separation.

3.3. Heat Budget for 2011–2012

[13] The depth-averaged heat budget can be approximated as:

$$\frac{\partial T}{\partial t} = \frac{Q}{\rho_o c_p H} - \int_{-H}^{0} \mathbf{u} \bullet \nabla T' dz \qquad (1)$$

where T is the depth-averaged temperature; ρ_0 is the average seawater density (1024 Kg m^{-3}); c_p is the specific heat of seawater (4190 J Kg^{-1}°C^{-1}); H is the local water depth; Q is the net atmospheric heat flux; and $\mathbf{u}$ and T' are the depth-dependent velocity vector and temperature, respectively.

[14] Due to the temporal similarities of the temperature anomalies throughout the MAB, it is reasonable to assume the temperature anomalies in the first half of 2012 are largely due to the atmospheric forcing. Thus, we examine the balance of the local rate of change of depth-averaged temperature and the net atmospheric heat flux, and attribute the residual to oceanic advective flux. To convert surface temperature T_s to depth-averaged temperature T at the

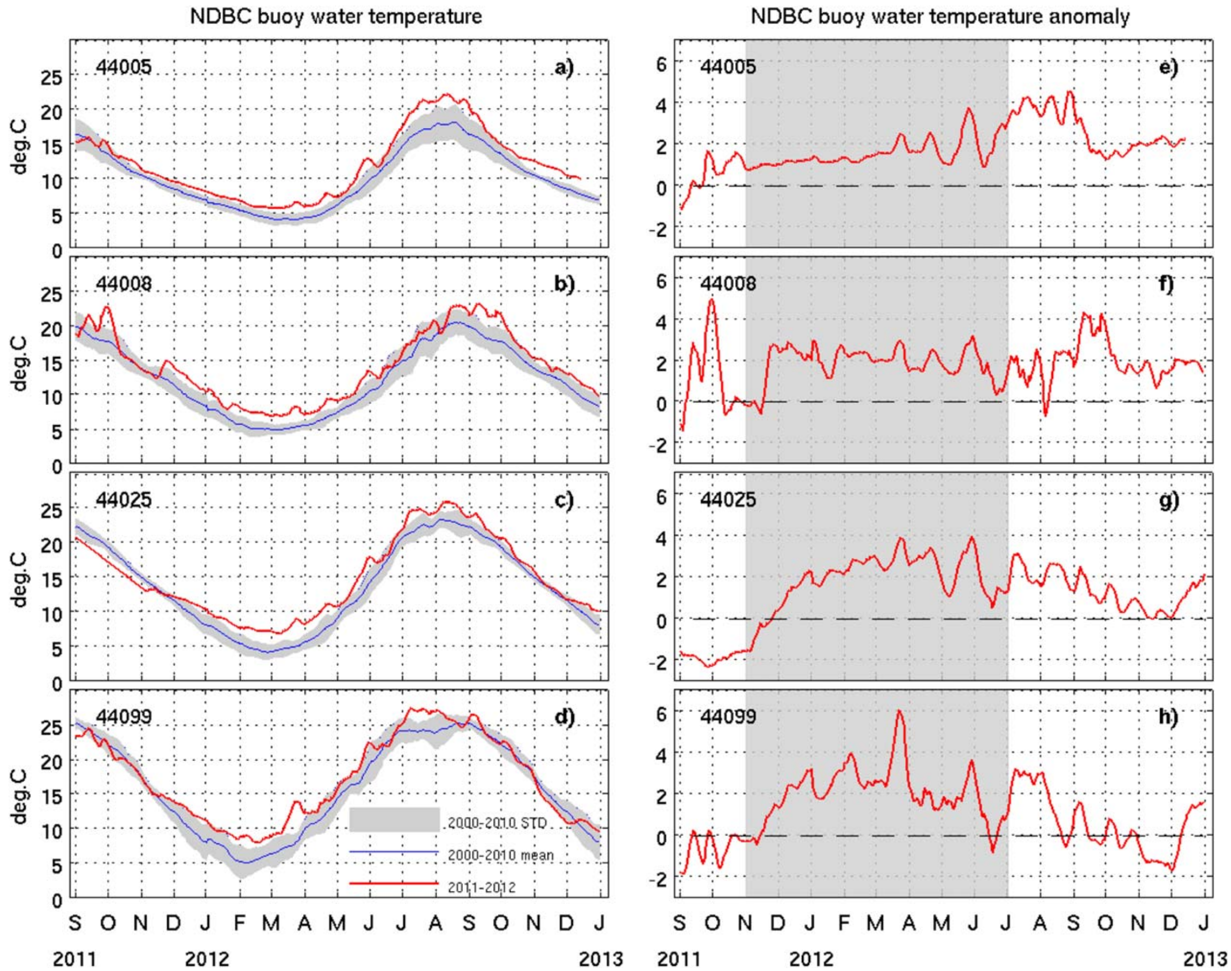

Figure 2. (a–d) SST during late 2011 and 2012 (red) compared to the 2000–2010 mean (blue) and standard deviation (shaded). The four buoys (from top to bottom) are located in the GoM (44005), and on the continental shelf near Nantucket (44008), Long Island (44025), and Virginia Beach (44099). (e–h) SST anomalies with respect to 2000–2010 mean at the same four buoys. The shelf-wide systematic warming period is demonstrated in the shaded area.

three buoy locations in the MAB, we utilize the nearby monthly climatology profiles from WOA 2009 (Figure 1) to compute the linear relationship between surface temperature and depth-averaged temperature. Monthly linear coefficients between T_s and T are then interpolated to each day and are used to generate daily time series of T.

Table 1. Maximum Cross-Correlation Coefficients Among Temperature Anomalies (Daily, 8 Day Low-Pass Filtered) in the First Half of 2012[a]

	Gulf of Maine (44005)	Nantucket Shoals (44008)	Long Island (44025)	Virginia Beach (44099)
Gulf of Maine (44005)	1 (0)	0.94 (0)	0.93 (0)	0.85 (0)
Nantucket Shoals (44008)	0.94 (0)	1 (0)	0.97 (0)	0.93 (0)
Long Island (44025)	0.93 (0)	0.97 (0)	1 (0)	0.91 (0)
Virginia Beach (44099)	0.83 (0)	0.93 (0)	0.91 (0)	1 (0)

[a]Lags (in days) corresponding to the maximum coefficients are shown in parentheses.

[15] Following *Lentz et al*. [2003], integration of (1) in time gives:

$$T - T_0 = Q_{cum} - Q_{adv} \quad (2)$$

where T_0 is the initial condition of T,

$$Q_{cum} = \int_0^t \frac{Q}{\rho_o c_p H} dt' \quad (3)$$

is the cumulative atmospheric net heat flux, and

$$Q_{adv} = \int_0^t \left(\int_{-H}^{0} u \bullet \nabla T' dz \right) dt'$$

is the advective heat flux.

[16] $T - T_0$ and Q_{cum} are then examined to characterize the relative importance of atmospheric forcing and ocean advection to the depth-averaged temperature budget at the three buoys in the MAB. During November 2011 to June

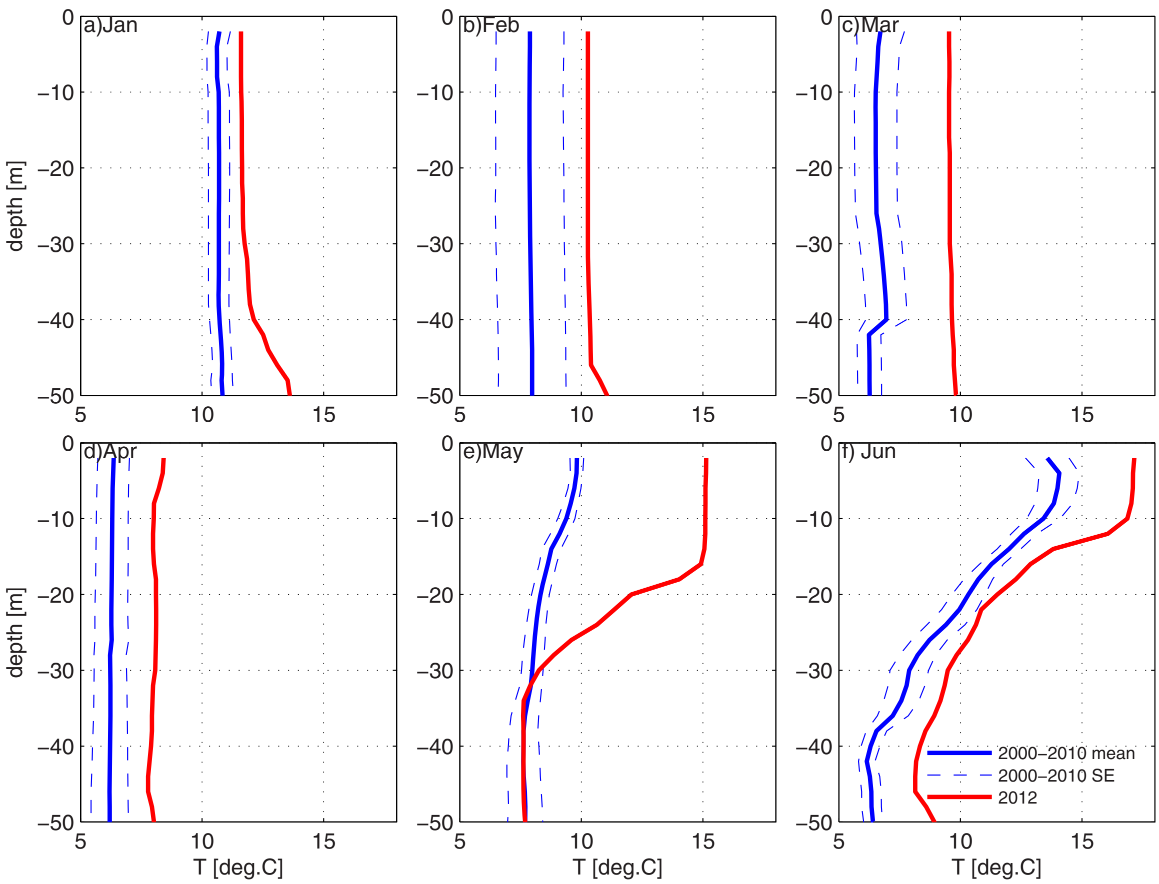

Figure 3. Comparison of Oleander XBT temperature profiles between 2012 (red) and 2000–2010 mean (blue) with standard errors shown by dashed lines. Profiles that are located closest to the 100 m isobath in each month are selected. To avoid near-bottom variability associated with shelf break frontal motions, only the upper 50 m are shown.

2012, the temperature budget of shelf water near either Nantucket (buoy 44008) or Long Island (buoy 44025) is largely balanced between the atmospheric heat flux and the local rate of change (Figure 4), consistent with previous studies at the southern flank of Georges Bank [*Brink et al.*, 2009]. However, at Virginia Beach (buoy 44099), the relationship between $T-T_0$ and Q_{cum} is relatively weak. Presumably, the proximity of the buoy location to the Gulf Stream and major estuaries leads to a significant horizontal heat flux due to both onshore intrusions of Gulf Stream and large temperature gradients, and these thus counterbalance the Q_{cum}. Considering the local water depth is about 200 m, the heat budget at the Gulf of Maine buoy (44005) is unlikely to have temperature changes balanced by the surface flux, and thus is excluded from analysis.

3.4. The Jet Stream Position and Variability During the First Half of 2012

[17] Buoy temperature records during March 2012 to May 2012 show in-phase oscillations of surface temperature from the GoM to Virginia Beach with a period of ~20 days (Figure 2), which is consistent with the typical periodicity of intraseasonal oscillations of the atmospheric jet stream [*Bane et al.*, 2007; *Barth et al.*, 2007]. The cause of the intraseasonal oscillations of the jet stream is normally attributed to the mountain torques [e.g., *Lott et al.*, 2004a, 2004b], but detailed discussion of this process is out of the scope of current study. Comparison between the SST anomalies and the jet stream latitude anomaly confirms that the surface temperature oscillation is related to north–south shifts of the jet stream's position (Figure 5). Correlation coefficients between the latitudinal anomaly of the jet stream and the SST anomalies during the first half of 2012 vary between 0.45 and 0.64 with lags of 3–6 days at different buoy locations. In particular, a higher correlation is found at all four buoys during March–May with increased coefficients varying from 0.55 to 0.84. Although the degrees of freedom [e.g., *Emery and Thomson*, 2004] are small during this 3 month period (~8–10), the correlation is significant (95%) at Nantucket and Virginia Beach. Around early March 2012, the net atmospheric heat flux turns positive (into the ocean) and increases water column stratification. Compared to the weakly stratified winter season (i.e., January–February), atmospheric forcing would have a more significant impact on the surface temperature as most of the atmospheric heat flux is limited to the surface mixed layer. That presumably explains the higher correlation between the jet stream position and the SST anomalies in the spring.

3.5. Atmospheric Forcing and the Jet Stream Position

[18] The intraseasonal oscillations of the jet stream have a clear impact on the SST oscillations in the GoM and the

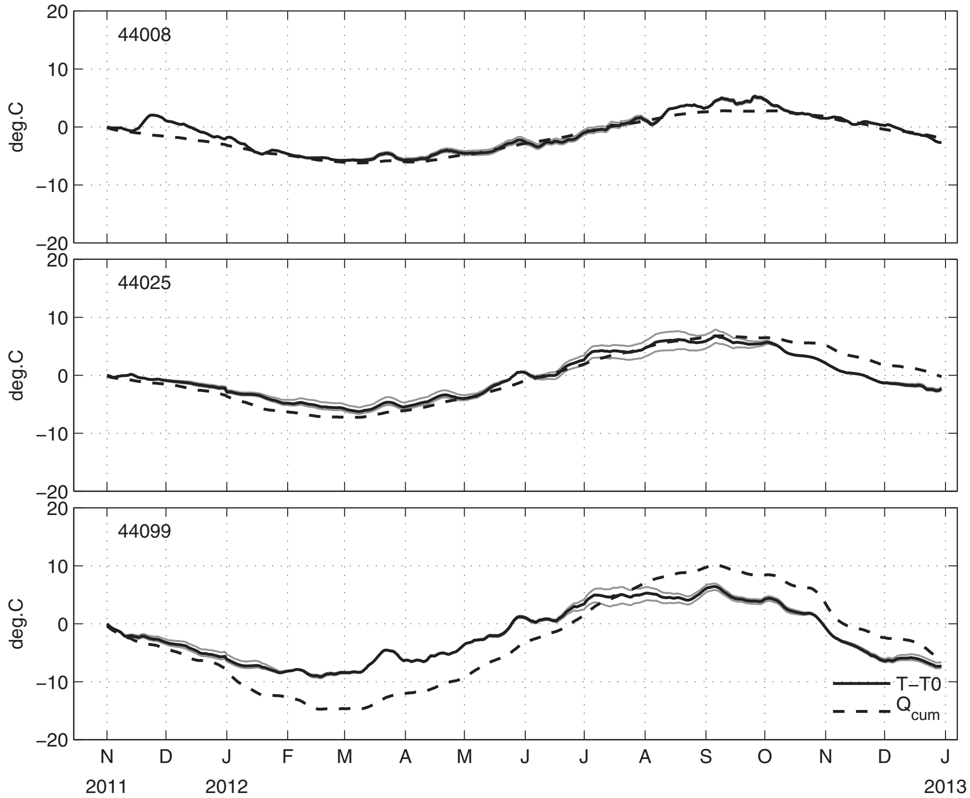

Figure 4. Depth-averaged temperature (solid) and cumulative heat flux (dashed) during late 2011 and 2012 at three buoys in the MAB. Gray curves represent the error range associated with the estimation of depth-averaged temperature. The mean bias of heat flux in the NCEP data set could be 5–10 W/m^2 low (negative bias) in the Middle Atlantic Bight (OAFlux group at WHOI, personal communication).

MAB. In general, the atmospheric forcing of the upper ocean includes both the net heat flux, net fresh water flux, and the wind stress. All three are potentially affected by meridional shifts in the position of the jet stream. During the late fall and winter of 2011–2012 (November 2011 to February 2012), the net atmospheric heat flux (downward into the ocean) over the GoM and the MAB was anomalously positive with a peak value up to 221 W m^{-2} (Figure 6), compared to the mean heat fluxes (about −200 to −100 W m^{-2} during November to February) during 2000–2010. The positive heat flux anomaly was closely connected to the anomalous northward shift of the jet stream, oscillating at a period of about 20–30 days. During this time, the shortwave and longwave radiation values were similar to the 2000–2010 means. However, the latent and sensible heat fluxes (downward into the ocean) were approximately 100 W m^{-2} larger, indicating the ocean was gaining more heat than usual. According to bulk flux formulas [e.g., *Fairall et al*., 1996], the upward latent heat flux, Q_L, and sensible heat flux, Q_S, are defined as:

$$Q_L = \rho_a L_E C_L U_{10}(q_s - q_a) \quad (4)$$

$$Q_S = \rho_a C_p^a C_S U_{10}(T_s - T_a) \quad (5)$$

where ρ_a is the air density (1.3 Kg m^{-3}); L_E is the latent heat of evaporation (2.5 × 10^6 J Kg^{-1}); C_L is the latent heat transfer coefficient (1.2 × 10^{-3}); U_{10} is the wind speed at 10 m above the sea surface; q_s and q_a are specific humidity of air at the sea surface and 10 m above the surface; C_p^a is the specific heat capacity of air (1030 J Kg^{-1}°C^{-1}); C_S is the sensible heat transfer coefficient (1.0 × 10^{-3}); and T_s and T_a are temperature at the sea surface and air temperature at 10 m above the sea surface. Analysis of U_{10}, T_a and q_a reveals that the wind speed was relatively weak during this cooling period (November 2011 to February 2012) while the air humidity and temperature were relatively higher than the mean condition (not shown). These anomalies decrease the latent and sensible heat fluxes from the ocean to the atmosphere and thus inhibit the total heat loss of the ocean. Indeed, at all four buoys from the GoM to Virginia Beach (44005, 44008, 44025, and 44099), the cooling rates during November 2011 to February 2012 were, respectively, 0.06°C d^{-1}, 0.08°C d^{-1}, 0.07°C d^{-1}, and 0.07°C d^{-1}, systematically smaller than 2000–2010 mean values of 0.07°C d^{-1}, 0.09°C d^{-1}, 0.10°C d^{-1}, and 0.10°C d^{-1}. Therefore, the anomalous atmospheric heat flux increased the heat content in the coastal ocean during the preceding winter of 2012. During March 2012 to May 2012, strong jet stream intraseasonal oscillations also induced a positive anomalous atmospheric heat flux, though not as large as that during the cooling period. With the development of stratification, the warming was not distributed evenly through the water column, which occurred during the winter, but was concentrated above the seasonal thermocline. Thus, the smaller heat flux anomalies could still drive large SST anomalies.

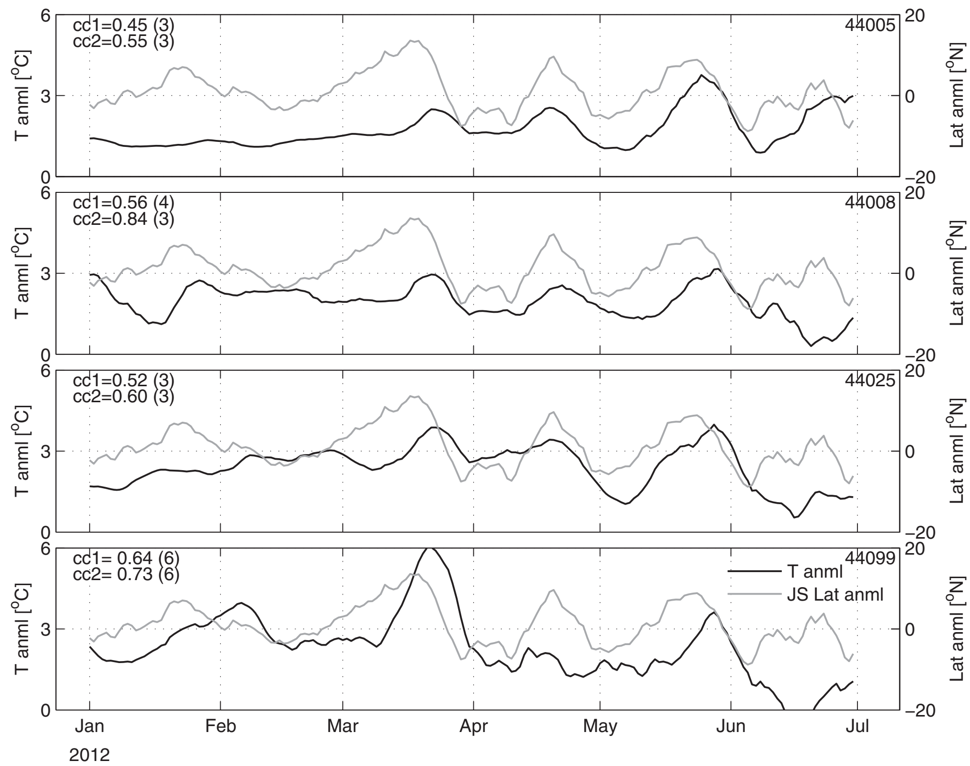

Figure 5. Correlation of buoy temperature anomaly (black) and jet stream latitude anomaly (gray) during the first half of 2012. Maximum lag correlation coefficients and lags (in days) corresponding to the maximum coefficients are shown (in parentheses), for January to June (cc1) and March to May (cc2), respectively.

[19] The wind stress anomalies also affect the SST changes. The total wind speed is inversely correlated with downward net heat flux (not shown) which is not surprising according to (4) and (5). Furthermore, considering the shallow water depth at three buoys, both the along-shelf wind and the cross-shelf wind are of dynamical importance to the cross-shelf advection [*Fewings et al.*, 2008; *Horwitz*, 2012], which would potentially change the advection term, $\int_{-H}^{0} \mathrm{u} \bullet \nabla \mathrm{T}' \mathrm{dz}$. We find that on an intraseasonal time scale, the coupling between cross-shelf wind (positive shoreward) anomaly and the jet stream latitude anomaly is inconsistent at three buoys in the MAB. The correlations between the jet stream latitude anomalies and cross-shelf wind anomalies during November 2011 to June 2012 are 0.59, 0.60, and 0.35, and decrease from Nantucket Shoals to Virginia Beach. In particular, during March to May 2012, the cross-shelf wind anomalies are not consistent at the three buoys. In comparison, the correlation coefficients between the net atmospheric heat flux anomaly and the jet stream latitude anomaly are 0.62, 0.50, and 0.48 (at Nantucket Shoals, Long Island, and Virginia Beach), and heat flux variations are consistent over the entire MAB during March to May 2012. The relatively weak coupling between the cross-shelf wind and the jet stream latitude contributes more to the net air-sea heat flux than the cross-shelf advective flux. The correlation between the along-shelf wind anomaly (positive poleward) and the jet stream latitude anomaly is weak, being 0.07, 0.21, and 0.40, from Nantucket Shoals to Virginia Beach. The orientation of the coastline varies within the MAB, so a uniform wind direction in the MAB will have different cross-shelf and along-shelf components. The variation of the meridional/northward wind, versus along-shelf or cross-shelf wind has a better correlation with the shift of the jet stream (0.53, 0.57, and 0.46 from Nantucket Shoals to Virginia Beach), but that does not systematically drive onshore advection of warm slope water. Thus, wind-driven advective flux is not responsible for the consistent intraseasonal oscillations of SST in the spring of 2012 over the entire region.

4. Discussion and Conclusion

[20] Using available in situ observations and reanalysis data, we diagnosed the warming event over the continental shelf in the MAB in the first half of 2012. Due to recent long-term warming trends, we chose the mean SST of 2000–2010 for comparisons to the SST anomalies in 2011–2012. The thermal anomalies would be even larger if compared to multidecadal means. Our presentation of the magnitude of warm conditions during 2012 is consistent with the NOAA ecosystem advisory that SST during the first half of 2012 over the continental shelf in the MAB was the highest in 150 years of measurements.

[21] XBT profiles are only shown in the upper 50 m to reduce the possible influence of migration of the foot of the shelf break front [*Linder and Gawarkiewicz*, 1998; *Chen and He*, 2010]. We note that the Oleander XBT data near

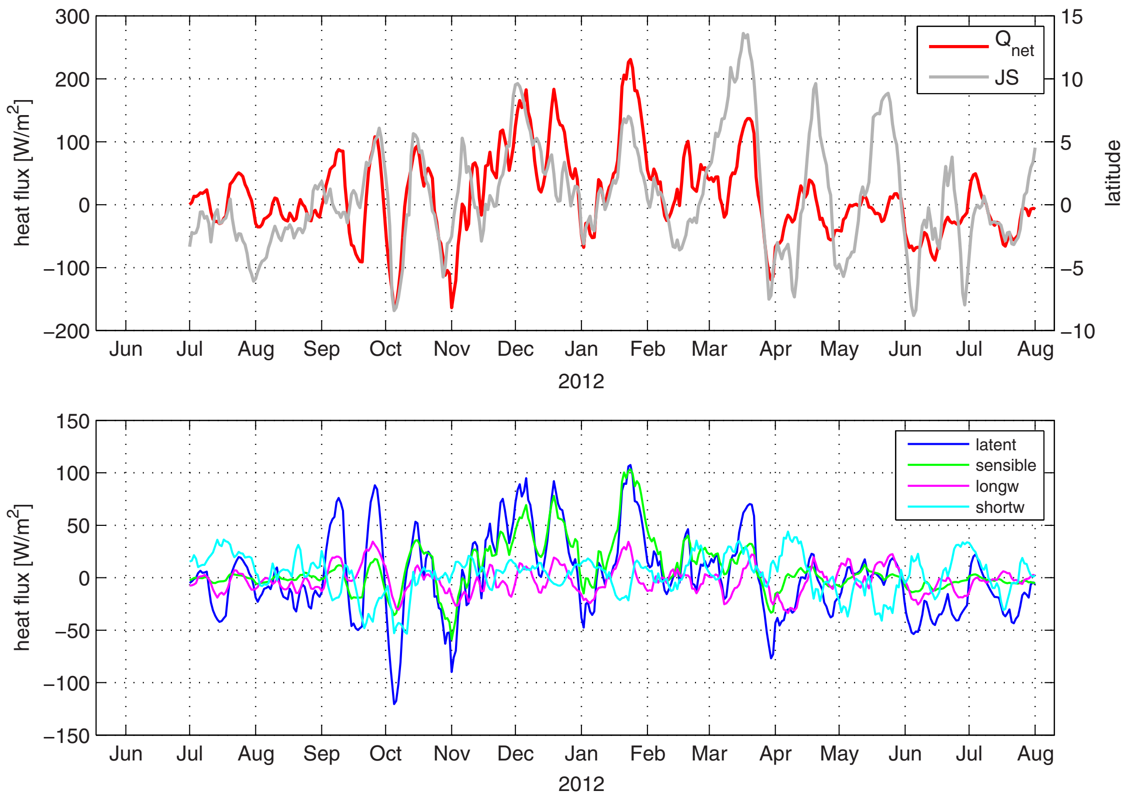

Figure 6. (top) The jet stream latitude anomaly (gray) during 2011–2012 and net atmospheric heat flux anomaly (red). (bottom) Different components of the air-sea heat flux, including latent heat flux (blue), sensible heat flux (green), longwave radiation (magenta), and shortwave radiation (cyan). The positive direction is defined as downward (into the ocean).

the New Jersey shelf break are not sampled consistently at the 100 m isobath each month. Temporal coverage varies from year to year as well, so temperature profiles are not available during each of these 6 months every year. These practical factors are unavoidable considering the sampling process, and they may add uncertainties to the profiles. Nevertheless, the profiles displayed in Figure 3 as well as other profiles at shallower depths indicate the warming signal extends through the water column and the anomaly is well represented by the overall shift of the temperature profiles before the development of the seasonal thermocline in May.

[22] Closing the heat budget is difficult in this study due to the lack of depth-dependent temperature data as well as current measurements. The estimation of depth-averaged temperature for 2011–2012 is largely dependent on the climatological SST and depth-averaged temperature relationship. This is generally valid for the seasonal scale but may not necessarily be true for short time scales. The overlap of Q_{cum} and $T - T_0$ at the Nantucket and Long Island buoys suggests the atmospheric heat flux largely controls the temperature change over monthly to seasonal scales. According to (1), the discrepancy between $T - T_0$ and Q_{cum} is due to horizontal advection. However, due to the uncertainties in estimating depth-averaged temperature, it is difficult to conclude that the short time scale departures between $T - T_0$ and Q_{cum} are entirely explained by oceanic advection. For an accurate estimate of the heat budget, full water column data along with continuous measurements of the currents and along-shelf and cross-shelf temperature gradients are necessary.

[23] In comparison, the link between the temperature anomaly and the jet stream related atmospheric forcing is more definitive. The anomalous northward shift of the jet stream during the winter of 2012 increased air temperature, and humidity, with oscillations occurring with periods around 20–30 days. These anomalies, together with relatively weak wind stress inhibited latent and sensible heat loss from the ocean from their typical winter values. Presumably strong vertical mixing during this period extended the temperature anomalies through the water column and thus increased the shelf-wide heat content. Strong jet stream intraseasonal oscillations during March 2012 to May 2012 systematically perturbed the shelf temperature from the GoM to Virginia Beach. The present analysis suggests that the ocean advective heat flux might be secondary during this extreme event. Further refinement of the heat budget will require focused numerical modeling studies to account for continental shelf and slope processes and their impact on advection of heat.

[24] The anomalous jet stream latitude in the cooling period of late 2011 and early 2012 clearly plays an important role in the warm anomalies. Based on the SST record at the Nantucket buoy (44008) since the 1980s, the relationship between the mean jet stream latitude and the mean SST during November to February is robust (Figure 7). Besides the anomalous 2012 condition, the relationship tends to be quasi

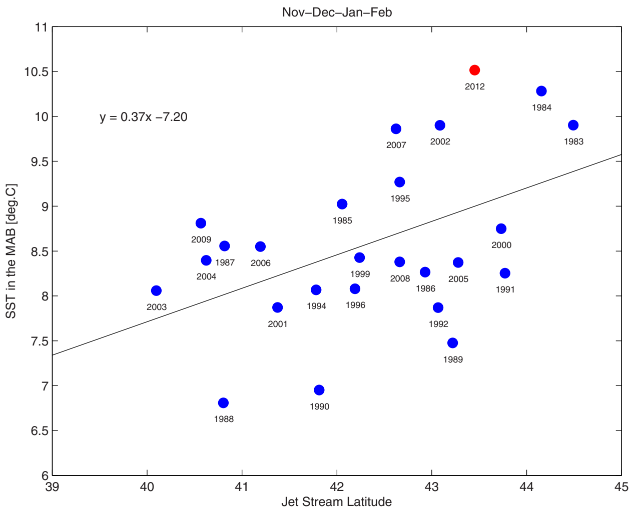

Figure 7. The mean jet stream latitude and the corresponding mean SST during the cooling season (November to February) at the Nantucket buoy (44008). Original data are available from 1983. For each year, data with a gap longer than 2 months are excluded from temporal averaging. The solid line represents the linear fit with the expression shown on the top left.

linear, in that more northern jet stream positions correlate to warmer SST near Nantucket. There is scatter in the interannual variability of the relationship and the extent to which the shift of wintertime jet stream latitude controls the sea surface temperature variability from year to year is worthy of future study. The quasi-linear relation shown in Figure 7 also suggests the seasonal time scale (4 month) connection between the jet stream latitude and SST in the coastal ocean in addition to the correlation on the intraseasonal time scale (20–30 days) presented previously.

[25] An important aspect of the large-scale atmospheric warming of the continental shelf is the large along-shelf scale in the ocean. *Shearman and Lentz* [2010] have shown that long-term variability of temperature anomalies is primarily a two-dimensional advective process rather than a one-dimensional process dominated by air-sea fluxes. For the advective processes, there is a time scale of months for signals to travel between the GoM and Cape Hatteras, rather than the concurrent shifts from the anomalous air-sea fluxes presented here. Further work is necessary to examine seasonal anomalies over the past several decades.

[26] An interesting factor in the warming is the northward diversion of the Gulf Stream in October 2011 [*Gawarkiewicz et al*., 2012; *Ezer et al*., 2013]. Bottom temperature measurements over the continental shelf south of New England indicate large temperature increases and thus the heat content of the continental shelf was increased. Further investigation of the role of this anomalous motion of the Gulf Stream is important in order to establish the heat content of the continental shelf before the anomalous atmospheric warming as well as the possible influence of anomalous SST over the continental slope in the late autumn affecting the overlying atmospheric circulation.

[27] Based on the limited observations from 2011 to 2012, a direct link was established between the jet stream variability and continental shelf temperature anomalies in the MAB for the first time. Due to the importance of the warming of ocean temperature to the marine ecosystem and commercial fisheries, further study of the links between jet stream variability and ocean temperature anomalies over a longer time scale are necessary, especially within the context of climate change in recent decades. Further study of this event is important for improving management of living marine resources during a time of rapid change in the coastal ocean, as discussed in *Mills et al*. [2013].

[28] **Acknowledgments.** K.C. was supported by the Woods Hole Oceanographic Institution Postdoctoral Scholarship, with funding provided by the Cooperative Institute for North Atlantic Region. G.G.G. was supported by grant N00014-11-1-0160 from the Office of Naval Research. S.J.L. was supported by the National Science Foundation under grant OCE-1154575. K.C. appreciates many insightful discussions and valuable suggestions from Young-Oh Kwon. The authors thank the NEFSC SOOP program (http://www.nefsc.noaa.gov/epd/ocean/MainPage/soop.html) and the AOML High Density XBT Transect Program (http://www.aoml.noaa.gov/phod/hdenxbt/index.php) for the XBT data. Constructive comments from three anonymous reviewers are much appreciated.

References

Bane, J. M., Y. H. Spitz, R. M. Letelier, and W. T. Peterson (2007), Jet stream intraseasonal oscillations drive dominant ecosystem variations in Oregon's summertime coastal upwelling system, *Proc. Natl. Acad. Sci. U. S. A.*, *104*(33), 13,262–13,267.

Barth, J. A., B. A. Menge, J. Lubchenco, F. Chan, J. M. Bane, A. R. Kirincich, M. A. McManus, K. J. Nielsen, S. D. Pierce, and L. Washburn (2007), Delayed upwelling alters nearshore coastal ocean ecosystems in the northern California current, *Proc. Natl. Acad. Sci. U. S. A.*, *104*(10), 3719–3724.

Brink, K. H., R. C. Beardsley, R. Limeburner, J. D. Irish, and M. Caruso (2009), Long-term moored array measurements of currents and hydrography over Georges Bank: 1994–1999, *Prog. Oceanogr.*, *82*, 191–223.

Chen, K., and R. He (2010), Numerical investigation of the Middle Atlantic Bight shelfbreak frontal circulation using a high-resolution ocean hindcast model, *J. Phys. Oceanogr.*, *40*, 949–964.

Emery, W. J., and R. E. Thomson (2004), *Data Analysis Methods in Physical Oceanography*, 654 pp., Elsevier, San Diego, Calif.

Ezer, T., L. P. Atkinson, W. B. Corlett, and J. L. Blanco (2013), Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast, *J. Geophys. Res.*, *118*, 685–697, doi:10.1002/jgrc.20091.

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson, and G. S. Young (1996), Bulk parameterization of air-sea fluxes for tropical ocean-global atmosphere coupled-ocean atmosphere response experiment, *J. Geophys. Res.*, *101*(C2), 3747–3764.

Fewings, M., S. J. Lentz, and J. Fredericks (2008), Observations of cross-shelf flow driven by cross-shelf winds on the inner continental shelf, *J. Phys. Oceanogr.*, *38*(11), 2358–2378.

Fogarty, M. J., and S. A. Murawski (1998), Large-scale disturbance and the structure of marine systems: Fishery impacts on Georges Bank, *Ecol. Appl.*, *8*(1), S6–S22.

Friedland, K. (2012), Ecosystem Advisory for the Northeast Shelf Large Marine Ecosystem, Advis. 2012, No. 2., Northeast Fishery Science Center, Woods Hole, Mass.

Gawarkiewicz, G., G. Lawson, M. Petruny-Parker, P. Fratantoni, and J. Hare (2013), *The Shelf Break Ecosystem off the Northeastern United States: Current Issues and Recommended Research Directions*, pp. 29, Coop. Inst. for the North Atl. Reg., Woods Hole, Mass. [Available at http://cinar.org/ fileserver.do?id=166024&pt=2&p=159709.]

Gawarkiewicz, G. G., R. E. Todd, A. J. Plueddemann, M. Andres, and J. P. Manning (2012), Direct interaction between the Gulf Stream and the shelfbreak south of New England, *Sci. Rep. 2*, 553, doi:10.1038/srep00553.

He, R., K. Chen, K. Fennel, G. Gawarkiewicz, and D. McGillicuddy (2011), Seasonal and interannual variability of physical and biological dynamics at the shelfbreak front of the Middle Atlantic Bight: Nutrient supply mechanisms, *Biogeosciences*, *8*, 2935–2946.

Horwitz, R. (2012), The effect of stratification on wind-driven, cross-shelf circulation and transport on the inner continental shelf, PhD thesis, 215 pp., Mass. Inst. of Technol., Cambridge.

Ji, R., C. Davis, C. Chen, and R. Beardsley (2008), Influence of local and external processes on the annual nitrogen cycle and primary productivity on Georges Bank: A 3-D biological-physical modeling study, *J. Mar. Syst.*, *73*(1–2), 31–47.

Lentz, S. J., R. C. Beardsley, J. D. Irish, J. Manning, P. C. Smith, and R. A. Weller (2003), Temperature and salt balances on Georges Bank February-August 1995, *J. Geophys. Res.*, *108*(C11), 8006, doi:10.1029/2001JC001220.

Linder, C., and G. Gawarkiewicz (1998), A climatology of the shelf-break front in the Middle Atlantic Bight, *J. Geophys. Res.*, *103*(C9), 18,405–18,423.

Loder, J. W., B. Petrie, and G. Gawarkiewicz (1998), The coastal ocean off northeastern North America: A large-scale view, in *The Sea*, vol. 11, edited by A. R. Robinson and K. H. Brink, pp. 105–133, Harvard Univ. Press, Cambridge, Mass.

Lott, F., A. W. Robertson, and M. Ghil (2004a), Mountain torques and Northern Hemisphere low-frequency variability. Part I: Hemispheric aspects, *J. Atmos. Sci.*, *61*, 1259–1271.

Lott, F., A. W. Robertson, and M. Ghil (2004b), Mountain torques and Northern Hemisphere low-frequency variability. Part II: Regional aspects, *J. Atmos. Sci.*, *61*, 1272–1283.

Marra, J., R. W. Houghton, and G. Christopher (1990), Phytoplankton growth at the shelf-break front in the Middle Atlantic Bight, *J. Mar. Res.*, *48*(4), 851–868.

Mills, K., et al. (2013), Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the Northwest Atlantic, *Oceanography*, *26*, 191–195, doi:10.5670/oceanog.2013.27.

O'Reilly, J. E., C. E. Evans-Zetlin, D. A. Busch, R. H. Backus, and D. W. Bourne (1987), Primary production, in *Georges Bank*, pp. 220–233, MIT Press, Cambridge, Mass.

Ryan, J. P., J. A. Yorder, and P. C. Cornillon (1999), Enhanced chlorophyll at the shelfbreak of Mid-Atlantic Bight and Georges Bank during the spring transition, *Limnol. Oceanogr.*, *44*(1), 1–11.

Shearman, R. K., and S. J. Lentz (2010), Long-term sea surface temperature variability along the U.S. East Coast, *J. Phys. Oceanogr.*, *40*, 1004–1016.