

Mean circulation in the coastal ocean off northeastern North America

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Mean circulation in the coastal ocean off northeastern North America from a regional-scale ocean model

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Abstract

A regional-scale ocean model was used to hindcast the coastal circulation over the Middle Atlantic Bight (MAB) and Gulf of Maine (GOM) from 2004 to 2013. The model was nested inside a data assimilative global ocean model that provided initial and open boundary conditions. Realistic atmospheric forcing, tides and observed river runoff were also used to drive the model. Hindcast solutions were compared against observations, which included coastal sea levels, satellite altimetry sea surface height, temperature and salinity time series in the GOM, glider transects in the MAB, and observed mean depth-averaged velocities by Lentz (2008a). Good agreements with observations suggest that the hindcast model is capable of capturing the major circulation variability in the MAB and GOM. Time- and space-continuous hindcast fields were used to depict the mean circulation, along- and cross-shelf transport and the associated momentum balances. The hindcast confirms the presence of the equatorward mean shelf circulation, which varies from 2.33 Sv at Scotian Shelf to 0.22 Sv near Cape Hatteras. Using the 200 m isobath as the shelf/slope boundary, the mean cross-shelf transport calculations indicate that the shelfbreak segments off the Gulf of Maine (including the southern flank of Georges Bank and the Northeast Channel) and Cape Hatteras are the major sites for shelf water export. The momentum analysis reveals that the along-shelf sea level difference from Nova Scotia to Cape Hatteras is about 0.36 m. The nonlinear advection, stress, and horizontal viscosity terms all contribute to the ageostrophic circulation in the along-isobath direction, whereas the nonlinear advection plays a dominant role in determining the ageostrophic current in the cross-isobath direction.

1 Introduction

The northeastern coast of North America borders the Atlantic Ocean, with a continental shelf extending over 5000 km. For our purpose, we focus on the coastal segment between Cape Hatteras in the southwest and Nova Scotia in the northeast (Fig. 1).

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frontal meandering (Garvine et al., 1988; Gawarkiewicz et al., 2004) and topography and channels (e.g., Churchill et al., 1986; Ramp et al., 1985) also significantly affect the shelf–ocean exchange.

Quantifying along-shelf transport and cross-shelf exchange and their seasonal variations in this area is the key to understand and quantify the distribution of material properties, such as heat, salt, nutrient and carbon fluxes, that are vital to MAB-GOM coastal ecosystem dynamics (e.g., Walsh et al., 1988). Although several long-term records of coastal current measurements have been obtained over the study area, the different conditions during the observational periods made it difficult to reach a consistent conclusion on spatial and temporal variations of shelf circulation. For instance, the seasonal reversal of the slope current observed in the Nantucket Shoals Flux Experiment (NSFE79) (Beardsley et al., 1985) was not apparent in the Shelf Edge Exchange Processes (SEEP-I) experiment (Aikman et al., 1988). Those one or two year long records are too short to compute an accurate annual mean and seasonal cycle, or to study the interannual variations. In this regard, an important step forward was made recently by Lentz (2008a). Utilizing 33 historical velocity time series from the MAB, each being longer than 200 days, this study confirmed a consistent equatorward mean circulation over the MAB continental shelf. The mean cross-shelf flow is typically offshore near the surface and onshore at depth. Near the bottom, the cross-shelf flow increases with increasing water depth from coast to shelf slope, with the change in direction at the 50 m isobath. Furthermore, Lentz (2008b) studied the shelf circulation seasonal variation using a subset of the same velocity data, and identified significant variations in the along-shelf circulation, which is related to seasonal variations in the wind stress and the cross-shelf density gradient. Although observations presented in these two recent studies provide a remarkably consistent picture of MAB circulation, Lentz (2008a) also noted that the spatial coverage of the current observations is still very sparse and uneven. While the results suggest the important roles of along-shelf pressure gradient and bottom stress, direct measurements are very difficult to achieve due to large observational uncertainties. In an effort to understand the origin of the along-shelf pres-

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In addition, fresh water (salinity = 0 unit) outflow from nine major rivers in the MAB-GOM area was considered (Fig. 1). These include the St. Johns, Penobscot, Kennebec, Androscoggin, Merrimack, Connecticut, Hudson, Delaware, and Potomac Rivers. For each, the transport was specified using the volume time series measured by a river gauge from United State Geological Survey (USGS).

We started the MABGOM model hindcast on 1 November 2003 and ran the simulation continuously until 31 December 2013. Initial hydrodynamic conditions for the hindcast were taken from bias-adjusted HYCOM/NCODA fields on 1 November 2003.

3 Results

Standard circulation state variables (sea level, currents, temperature, and salinity) were archived daily. Animations of modeled sea level, surface current, surface temperature and salinity fields display complex spatial and temporal variability, highlighting the synergy of using realistic model simulations in conjunction with in situ observations to study coastal ocean processes. For model validations and analyses described below, we concentrated on the ten full years of model hindcast solutions spanning from 1 January 2004 to 31 December 2013.

3.1 Model validation

3.1.1 Coastal sea level

Because the material property transport in the coastal region is largely determined by sub-tidal circulation, we focus on examining the model's fidelity in reproducing sub-tidal variability. Point-by-point sea-level comparisons were made at five coastal tide gauges that can be resolved by MABGOM model grid resolution (Fig. 3). For clarity, the high-frequency variability was removed from both modeled and observed 10 year long sea level time series with a 10 day low-pass filter. Direct comparisons show the model is able to resolve sea level variations reasonably well through the course of simulation. At

the 95 % confidence level, the correlation coefficients between the two are above 0.40 at all these stations. Both wind-driven Ekman dynamics (Gill, 1990) and continental shelf wave dynamics (Brink, 1991) dominate coastal sea level variations. The model-data agreements in coastal sea levels suggest the model is faithfully capturing these dynamics.

3.1.2 Satellite altimeter data

The model skill in reproducing the shelf-wide sea surface height (SSH) distribution can be examined by comparing to satellite altimeter data. Although altimetry observations have large uncertainties nearshore due to problems such as tidal aliasing, they constitute extremely valuable observations of sea level for the outer shelf and deep-sea regions. We downloaded $1/3^\circ \times 1/3^\circ$ absolute SSH product from the French Archiving, Validation and Interpolation of Satellite Oceanographic Data [AVISO] (Rio and Hernandez, 2004) and mapped them for the MABGOM region. Because the temporal interval of AVISO data is one day, MABGOM model SSH solutions (averaged over M2 tidal cycle, ~ 12.42 h) were sampled at the times when altimeter data were available. The respective SSH standard deviations (SD) were then computed to quantify their corresponding sea level variability. SSH SD comparisons (Fig. 4) reveal that the MABGOM model underestimates the magnitude of observed sea level variations, but captures its spatial distribution very well. Both AVISO and ROMS indicate that large SSH SD with a magnitude of up to about 0.4 m are present in the Slope Sea. This is the region where energetic meanders and eddies often occur, exerting a strong offshore influence on the MABGOM shelf circulation (Joyce et al., 1992).

3.1.3 Mooring data

We next examined the model with hydrographic data observed by moorings of the Northeastern Regional Association of Coastal Ocean Observing System (NERACOOS, <http://www.neracoos.org>). Most of the NERACOOS mooring data cover the

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approximately along-isobath. For a direct comparison, we used detided output of the MABGOM model, sampled the simulated depth-average currents at the same mooring locations and averaged them over the 10-year simulation duration. This comparison (Fig. 7) shows the MABGOM model captures the uniformly southwestward motions at all 14 mooring sites. Both the observation and model show that the largest mean current is off Georges Bank, moving at 0.1 ms^{-1} . The smallest current is nearshore by Delaware Bay, moving at about 0.03 ms^{-1} . Differences in speed and direction are present for each pair of velocity comparisons. This is in part due to the model resolution. Overall, it is encouraging to see that the model is capable of reproducing the mean shelf circulation structure correctly.

3.2 Mean circulation

Given that the MABGOM model hindcast can produce a credible shelf circulation hindcast, we next use the space- and time-continuous model solutions to depict the domain-wide mean circulation fields. As discussed earlier, model-simulated state variables were temporally averaged from 1 January 2004 to 31 December 2013 to calculate the mean circulation.

3.2.1 Mean circulation fields

The temporal means and SD of near surface (vertical layer 36), near bottom (vertical layer 2), mid-depth (vertical layer 18) and depth-averaged velocity fields, along with their respective SD, highlight the spatial complexity of MABGOM shelf circulation (Fig. 8). Three-dimensionality arises from geographic factors such as blocking by capes, coastal changes, and nearshore penetration of deep isobaths, as well as from the effects of baroclinicity and surface and bottom Ekman layers. The mid-depth and depth-averaged velocity fields are similar, showing the general nature of the mean currents exclusive of the Ekman layer effects.

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MABGOM model-simulated mean surface currents (Fig. 8a) are consistent with the present knowledge of regional oceanography. Known circulation features are well represented, including inflow from the Scotian Shelf, cyclonic circulation in the GOM, anticyclonic circulation on Georges Bank, and equatorward (southwestward) mean shelf flow over the MAB. Also visible is the region near Cape Hatteras where southwestward-moving MAB shelf waters converge with northward moving South Atlantic Bight (SAB) and Gulf Stream (GS) waters. While there is a clear GS flow axis, abundant meso-scale eddy fields strongly perturb its mean velocity state. The SD of the velocity field are greatest in the GS/Slope Sea and shelf break area, where meanders, eddies, and cross-shelf exchanges cause 20–50 % fluctuations in speed.

The mean bottom current map (Fig. 8b) shows that velocities are much weaker than surface velocities, which is probably due to bottom friction. Additionally, in contrast to the northward-moving GS surface flow, the bottom flow beneath the GS is moving equatorward. This is part of the deep western boundary current that constitutes the lower limb of the Atlantic Meridional Overturning Circulation (e.g., Hogg, 1983; Pickart and Smethie, 1993).

The depth-averaged current field (Fig. 8d) is similar to the mid-depth (layer 18) current field (Fig. 8c), and shows a clear cyclonic gyre in the Slope Sea between the shelfbreak and the GS. This circulation feature is consistent with the concept of a “slope water gyre”, which was first proposed by Csanady and Hamilton (1988) based on observational analyses.

3.2.2 Mean velocity and thermohaline structure

Mean shelf temperature, salinity, and velocity were sampled along five cross-shelf transects (Fig. 9) off Cape Cod, Long Island, New Jersey, Maryland and Cape Hatteras/North Carolina (see locations in Fig. 1). For illustration purposes, the mean velocity fields were rotated into the normal and tangential directions of each transect, precisely reproducing alongshore and cross-shelf velocity components.

is consistent with both theoretical model results of (Lentz, 2008a) and drifter trajectory observations of Bumpus (1965). We also note that near the shelf break there is a convergence of seaward shelf flow and shoreward deep ocean flow. A similar bottom divergence pattern is also seen off New Jersey and Maryland transects at ~ 50 m isobath, albeit with much weaker magnitude. Interested readers are referred to (Lentz, 2008a) for the theoretical reasoning on why the bottom divergence occurs.

4 Discussion

4.1 Mean mixed layer depth

The ocean mixed layer depth (MLD) is an important parameter that accounts for upper ocean physical and biological properties, air–sea interaction, and long-term climate change. Given that the MABGOM is a coastal region supporting many important biogeochemical processes and experiencing climate regime shifts (Greene and Pershing, 2007), we used the model hindcast fields to estimate the mean MLD for the region. We followed the approach of Monterey and Levitus (1997) and defined the MDL as the physical depth at which the ambient temperature within a profile is within 0.5°C of the sea surface temperature (Fig. 10). It is noted that MLD cannot be identified in regions with strong tidal mixing, such as the Bay of Fundy and Georges Bank, and some shallow estuaries. For most coastal and Slope Sea areas, the MLDs are 10–15 m. MLDs are deeper in the GS and offshore basins of the Gulf of Maine, with typical values of 30–50 m. The mean MLD distribution exhibits some high-resolution details, but the overall features are largely consistent with the coarse resolution (1° × 1°) World Ocean Atlas (not shown). Embedded in this long-term mean are strong seasonal variations in the MLD fields, discussions of which are left for a future correspondence.

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4.2 Mean transport

Quantifying the alongshore transport between different coastal segment and the cross-shelf exchange between the shelf sea and the Slope Sea have been long-term objectives of regional circulation studies (e.g., Beardsley and Boicourt, 1981; Fratantoni et al., 2001; Loder et al., 1998; Lozier and Gawarkiewicz, 2001). With space- and time-continuous circulation hindcast fields, we can explore this problem from a numerical modeling perspective. We first divided the 200 m isobath that defines the shelf-slope boundary into seven segments from North Carolina to Nova Scotia. Transports cross this isobaths were used to assess water exchange between the MAB-GOM coastal sea and the Slope Sea. Every segment is 200 km long except the Georges Bank to Scotian Shelf Segment, which is 600 km long to include the entire seaward perimeter. We then selected in the model domain from north to south seven cross-shelf transects, extending from the coast to the 200 m isobaths, to calculate the along-shelf transport.

Simulated 3-D velocity fields were rotated into the normal and tangential components based on the local orientations of each transect and segment. The normal component of velocity U_N was then integrated with local depth z and local transect/segment length s to compute the volume transport according to:

$$Q = \int_0^{s_o} \int_{-H}^{\eta} u_N(s, z) ds dz \quad (3)$$

We calculated both mean transport values and their SD over the 10 year simulation. Together these values constitute a mean volume budget estimate for the MABGOM coastal ocean (Fig. 11).

In the along-shelf direction, the mean transport values experience a gradual downstream reduction, decreasing from 2.33 Sv along the Nova Scotia transect to 0.52 Sv along the Cape Cod transect, and further to 0.22 Sv along the North Carolina transect. The results here are largely consistent with volume estimates by Lentz (2008a)

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and the “leaking” shelf concept proposed by Lozier and Gawarkiewicz (2001). SD of these along-shelf mean transport values are of the same order of magnitude, implying along-shelf flow reversals are possible subject to different local (e.g., wind) and open ocean forcing scenarios. For instance, both satellite observations and MABGOM model model simulations (not shown) indicate a large warm-core eddy impinged upon the MAB shelfbreak in summer 2006, resulting in strong northeastward shelf current during that period (Chen et al., 2014).

Volume variations of the along-shelf transport are balanced by cross-shelf water mass exchanges. Over the 10 year analysis period, the mean cross-shelf transports across the 200 m isobath were seaward. In particular, the mean cross-shelf transports off Cape Hatteras and the Gulf of Maine are much larger than others, signifying they are important sites for shelf water export. In the MAB, the cross-shelf transports are smaller, but exports at the southern New England and New Jersey/Delaware shelf break are larger. On average, a total of 3.03 Sv of coastal water is transported from the shelf to the open ocean.

It is worth noting that these cross-shelf transports are characterized by very small means and significantly larger SD. These SD are at least an order of magnitude larger than the means, suggesting highly variable shelf/deep ocean exchange processes are at work. Presumably, such exchanges are closely related to eddy activities that often occur in these areas. Measuring the cross-shelf transport at these locations will therefore be very challenging. A carefully designed observational array is needed to resolve circulation variability in order to achieve statistically robust in situ transport measurements.

4.3 Mean dynamical balances along the 200 m isobath

To further understand the circulation dynamics associated with transport across the 200 m isobath, we performed term-by-term depth-averaged momentum balance analysis. Each momentum term was averaged over the entire 10 year model analysis period.

They were interpolated onto the 200 m isobath, and then rotated into the along- and cross-isobath directions according to local bathymetric orientation.

One immediate estimate this allowed us to make is the mean sea level gradient along the 200 m isobath, which can be computed according to:

$$\frac{\Delta\eta}{\Delta L} = -\frac{1}{gS} \int_0^S \left(-\frac{1}{\rho} \frac{\partial P}{\partial l} \right) dl = 2.24 \times 10^{-7} \quad (4)$$

where $\partial P/\partial l$ is the temporal mean pressure gradient from the model, and S is the along-isobath distance of the 200 m isobath in the domain. This sea level gradient is consistent with the value estimated by Xu and Oey (2011), which reported a slope of 4.8×10^{-8} with a range of 10^{-7} , and is also consistent with the estimate by Zhang et al. (2011), which is $0.2\text{--}2.5 \times 10^{-7}$. It is equivalent to a 0.36 m mean sea level difference over the 1600 km distance from the Nova Scotia shelf to the North Carolina shelf, arguably contributing to the equatorward mean shelf circulation.

As expected, geostrophy dominates the dynamical balance in both the along- and cross-isobath directions. The residue of the pressure gradient term plus the Coriolis term constitutes the ageostrophic component, which is responsible for smaller-scale circulation variability in the study domain. Contributions to the ageostrophic component come from the nonlinear advection term, surface and bottom stress terms, and horizontal viscosity term, as presented together in Fig. 12. In both the along- and cross 200 m isobath directions, the ageostrophic term is largely balanced by nonlinear advection. This is especially the case off Cape Hatteras and Georges Bank, where currents are very energetic. Compared to advection, the combined contribution of horizontal viscosity and stress (the sum of surface and bottom stress) to the ageostrophic term are, in general, an order of magnitude smaller.

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5 Summary

A nested regional ocean model was developed to hindcast coastal circulation over the Middle Atlantic Bight and Gulf of Maine (MABGOM) shelf from 2004 to 2013. This hindcast model was nested inside the data assimilative global HYCOM/NCODA circulation analysis. At its surface and lateral boundaries, it was driven by realistic atmospheric forcing, tidal harmonics and observed river runoff. Extensive model/data comparisons indicate this MABGOM model model is capable of reproducing the temporal and spatial variability of regional circulation. Using the time- and space-continuous circulation hindcast fields from January 2004 to December 2013, we further described the mean coastal circulation and its three-dimensional structures. The along-shelf and cross-shelf transports were quantified. In the latter case, the 200 m isobath was used as the boundary between the shelf sea and the deep ocean. Our calculations confirmed the presence of the equatorward alongshore current. The alongshore transport values gradually decrease from north to south, supporting the “leaky shelf” concept proposed by earlier observational studies. The shelfbreak segments offshore of the Gulf of Maine and Cape Hatteras appear to be the major sites of shelfwater export. Other segments along the 200 m isobath are characterized by significantly large cross-shelf transport variability, with SD up to an order of magnitude larger than the means. The momentum analysis further indicates that the along-shelf sea level gradient from Nova Scotia to Cape Hatteras is about 0.36 m. Although measuring such a sea level gradient would be technically challenging, such a pressure gradient can play an important role in driving the equatorward mean shelf current. The nonlinear advection dominates the ageostrophic circulation in the cross-isobath direction, whereas the advection, stress and horizontal viscosity terms all contribute ageostrophic circulation in the along-isobath direction.

While the mean shelf circulation is the focus of this study, we note that the hindcast solutions reveal that significant interannual variations are present in the MABGOM shelf circulation. We leave the discussion of those to a future study. Admittedly,

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this MABGOM model model is still of coarse resolution, so our discussions on the shelf water transport have emphasized the mean flow advection. This is not to say that transport associated with smaller-scale wave, turbulence, and transitory events such as the shelfbreak secondary circulation (e.g., Linder et al., 2004) are not important.

Deterministic predictions of circulation and transport in this area will clearly require advanced observational infrastructure and a higher-resolution circulation model together with sophisticated techniques for data assimilation.

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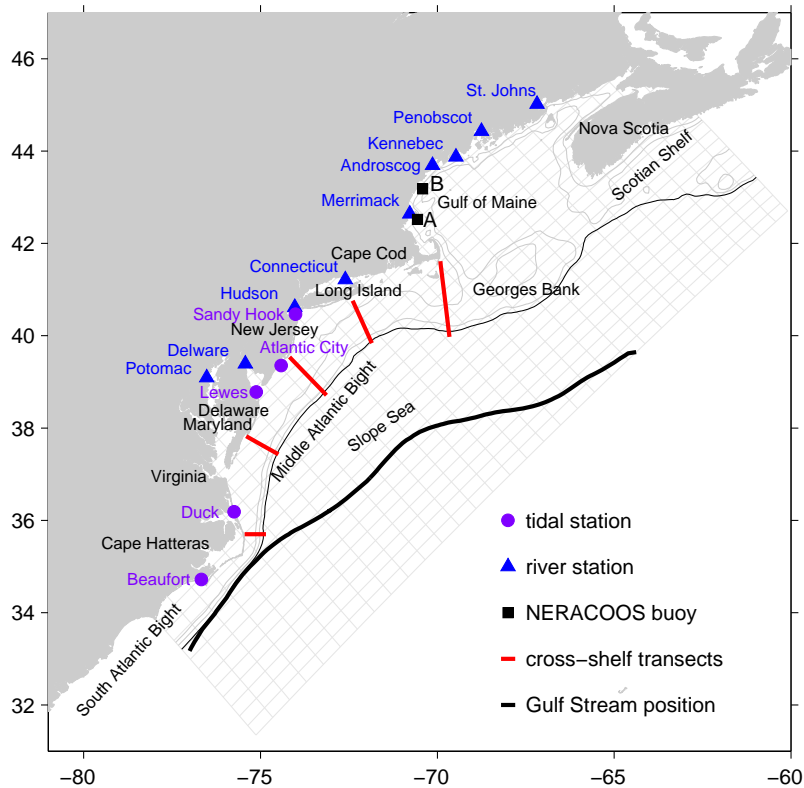


Figure 1. The MABGOM model grid (light gray, plotted every five grid points) and locations of coastal sea level stations (purple circle), USGS river gauges (blue triangle), NERACOOS buoys (black square), and cross-shelf transects (red line) where the circulation was sampled, as discussed in Sect. 3.2.2. The thick black line denotes the mean path of Gulf Stream, determined by the 15°C isotherm at 200 m (Joyce et al., 2000). The 50 and 100 m isobaths are shown in light gray, and the 200 m isobath is plotted in black. Geographic locations discussed in the text are also labeled.

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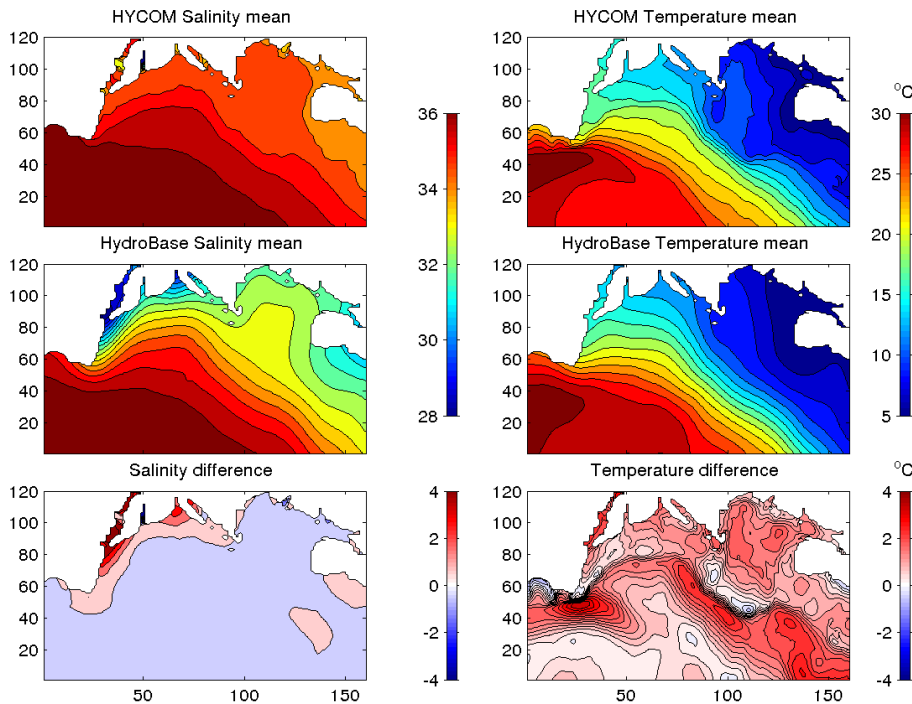


Figure 2. Comparisons of surface (layer 36 in the model) salinity and temperature fields between HYCOM/NCODA (top panels) and HydroBase (mid-panels), and their misfits (bottom panels). x and y axes denote grid numbers of the model.

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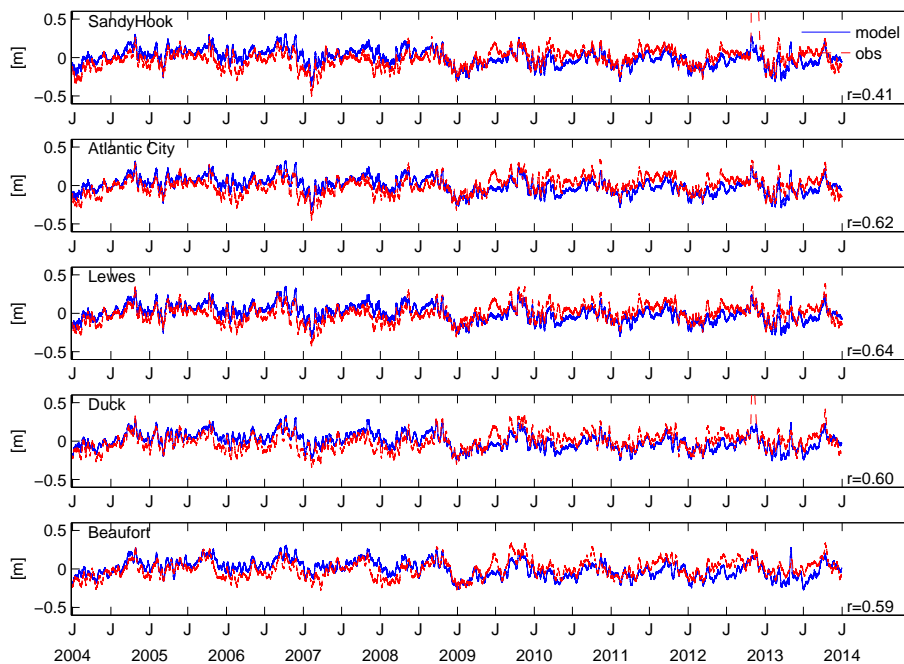


Figure 3. Comparisons of modelled and observed coastal sea levels. Time series are all 10 day low-pass filtered. The correlation coefficient (r , above 95 % confidence level) is also included for each comparison.

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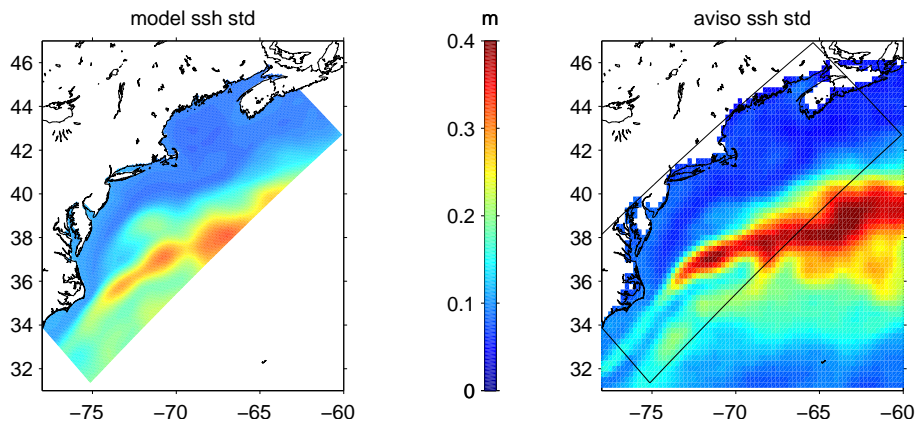


Figure 4. Comparison of altimeter-mapped and model-simulated sea surface height SD for the period from January 2004 to December 2013.

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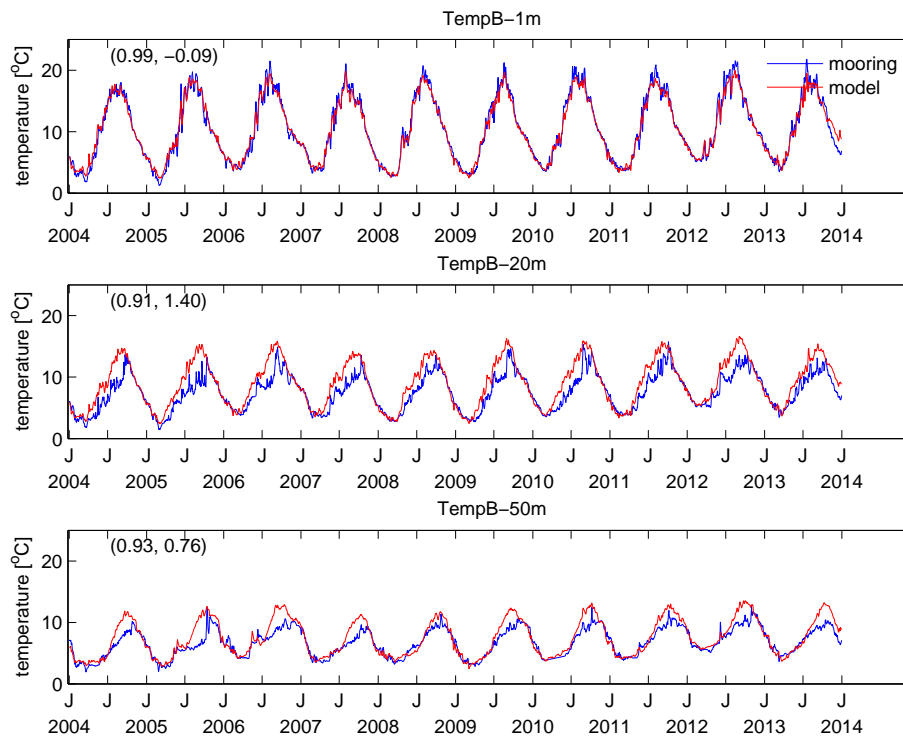


Figure 5. Comparison of observed (mooring) and simulated temperature time series at NERA-COOS mooring B. Linear correlation coefficients (r) and mean bias (b) are shown in parentheses (r , b) respectively in each panel.

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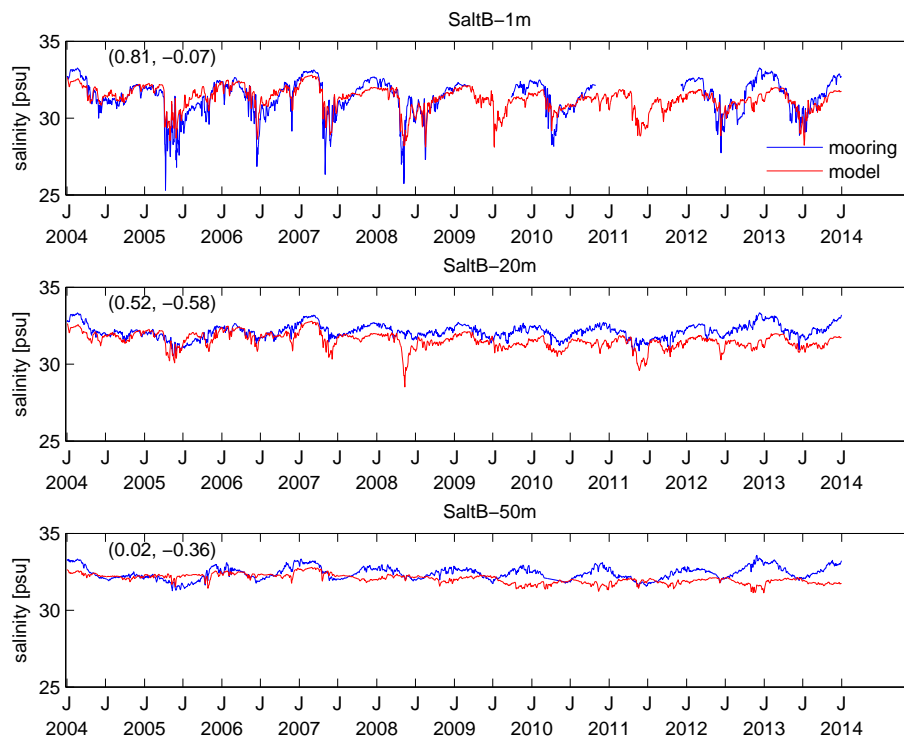


Figure 6. Comparison of observed (mooring) and simulated salinity time series at NERACOOS mooring B. Linear correlation coefficients (r) and mean bias (b) are shown in parentheses (r , b) respectively in each panel.

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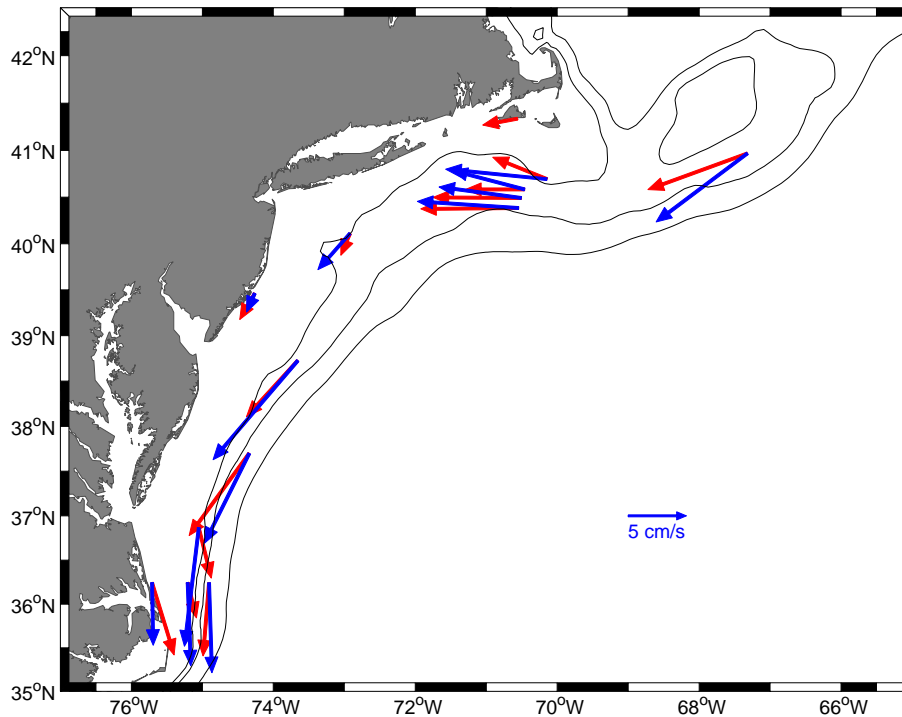


Figure 7. The comparison between observed (red, Lentz, 2008a) and MABGOM simulated (blue) mean depth-averaged currents.

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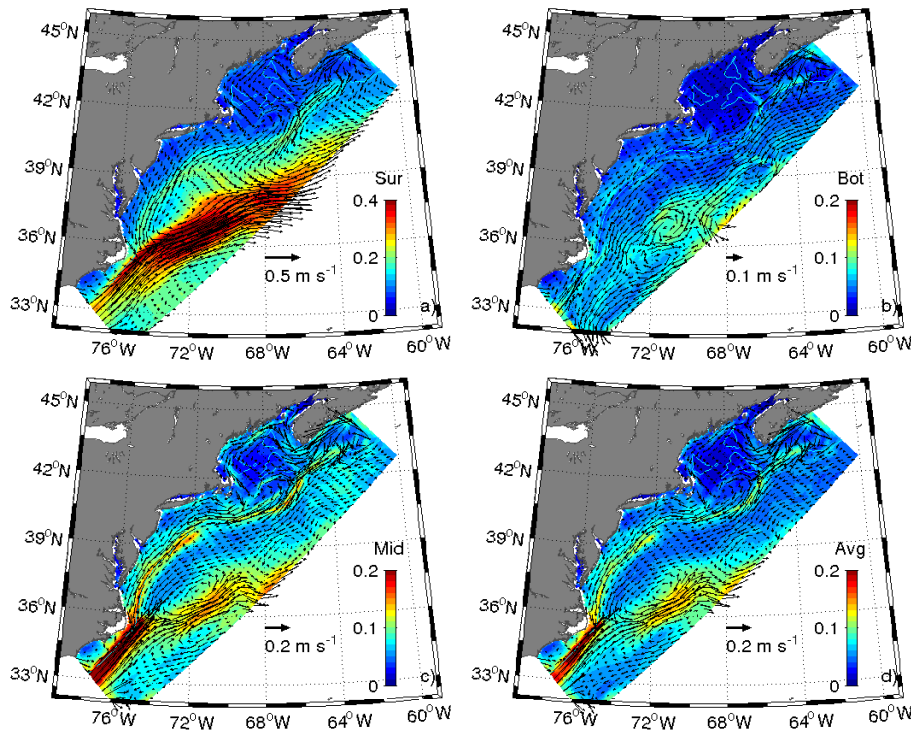


Figure 8. Domain-wide mean velocity fields (vectors) and their associated speed SD (color contour) at: surface (a), bottom (b), and mid-depth (c). Depth-averaged velocity field is shown in (d). Near-surface currents are larger than those near the bottom; note scale changes.

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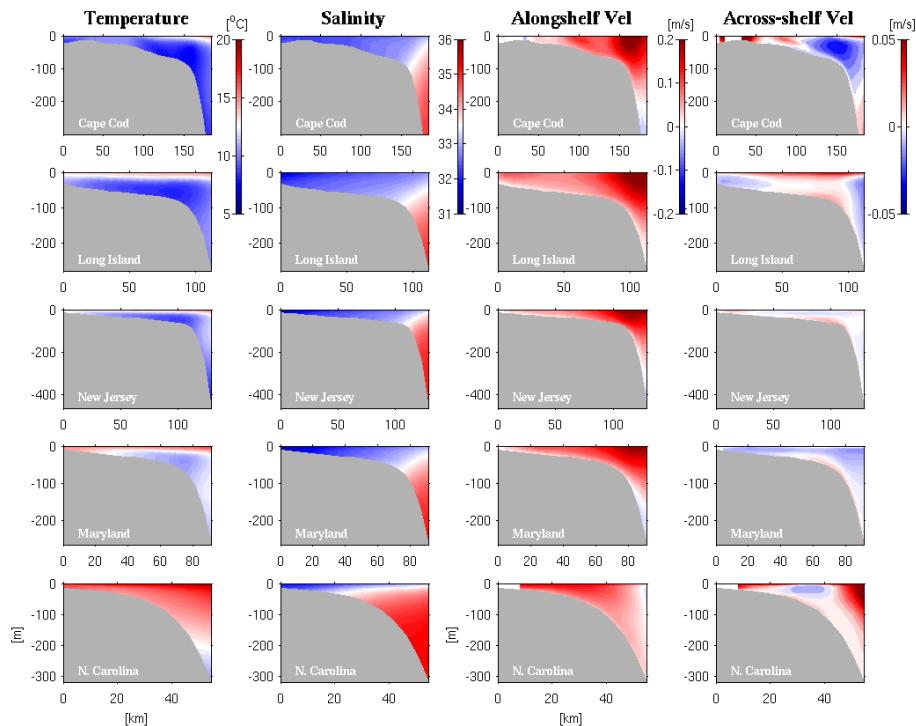


Figure 9. Mean cross-shelf transects (top transect to bottom transect is north to south) of temperature, salinity, alongshore and cross-shelf velocity. For velocity components, positive (red color) indicates equatorward and offshore, and negative (blue color) indicates pole-ward and onshore.

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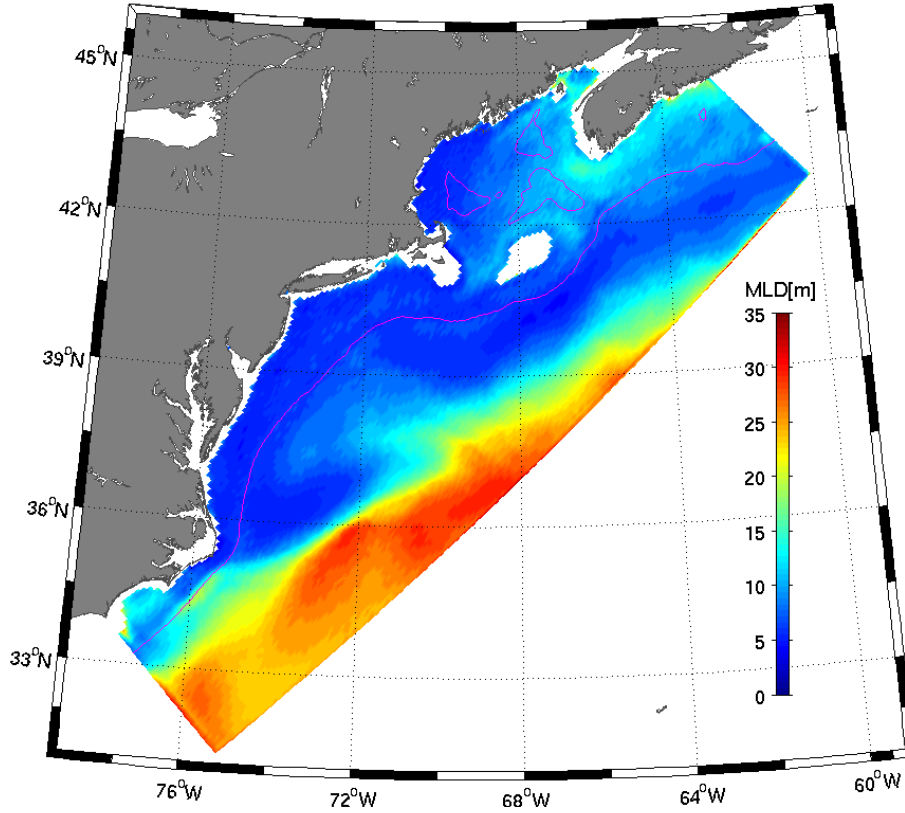


Figure 10. Simulated mean mixed layer depth (m) in the MABGOM domain.

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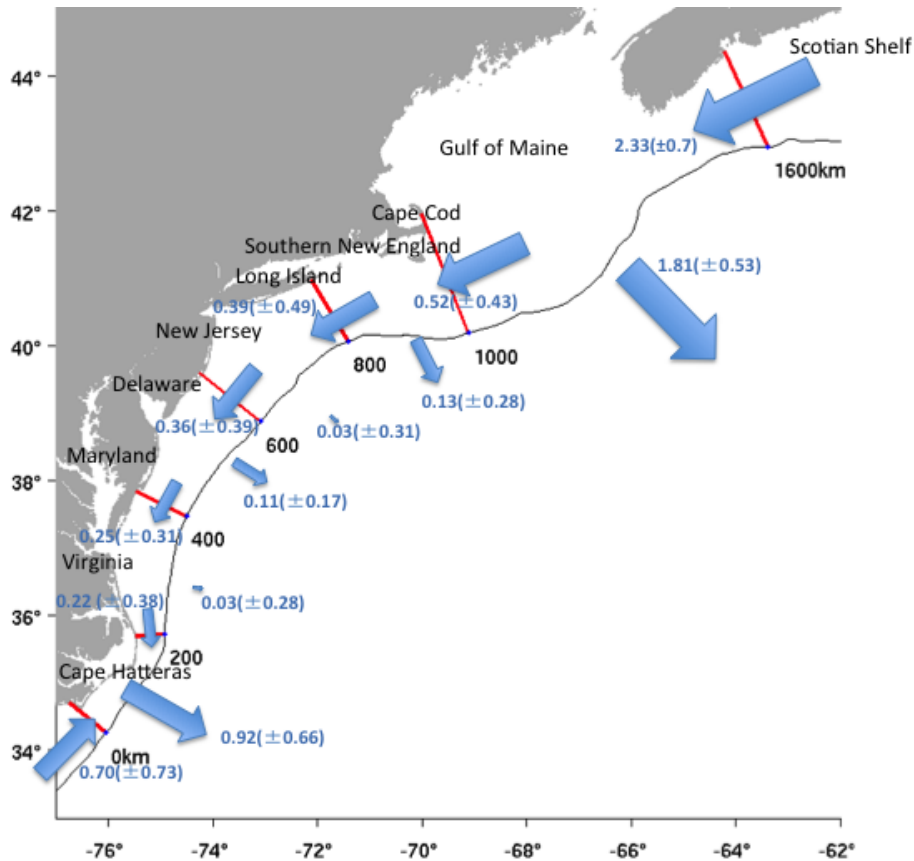


Figure 11. A schematic showing the mean circulation pattern in the MAB and GoM. The means (in Sv) and SD (in parentheses) of transports (blue arrows) across transects in the model domain are shown.

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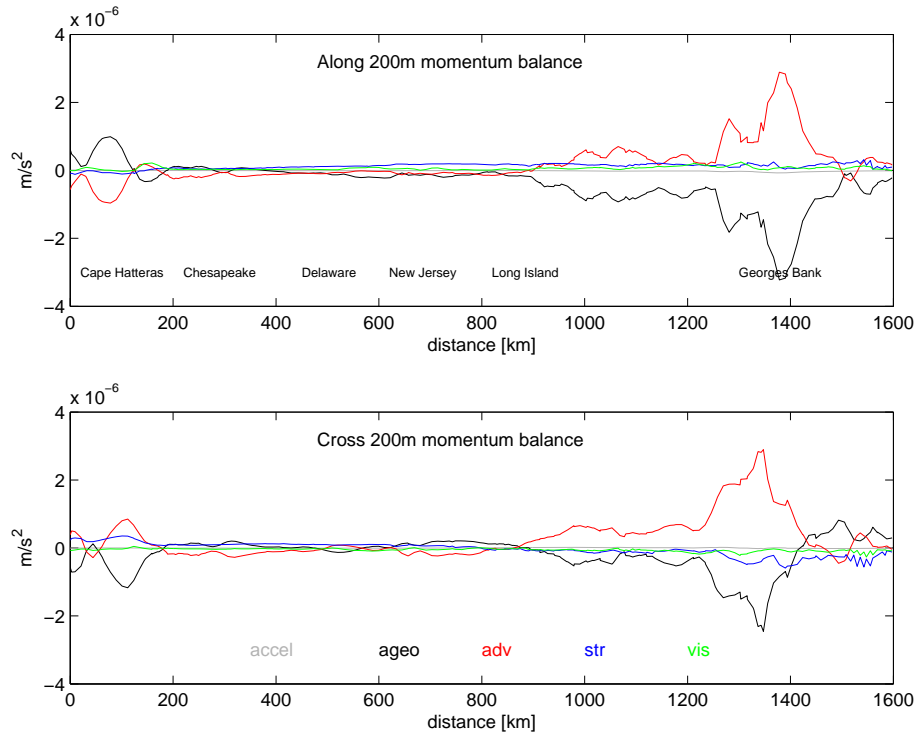


Figure 12. Mean momentum term-by-term balances in along (upper) and across (lower) the 200 m isobath directions.

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