

Seasonal evolution of hydrographic fields in the central Middle Atlantic Bight from glider observations

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[1] The first sustained glider observations in the Middle Atlantic Bight are used to describe the seasonal evolution of hydrographic fields off New Jersey. Near-surface temperatures respond to the seasonal cycle of surface heating, while waters at depth are primarily influenced by advection of cold waters from the north in the cold-pool during spring/summer, and warming due to mixing during fall. The thermocline thickness increases in the offshore direction. Salinity presents seasonal variability due to river discharge and wind variations, with low-salinity waters spanning ~100 km across the shelf from May to September in a ~10 m thick surface layer. Stratification intensifies from April/May to late summer, especially within 80 km from the coast. The pycnocline deepens in the water column during late summer, while the passage of storms during fall rapidly reduces the stratification. The glider high-resolution observations allowed for unprecedented detailed characterization of the spatial scales of variability.

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1. Introduction

[2] The hydrography over the shelf in the Middle Atlantic Bight (MAB) undergoes a substantial evolution throughout the year. Previous studies [e.g., *Houghton et al.*, 1982; *Linder and Gawarkiewicz*, 1998] have shown that, during winter, the water column is nearly vertically homogeneous, with cross-shelf gradients dominating particularly near the shelfbreak. Vertical gradients are strong during summer, especially those associated with the seasonal thermocline at about 20 m, although remnants of the winter horizontal gradients are still present, particularly near the bottom [*Chapman and Gawarkiewicz*, 1993]. A band of cold water, usually referred to as the “cold-pool” [*Houghton et al.*, 1982], is commonly found below the thermocline over the middle and outer shelf.

[3] The majority of previous studies were based on either mooring [e.g., *Lentz et al.*, 2003] or relatively coarse conductivity-temperature-depth (CTD) observations [e.g., *Linder and Gawarkiewicz*, 1998]. Here, we use very high-resolution data to describe the seasonal evolution of temperature, salinity and stratification in the central MAB shelf. The use of gliders as observational platforms allowed for

shelf waters to be sampled frequently over long periods of time, with a total of 15902 CTD casts in 12 months. In addition, the high-resolution observations provide a better characterization of the spatial scales of variability than in the past.

2. Methods

[4] Repeated surveys over the shelf off New Jersey were conducted from late October 2003 to early November 2004, as part of the Rutgers University Glider Endurance Line (RUEL, Figure 1). During these 12 months, the RUEL was sampled 19 times. The surveys were composed of cross-shelf sections up to 130 km long, generally extending from the 20 to the 100 m isobaths. Hydrographic data were collected using a fleet of Webb Slocum Coastal Electric Gliders, which cycle from the surface to 3–5 m above the bottom while moving forward at an average speed of 24 km per day. Each transect takes approximately 4–5 days to be completed. Observations can adequately resolve seasonal variability, but high frequency variations (e.g., tides) are not fully resolved. All gliders are equipped with a Sea-Bird CTD instrument. Typical along-track resolution is about 200 m near the shelfbreak improving to about 100 m over the shallower regions. For each glider transect, a straight line is fit to the actual vehicle trajectory. Each variable is then averaged onto that line vertically to 1 dbar bins and horizontally to 2 km.

3. Results and Discussion

3.1. Seasonal Evolution of Hydrographic Fields

[5] Examples of hydrographic fields along the Endurance Line are shown in Figure 2. Salinity and temperature vertical gradients during fall are relatively weak. Temperature is nearly homogeneous in a surface layer, with slightly colder waters found near the bottom offshore. The salinity difference across the shelf is high, with low-salinity waters restricted to near the coast extending to the bottom. Salinity increases in the offshore direction. During winter, temperatures are lower than during fall, and also vary across the shelf, with colder water close to the coast, and warmer water near the shelfbreak. During that time, temperature increases with depth, especially in the offshore region. During spring and summer, the area influenced by low-salinity water is much larger, with the freshwater plume reaching almost 100 km from the coast. Salty intrusions near the shelfbreak at about the thermocline level (e.g., Figure 2, August 2004) are often found during this period [*Lentz*, 2003], and a detailed description of those is given by D. Gong et al. (Characterizing summer time shelf-slope exchange processes

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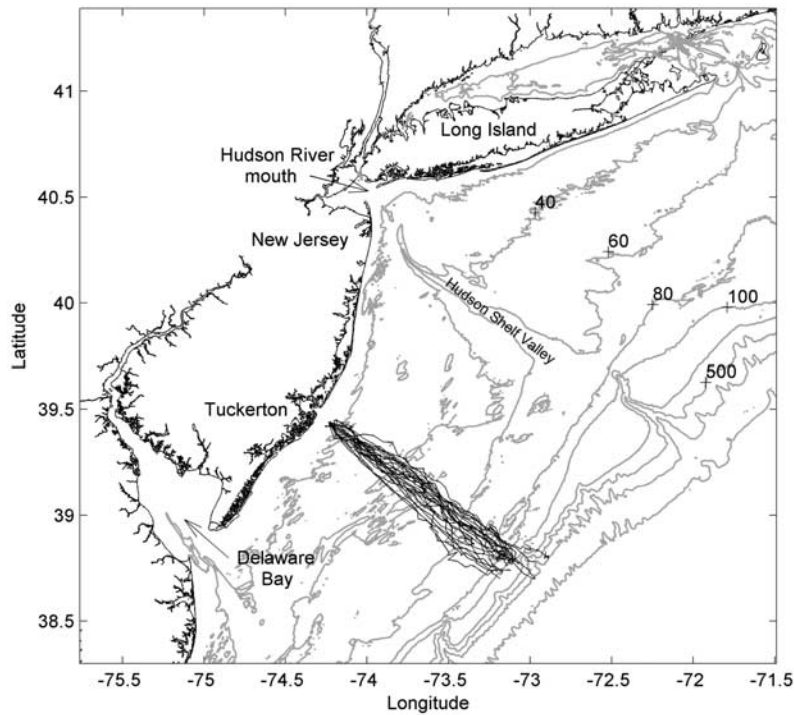


Figure 1. Study area showing glider tracks (black lines).

on the New Jersey shelf, submitted to *Limnology and Oceanography*, 2007, hereinafter referred to as Gong et al., submitted manuscript, 2007). Surface waters are also considerably warmer, and a strong thermocline is formed. The cold-pool is found in the offshore region at depth, with its core around 100 km from the coast. By early November 2004, the general characteristics are similar to fall 2003, and the vertical stratification is considerably reduced. The

temperature is almost homogeneous and surface salinities across the shelf are much higher than during summer, with the freshwater plume again confined to the coast.

3.2. Dominant Modes of Variability

[6] An empirical orthogonal function (EOF) decomposition of the temperature, salinity and buoyancy frequency squared $N^2 = (-g/\rho_0)\partial\rho/\partial z$ fields was performed in order to

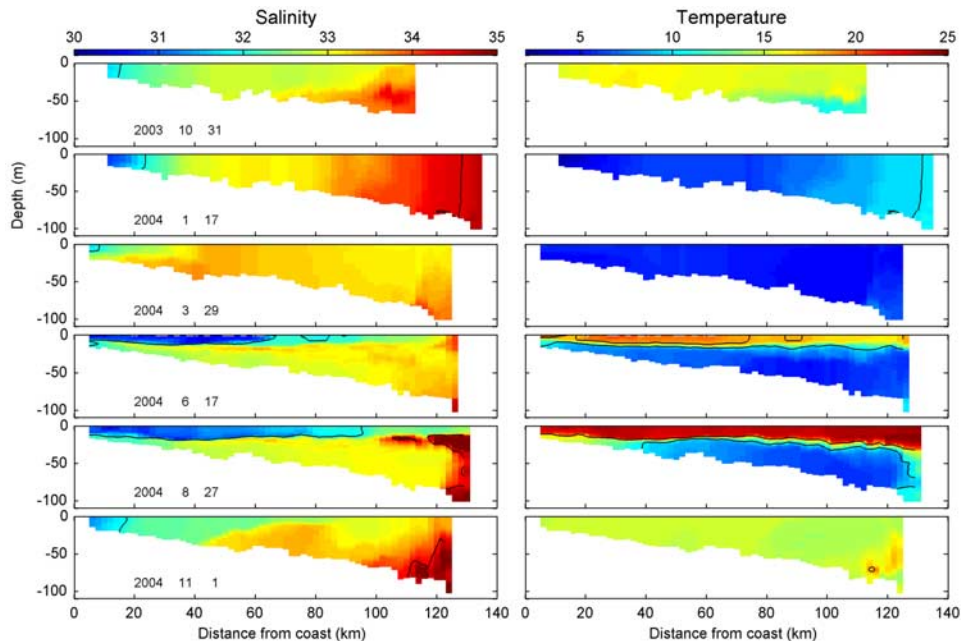


Figure 2. Salinity and temperature vertical sections of selected transects along the Endurance Line. The 32 and 34.5 (10°C and 18°C) salinity (temperature) contours are shown.

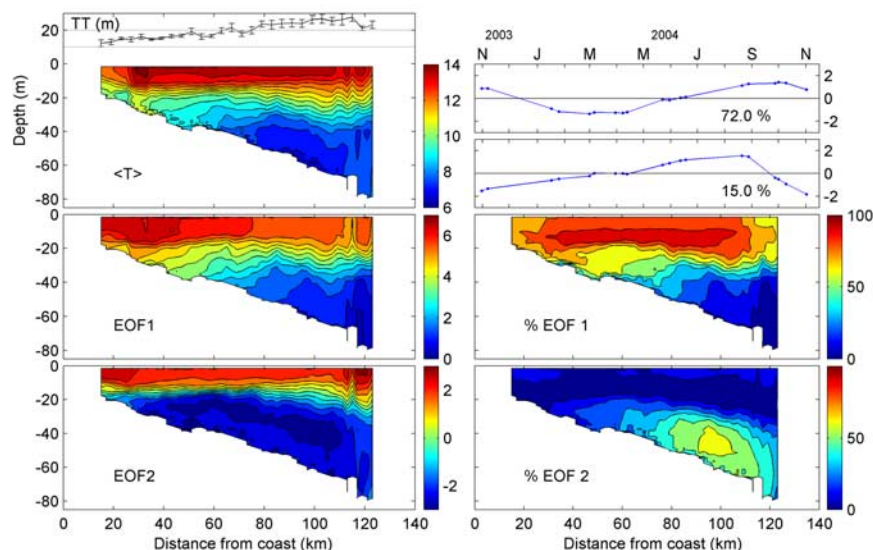


Figure 3. (left) Average, first, and second EOFs of temperature ($^{\circ}\text{C}$) along the Endurance Line. The average thermocline thickness (TT, in meters) over the stratified season is also shown. Error bars are ± 1 standard error of the mean. (right) Amplitude time series for modes 1 and 2 and the percentage of the local variance explained by each mode.

determine the dominant modes of variability. In the expression above, g is the acceleration of gravity, ρ is the density, and ρ_0 is a constant reference density. For each variable, the temporal mean at each bin was removed from the corresponding time series.

3.2.1. Temperature

[7] The average temperature (Figure 3) decreases with depth almost everywhere. The surface mixed layer is approximately 10–12 m thick. The characteristics below are very different across the shelf. The thermocline is about 12–15 m thick inshore of ~ 60 km from the coast with its center located above 20 m. Offshore of ~ 80 km from the coast, the thermocline is more diffuse (~ 25 m thick). The thermocline thickness (TT) was computed for each individual section, and then averaged over the stratified season (late May to early October). TT was defined as the continuous region where the vertical temperature gradient is at least 30% of the maximum value at the center of the thermocline. Tests fixing the cutoff at 40% or 50% produced qualitatively similar results. The difference in thickness across the shelf may be due to increased stratification close to the coast due to the presence of freshwater, which helps trap the solar heating near the surface, and to more intense mixing in the offshore region (e.g., due to internal tides). The cold-pool is found below the thermocline between 70 and 110 km from the coast.

[8] The first EOF explains 72% of the total variance, and is related to the seasonal cycle of surface heating. It explains most of the variance in the upper water column across the shelf (more than 70% in the top 30 m), decreasing in importance below. The spatial mode is positive everywhere, with higher values near the surface and with little variation in the cross-shelf direction for a given depth. The exception are the higher values found within 50 km from the coast near the surface that are presumably associated with freshwater plumes found during spring/summer (see Figure 2). The amplitude time series is symmetric, indicating warming

from April to mid-September, and cooling from October to March.

[9] The second EOF exhibits a zero crossing at about 15 m. It is characterized by horizontally uniform positive values near the surface, and by negative values at depth, especially between 50 and 110 km from the coast. It explains 15% of the total variance, but up to 60% of the local variance at depth at the offshore half of the section, where the outer edge of the cold-pool is found. The amplitude time series increases steadily from November 2003 to sometime between late June and late August 2004 (there is a 2-month gap in the data record during that period). Since the EOF is negative at depth at the offshore half of the section, this mode represents a continuous cooling of water during that period, with the coldest water being found during summer. This is in agreement with results from *Houghton et al.* [1982], who observed that, south of the Hudson Shelf Valley, cold-pool temperatures decrease during summer as colder water from the north is advected southwestward along the coast. During winter, the cooling at depth extracted by the second EOF might be, at least partially, due to mixing with surface cold waters. During spring and summer, however, the surface layer is already warmer, so the cooling at depth must be balanced by advection. During mid-April to mid-August 2004, the mode represents a cooling of about 4°C at depth and, therefore, the rate of cooling is approximately $3.86 \times 10^{-7} \text{Cs}^{-1}$. The Marine Resources Monitoring Assessment and Prediction (MARMAP) program observations [*Houghton et al.*, 1982] show a 1.5°C near-bottom temperature difference along the New Jersey outer shelf (~ 170 km, cooler to the north) in May 1979. Estimations based on climatology (C. G. Law and J. A. Quinlan, unpublished data) also reveal a similar average gradient, with an 8°C near-bottom temperature difference between Cape Cod and Cape Hatteras (~ 900 km) in May/June. Therefore, for advection to balance the local cooling extracted by mode 2, the average alongshore velocity must

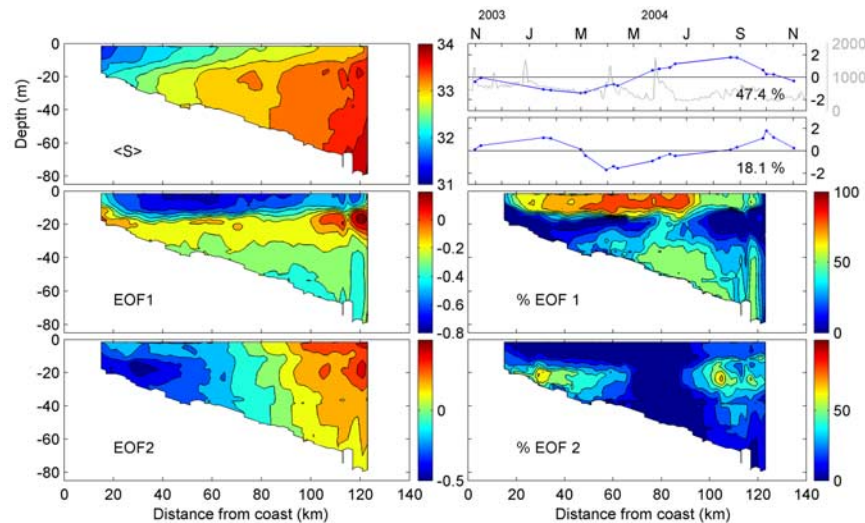


Figure 4. Same as in Figure 3, except for salinity. The Hudson River discharge (m^3s^{-1} gray line) is shown in the amplitude time series panel.

be southwestward at about $0.04\text{--}0.05\text{ ms}^{-1}$, which is consistent with the mean flow in the MAB [Beardsley *et al.*, 1985].

[10] The amplitude time series of the second mode is asymmetric. While the cooling at depth occurs over 8–10 months, the warming occurs very rapidly, in September and October. The rapid warming at depth is a result of storm events in the MAB, which help mix the water column, decreasing the temperature near the surface and the vertical gradients. Indeed, during late September 2004, the passage of Hurricane Ivan led to a substantial cooling of the upper water column. A detailed description of the effects of storms on hydrographic fields in the region is presented by Gong *et al.* (submitted manuscript, 2007). Note that the amplitude time series of the first mode is high during September, suggesting that convective overturning due to surface cooling is not the primary reason for the decrease in the thermal stratification observed in mode 2 during that period. This is in agreement with results from elsewhere in the MAB [Lentz *et al.*, 2003].

3.2.2. Salinity

[11] The average salinity increases in the offshore direction off New Jersey (Figure 4). Waters close to the coast are more heavily influenced by the Hudson River outflow, while the offshore region is more heavily influenced by salty slope waters.

[12] The first EOF exhibits negative values almost everywhere in the water column. Maximum magnitudes are found in a 10–12 m thick near-surface layer, extending from 20 to 100 km from the coast. This mode represents the seasonal widening of the region influenced by freshwater delivered by the Hudson River, explaining more than 70% of the variance in the surface layer. The amplitude time series increases from April to late summer, representing a decrease in surface salinity across the shelf of as much as 1.2. This widespread decrease is related to the increase in the Hudson River discharge that occurs in spring (peaks in early April and late May 2004) and to persistent upwelling-favorable winds (from mid-April to early September) that advect freshwater offshore from the coastal current in a

surface Ekman layer [e.g., Fong and Geyer, 2001]. In addition to Ekman transport, a jet directed offshore and to the south, from near the Hudson River mouth toward the offshore half of the sections is often present during summer, and was shown to play an important role in the cross-shelf transport of freshwater in the region [Castelao *et al.*, 2008]. The near-surface salinity increases from September on, since the river discharge is small in the preceding months and winds become predominantly downwelling-favorable. The freshwater previously over the shelf is exported from the region.

[13] The second mode is related to variability in the cross-shelf salinity gradient. It exhibits negative values near the bottom inshore of ~ 50 km from the coast, and a lateral gradient offshore of that. The amplitude time series is positive during winter, indicating a decrease in the near-bottom salinity close to the coast. During that time, isohalines are more vertical, as the freshwater plumes are in contact with the bottom and enhanced mixing (e.g., due to storms) help to increase the vertical homogeneity. In addition to explaining 30–40% of the variance in this nearshore region, the mode also explains a similar percentage of the variance at mid-depth at ~ 100 km from the coast. There, the mode is related to top-to-bottom increases in salinity during fall and winter (see, e.g., Jan 2004, Figure 2), perhaps associated with migrations in the position of the shelfbreak front. Climatological observations show that the foot of the front is over shallower waters during those seasons [Linder and Gawarkiewicz, 1998]. During spring, the amplitude time series is negative, indicating a decrease in the salinity cross-shelf gradient.

3.2.3. Buoyancy Frequency

[14] Consistent with results discussed in the previous sections, the averaged buoyancy frequency squared reveals a cross-shelf gradient in the intensity of the pycnocline (Figure 5). The stratification is stronger within 80 km from the coast, probably due to the influence of low-salinity water from the Hudson River, which also helps trap the surface heating in a thin surface layer further increasing its buoyancy. The offshore half of the section presents a weaker and more diffuse pycnocline. This is often observed in

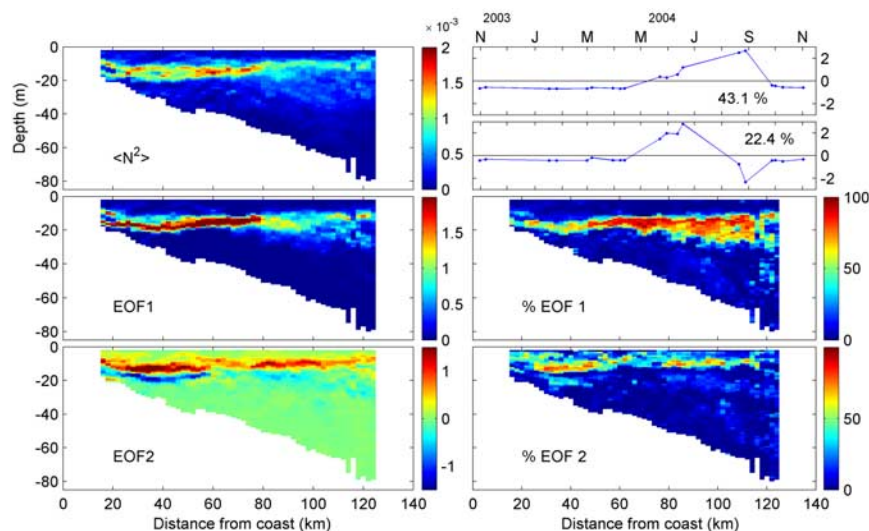


Figure 5. Same as in Figure 3, except for buoyancy frequency squared (s^{-2}).

individual sections during the stratified season, and is not a result of the averaging process.

[15] The first EOF is similar to the average. The amplitude time series is negative during winter and early spring 2004, indicating that stratification is very weak. From mid-April/mid-May on, the stratification increases continuously until late summer. The stratification is rapidly destroyed during September, presumably due to the effect of storms (e.g., Hurricane Ivan). This mode explains about 70% of the local variance at the pycnocline (43.1% of the total variance).

[16] The second EOF presents a zero crossing at about 15 m, and is related to the position of the pycnocline in the water column. During spring and early summer, the mode represents stronger stratification between 10 and 15 m, and weaker between 15 and 20 m, i.e., a shallow pycnocline. During late summer, the amplitude time series becomes negative, indicating a deepening of the pycnocline. The mode explains about 30% of the variance at the pycnocline level, with a few isolated patches reaching $\sim 60\%$.

4. Summary and Conclusions

[17] The seasonal evolution of hydrographic fields off southern New Jersey is examined using the first sustained glider observations in the region. The use of gliders provides observations with very high spatial resolution and with good temporal coverage. A total of 15902 casts were obtained during 12 months, a number much higher than typically obtained by conventional research cruises.

[18] The observations reveal strong seasonal variations in all fields. Surface salinity variations are related to the variability in the Hudson River discharge and the wind forcing. During the upwelling season, a thin, ~ 10 m thick surface layer of low-salinity water extends for ~ 100 km from the coast. Temperature variations in the upper 30 m are related to variations in surface heating, while variations at depth are consistent with advection of colder waters from the north during spring/summer and with mixing during fall. The thermocline thickness doubles in the outer shelf compared to regions inshore of the 40 m isobath. The stratification exhibits an asymmetric evolution, becoming slowly

stronger from mid spring to late summer, and being rapidly destroyed during early fall, presumably due to the passage of storms. From early to late summer, the pycnocline also deepens in the water column.

[19] The general characteristics of the seasonal evolution of the fields in the MAB are already known. The high-resolution observations, however, allowed for an unprecedented characterization of the scales of variability in detail (how thick and wide the surface freshening is during spring and summer, for example). Repeating the analyses presented here, but using observations sub-sampled at a resolution typical of previous studies (7 CTD casts from the coast to the 80-m isobath, 5 transects per year) show the same general characteristics. However, the timing of several phenomena (e.g., peaks of stratification and surface freshening during summer) can be off by up to a few months, and sharp transitions (e.g., decrease in stratification during fall) are smeared over several months. Some processes (e.g., deepening of the pycnocline) are missed completely, while others, although partially captured, are represented with incorrect spatial and temporal scales (e.g., freshening of surface layer during summer is restricted to within 60 km from coast, rather than extending the entire shelf width). This demonstrates the usefulness of gliders when a coastal transect is occupied repeatedly.

[20] **Acknowledgments.** We thank the Rutgers University Coastal Ocean Observation Laboratory for the highly successful glider operations. This research was supported by ONR (grants N000140610283 and N000140610739) and NSF (grant OCE 0238957). The observatory data used were supported by ONR, NSF, NOAA, NOPP, DHS, DoD, and the State of NJ.

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