Modeling the Pathways and Mean Dynamics of River Plume Dispersal in the New York Bight

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(Manuscript received 20 June 2008, in final form 17 November 2008)

ABSTRACT

This study investigates the dispersal of the Hudson River outflow across the New York Bight and the adjacent inner- through midshelf region. Regional Ocean Modeling System (ROMS) simulations were used to examine the mean momentum dynamics; the freshwater dispersal pathways relevant to local biogeochemical processes; and the contribution from wind, remotely forced along-shelf current, tides, and the topographic control of the Hudson River shelf valley. The modeled surface currents showed many similarities to the surface currents measured by high-frequency radar [the Coastal Ocean Dynamics Applications Radar (CODAR)]. Analysis shows that geostrophic balance and Ekman transport dominate the mean surface momentum balance, with most of the geostrophic flow resulting from the large-scale shelf circulation and the rest being locally generated. Subsurface circulation is driven principally by the remotely forced along-shelf current, with the exception of a riverward water intrusion in the Hudson River shelf valley. The following three pathways by which freshwater is dispersed across the shelf were identified: (i) along the New Jersey coast, (ii) along the Long Island coast, and (iii) by a midshelf offshore pathway. Time series of the depth-integrated freshwater transport show strong seasonality in dispersal patterns: the New Jersey pathway dominates the winter-spring seasons when winds are downwelling favorable, while the midshelf pathway dominates summer months when winds are upwelling favorable. A series of reduced physics simulations identifies that wind is the major force for the spreading of freshwater to the mid- and outer shelf, that remotely forced along-shelf currents significantly influence the ultimate fate of the freshwater, and that the Hudson River shelf valley has a modest dynamic effect on the freshwater spreading.

1. Introduction

Freshwater discharged into the coastal ocean from rivers and runoff is often observed to be incorporated into a narrow coastal current that is typically a few internal Rossby radii wide and that rapidly transports freshwater downshelf, which appears similar to the classical model of buoyant outflow onto coastal oceans (Garvine 1999). However, more recent theoretical, modeling, and laboratory studies (Avicola and Huq 2003a; Fong and Geyer 2002; Nof and Pichevin 2001) revealed a tendency for the formation of a recirculating bulge structure in the vicinity of the outflow in the absence of wind and alongshore current. In reality, the outflow pattern depends on outflow angle (Avicola and Huq 2003a,b; Garvine 1999), wind forcing (Fong and

DOI: 10.1175/2008JPO4082.1

Geyer 2001; García Berdeal et al. 2002; Lentz and Chapman 2004), ambient current (Fong and Geyer 2002; García Berdeal et al. 2002; Hickey et al. 2005), tides, and local topography. These factors and forcing modify the pathways of the river plume and can make it similar to the classical theory. Given the temporal variation of some of the forcing, freshwater pathways are often highly mobile, and the unsteady freshwater transport pathways have important ecological implications regarding contaminant, larval, and nutrient transport (Cahill et al. 2008; Ciotti et al. 1995; Tilburg et al. 2005). Moreover, the details of freshwater dispersal processes can affect ocean stratification, and parameterization of these processes impacts climate model results (Garvine and Whitney 2006).

In this study we use a numerical model to elucidate processes dispersing freshwater discharged from the Hudson River across the New York Bight (NYB). The region is adjacent to a wide, shallow continental shelf, and on this coast tides, freshwater input, air–sea exchange, large-scale shelf-wide circulation, and variable

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bathymetry all influence circulation processes to varying degrees. Southwestward along-shelf mean currents of approximately 5 cm s⁻¹ occur in the NYB (Beardsley and Boicourt 1981; Chapman and Beardsley 1989), and it is argued that this equatorward mean current is forced remotely by along-isobath pressure gradients associated with freshwater runoff extending as far north as the Arctic (Chapman and Beardsley 1989; Chapman et al. 1986). An analysis combining a simple steady model of the shelf-wide momentum balance and historical longterm moored current meter data (Lentz 2008) indicates that the vertically averaged along-shelf current is proportional to water depth, and hence the transport increases quadratically when moving offshore. This suggests that while the southwestward mean flow may steer the Hudson's outflow once it reaches the outer shelf, on the inner shelf, and particularly in the apex of the New York Bight in the shadow of Long Island, the ambient flow is relatively weak given its depth, and its impact on freshwater pathways is unclear.

Observational and modeling studies have described a variety of freshwater transport pathways on the inner shelf and the NYB apex. For example, several studies describe the role of coastally trapped currents (Johnson et al. 2003; Münchow and Chant 2000; Yankovsky and Garvine 1998), while others note that the outflow is susceptible to bulge formation and is highly responsive to wind forcing (Chant et al. 2008; Choi and Wilkin 2007). Chant et al. (2008) presented the evidence of rapid cross-shelf transport of the Hudson River-injected freshwater during early summer. Relatively swift crossshelf mixing is also evident in repeat autonomous coastal glider transects (Castelao et al. 2008a,b) that show the expansion of low-salinity water over the entire shelf during the summer months, and the cross-shelf transport is correlated with upwelling wind that dominates the NYB during the summer months. This crossshelf transport over summer is consistent with Mountain's (2003) analysis of historical hydrographic data that revealed significant annual cycles of shelf water salinity in the NYB with a summer salinity minimum. However, the mechanisms that drive freshwater dispersal to the midshelf and its subsequent fate on the mid- and outer shelf are not fully known. One explanation given is that a fast cross-shelf pathway is created by upwellingfavorable winds that drive short-term freshwater extension events (Castelao et al. 2008b), but beyond this there have been few studies that trace the fate of the river plumes in the region after their initial entry into shelf waters. The major objectives of this study are to characterize the shelf-wide spreading of freshwater input from the Hudson River, describe its seasonal variability, and elucidate the dynamics that drive the variability. The Hudson River discharge has high levels of nutrients, phytoplankton, dissolved organic matter, and contaminants, and characterizing its dispersal is of fundamental importance to regional studies of biogeochemical processes.

The outline of this paper is as follows: section 2 introduces the model configurations and verification, section 3 presents the simulated mean momentum dynamics, and the corresponding mean freshwater dispersal patterns are given in section 4. In section 5, the temporal variation of the freshwater transport on NYB is presented and discussed. The results are summarized in section 6.

2. Model configuration and comparison to observations

The Regional Ocean Modeling System (ROMS; information available online at http://www.myroms.org) is used for the ocean circulation simulations. ROMS utilizes a terrain-following coordinate system in the vertical that allows a high resolution in shallow shelf seas. Details of the ROMS computational kernel are described by Shchepetkin and McWilliams (1998, 2003, 2005) and Haidvogel et al. (2008). The model domain shown in Fig. 1 covers the New Jersey coastal area from eastern Long Island to the south of Delaware Bay and from the coast to approximately the 70-m isobath on the continental shelf. Two rivers, the Hudson and Delaware, are included. The model has 30 vertical layers and horizontal resolution of about 1 km. Chapman (1985) and Flather (1976) open boundary conditions are used for sea level elevation and the barotropic component of velocity on the model perimeter, respectively. These conditions impose both a remotely forced along-shelf mean flow described below, and tidal harmonic variability (seven components: K_1 , O_1 , Q_1 , M_2 , S_2 , N_2 , K_2) extracted from a regional (parallel) advanced circulation model for oceanic, coastal and estuarine waters (ADCIRC) simulation (Mukai et al. 2002). For threedimensional velocity and tracers, tests comparing Orlanski-type radiation (Orlanski 1976) and simple "gradient" conditions revealed little difference for the mean circulation and freshwater dispersal. All of the results presented here are from simulations with gradient open boundary conditions for 3D velocity and tracers. To include the remotely forced along-shelf currents associated with the large-scale pressure gradient we prescribed depth-averaged normal flows on the open boundaries based on the water depth-flow speed linear relationship deduced by Lentz (2008). The normal flow on the offshore boundary was smoothed to suppress the effect of small-scale undulation of the local



FIG. 1. Bathymetry of the New York Bight (grayscale), mean wind over this area (gray arrow on land) over the 2-yr period of 2005–06, and barotropic inflow boundary condition (white arrows) on the northeast boundary of the model domain. The black frame indicates the model domain and contours are model isobaths (m). Scale vectors for wind and inflow boundary velocity are given at the lower-right corner.

topography and also to get a better fit with the Coastal Ocean Dynamics Applications Radar (CODAR) data. The normal flow on the northeastern boundary was adjusted to conserve the total volume of the model domain, and the gradient of depth-averaged normal flow with respect to depth was preserved. In this study, the ambient current is assumed to be steady.

The model applies bulk formulas (Fairall et al. 2003) using marine boundary layer winds, temperature, humidity, and pressure from the North America Regional Reanalysis (NARR; Mesinger et al. 2006), and ROMS sea surface temperature and current to compute air-sea fluxes of momentum and sensible, latent, and longwave heat. Quadratic bottom drag was used in all simulations with a drag coefficient of 0.003. We found that the results were insensitive to bottom drag because shelf circulation and freshwater dispersal were similar in simulations with and without tides, as will be discussed later. The river discharge was obtained from the U.S. Geological Survey (USGS) Water Data (available online at http://waterdata.usgs.gov/nwis/nwis) and was modified to include ungauged portions of the watershed following Chant et al. (2008). To avoid the ambiguity of reference salinity for ocean water in the NYB, and also to isolate the Hudson River from other sources of freshwater in the model, a passive tracer with unit concentration was introduced in the modeled Hudson River source. Following the simulated passive tracer concentration gives an unambiguous measure, anywhere in the model domain, of the volume fraction of water contributed by the Hudson River freshwater outflow. The model is initialized with zero "freshwater" Hudson tracer concentration everywhere. Three-year-duration simulations were conducted with the first year used as a spinup period; results presented here are from the analysis of the final 2 yr of each simulation.

Five different simulations are discussed here. The first, with all of the previously mentioned forces applied, is named the full physics simulation (FPS). Four additional simulations were carried out to investigate the



FIG. 2. (a) Modeled and (b) observed mean surface current over the 2-yr period of 2005–06. Color represents current magnitude and the arrows depict the direction. The 20-, 40-, and 60-m isobaths (red contours) are shown. The arcs of radius 100 km are centered at Sandy Hook (star symbol) and are used for the comparison of radial velocity in Fig. 3.

impact of remotely forced along-shelf current, wind, tides, and the presence of the Hudson River shelf valley (Fig. 1) on the pattern and dynamics of freshwater spreading and mean circulation. The approach followed is to withdraw each of these factors individually from the FPS. The case with wind, a shelf valley, and tides but no along-shelf mean current is termed the no-ambient current simulation (NAS); the case with ambient current, a valley, and tides, but no wind is the no-wind simulation (NWS); the case with an along-shelf current, wind, and tides, but with the model bathymetry altered to fill in the Hudson shelf valley, is called the no-valley simulation (NVS). For completeness, we also conducted a simulation with ambient current, wind, and the original bathymetry, but omitted the tides. This no-tide simulation (NTS) is discussed only partially in the interest of brevity. The other simulations are discussed in detail.

Before proceeding to an analysis of the results, it should first be established that the FPS modeled circulation has acceptable fidelity with respect to relevant observations. This study focuses on transport pathways of the buoyant freshwater discharge from the Hudson River, and so the veracity of the modeled surface velocity field is a key requirement.

Throughout much of the NYB region we have 2-5 yr of surface current observations available from landbased CODAR high-frequency radar systems (Kohut et al. 2006). Figure 2 compares the 2-yr (2005-06) mean surface current from the model and CODAR. The observed mean current is plotted only at locations where data are available for more than 70% of the time; the plotted model results are limited to the same area to aid comparison. Both the model and observations show strong southward flow to the south of the mouth of the Hudson shelf valley. The triangularly shaped zone of strong flow is somewhat more compact and stronger, and is located closer to the valley in the model than in the observations. This discrepancy in part may be due to the differing resolution between the model and observation-1 km in the model and 10 km at this range for CODAR. Nevertheless, the pattern correlation coefficient between the modeled and observed mean surface current is about 0.56 and the overall correspondence in pattern, direction, and location is good.



FIG. 3. The time series (color plots) and (top) 2-yr mean (blue lines) of modeled and observed radial velocity on the arc in Fig. 2. Positive velocity is outgoing direction. (top) The bathymetry along the arc with the y axes spanning 0–80 m (black lines).

To evaluate the simulated temporal variability, we plot (Fig. 3) time series of the modeled and observed daily averaged radial velocity across the arc depicted in Fig. 2. The arc is centered on the CODAR site at Sandy Hook (indicated by the star symbol in Fig. 2), which measures the radial current speed across the arc directly, with somewhat greater accuracy than the CODAR vectors derived from pairs of sites. In the analyses that follow, freshwater transport across concentric pathways at varying ranges from Sandy Hook will also be presented. Figure 3 shows many similarities between the model and observation: velocity south of the Hudson shelf valley is generally outgoing and to the north of the valley incoming; and the timing and duration of the flow events are consistent in model and observation. A statistically significant cross correlation of 0.69 is obtained between the modeled and observed radial velocity in a 50-km-wide band over the shelf valley where the CODAR observations have the most consistent availability. There are some issues regarding potential bias in the calculation of daily averaged CODAR values because sometimes, at some locations, there is only a handful of 1-hourly interval CODAR observations available to contribute to the 1-day average window, and the data gaps appear to correlate with low sea state and low current magnitude. Furthermore, the spatial resolution between the model and observations differ. Despite these possible limitations to the model-data comparison, we feel that the model captures the temporal variability of the surface current well, and that, overall, the model is valid for the statistical long-term average simulation of freshwater spreading in the NYB.

3. Mean dynamics

a. Sea surface height

Mean sea surface height (SSH) and surface current over the 2-yr period for all the simulations are given in Fig. 4. SSH contours (Figs. 4a-d) generally follow isobaths and show a recirculation pattern in the NYB apex. The mean SSH pattern differs substantially between the different simulations. In the FPS case (Fig. 4a), SSH contours are spaced closely on the mid- and outer shelf with a riverward detour over the shelf valley. Without the ambient current (NAS, see Fig. 4b), the SSH variation from the coast to the outer shelf is 3 times weaker than in the FPS case. This shows that the remotely forced along-shelf circulation has a significant impact on the local mean sea level elevation on the mid- and outer shelf, and this SSH variation is directly related with the surface mean geostrophic current that is described further in section 3c. From the comparison of the FPS and NAS cases we infer that about 75% of



FIG. 4. (a)–(d) Mean SSH contours, (e)–(h) mean surface current, and (i)–(l) mean current at 20-m depth over 2-yr period of different simulations. (e)–(l) Magnitude (color) and direction (arrows) are depicted. The 20-, 40-, and 60-m isobaths (solid white lines); (d),(h),(l) the corresponding isobaths after the Hudson shelf valley is filled (dashed white lines).

the local mean sea surface gradient, and therefore surface geostrophic current, is caused by the remotely forced shelf-wide circulation; it will be shown that the remaining 25% is locally generated.

In the NWS case the mean SSH (Fig. 4c) has a similar pattern to that in FPS, but the cross-shelf sea level gradient in NWS is much higher, with SSH contours closer to each other on the inner and midshelf. Given the absence of wind-driven lateral mixing of the freshwater, a stronger cross-shelf density gradient is expected that would cause stronger thermal wind and, ultimately, a stronger sea level gradient across the shelf. This suggests that the locally generated geostrophic balance is largely driven by the influence of river discharge on the crossshelf density gradient.

In the NVS (Fig. 4d), the mean SSH contours no longer detour over the valley on the mid- and outer shelf, though they do still diverge somewhat on the broadest part of the shelf south of the shelf valley. Meanwhile, at the river mouth, the almost-closed recirculation pattern trapped between the valley and the Long Island coast in FPS becomes an jug handle–shaped bulge next to the New Jersey coast, which echoes the results of Fong and Geyer (2002) for idealized simulations of the freshwater bulge at a river mouth on a straight coast in the absence of an ambient current. This suggests that the Hudson shelf valley perturbs the surface current shoreward on the mid- and outer shelf, traps freshwater on the north side of the valley in the apex area, and forms a closed recirculation there.

b. Sea surface current

The mean surface current in the FPS case (Fig. 4e) shows outflow that is faster than 10 cm s⁻¹ at the river mouth directed along Long Island coast. A substantial part of this coastal current departs the Long Island coast and turns to the south, with a portion recirculating in the apex of the NYB in an approximately 30-km-radius loop and the remainder crossing the Hudson shelf valley. The rest of the coastal current turns to the southeast gradually as it moves eastward along the Long Island coast. On the

New Jersey side, a southward coastal current forms at Sandy Hook. For most of the mid- and outer shelf, water moves south-southeastward on the surface.

Without the remotely forced along-shelf flow (NAS), the mean surface current in Fig. 4f is weakened substantially and is directed more eastward on the midand outer shelf. The region of strong southward current between the 40-m isobath and the valley on the outer shelf in FPS disappears in NAS, but the inner-shelf circulation differs little. Thus, the largely isobath-following remotely forced ambient current does not have much influence on the mean surface current on the inner shelf or NYB apex area, but it magnifies the surface current on the mid- and outer shelf, rotates the currents there clockwise, and forms the strong southward flow on the outer shelf.

Dramatic differences exist between Fig. 4g, the mean surface current of the NWS, and Fig. 4e (FPS), especially for the inner and midshelf. Without winds, the circulation pattern constitutes an elongated freshwater bulge that is greatly amplified compared to the bulge in FPS. Fong and Geyer (2002) demonstrated that the freshwater bulge in the vicinity of a river mouth can continually grow without reaching a steady state in the absence of any ambient current or surface mixing to aid its dispersal. The circulation here has similarities to Fong and Geyer's (2002) results, except that the bulge is squeezed between the coast and the bathymetry of the Hudson shelf valley, and the growth of the bulge is arrested by the remotely forced ambient current in the middle of the Long Island coast. The presence of the Long Island coast and the Hudson shelf valley makes the situation here much more complicated than that in Fong and Geyer (2002), and the extent to which bottom friction modifies the ballooning effect of the freshwater outflow, as described by Nof and Pichevin (2001), is uncertain. To discern this role clearly when the outflow is confined by the coastline and the shelf valley would require further analysis, which is beyond the scope of this paper. A strong southward coastal current emerges along the northern New Jersey coast that is joined by flow that crosses the shelf valley after branching off from the recirculation. This combined flow forms a strong current belt between the 40- and 60-m isobaths that extend all the way to the mouth of the Delaware Bay. The striking change from the FPS to the NWS case (Figs. 4e and 4g) indicates that wind plays a major role in shaping the circulation on the inner and midshelf on very short time scales, and strikes a cautionary note that simulation studies applying the bulk formulas in conjunction with low-frequency (e.g., monthly average) climatological winds might neglect important dynamical influences in this area.

Consistent with the SSH comparison, the surface recirculation loop at the river mouth in FPS disappears in NVS (Fig. 4h), and more of the river outflow turns to the south upon exiting the harbor to form a stronger New Jersey coastal current. In the offshore region, though the direction of surface velocity is similar in both FPS and NVS, the dramatic change of velocity magnitude immediately downstream from the Hudson shelf valley is less abrupt in NVS. These results confirm that the Hudson shelf valley acts as a dynamic boundary that redirects the surface current on the mid- and outer shelf and obstructs the southward flow of freshwater from the north side of the shelf valley in the NYB apex area.

c. Decomposition of the surface current

To understand the dynamics in greater detail, the surface mean geostrophic current (Figs. 5a-d) was computed from the 2-yr mean of SSH, enabling us to examine the mean residual ageostrophic current, that is, the difference between surface current and surface geostrophic current (Figs. 5e-h). Because of the strong nonlinearity in the estuaries created by tides and bottom friction, this linear decomposition is not informative inside the estuaries and is not discussed here. The surface mean geostrophic current of FPS (Fig. 5a) is very similar to that in Fig. 4e, especially the southwestward current on the outer shelf and the strong outflow at the river mouth and the Long Island coastal current. These major features of the surface current are geostrophically balanced, consistent with the conclusions we drew in section 3a. However, the direction of the flow everywhere in Fig. 5a is rotated clockwise with respect to Fig. 4e, and the strong offshore current on the outer shelf is weakened. On the mid- and outer shelf, and along the New Jersey coast, the residual flow vectors in Fig. 5e are directed almost uniformly southeastward at a speed of approximately 2.5 cm s⁻¹. From later analysis we know that this residual flow is basically Ekman transport on the surface. That Ekman transport is different at the New York apex area is expected because freshwater outflowgenerated stratification there is stronger than that on the rest of the shelf.

The differences between Figs. 5a and 5b–d reinforce the following three conclusions drawn in section 3: (i) on the outer shelf the geostrophic balance develops in response to the remotely forced along-shelf current; (ii) the action of the wind is to modify the pressure field, and hence the mean geostrophic circulation; (iii) the Hudson shelf valley modifies the surface geostrophic balance.

The comparison between surface ageostrophic velocity in Figs. 5e,g suggests that the surface mean residual flow is basically wind driven. To confirm that it is Ekman transport, the drift current was estimated using



FIG. 5. Two-year mean surface (a)–(d) geostrophic and (e)–(h) residual ageostrophic current of different simulations. Magnitude (color) and direction (arrows) are depicted. The 20-, 40-, and 60-m isobaths (solid white lines); (d),(h) corresponding isobaths after the Hudson shelf valley is filled (dashed white lines); (e) 2-yr mean wind (gray arrow).

Madsen's (1977) steady-state Ekman spiral equation. The average 10-m wind in the NYB in NARR is about 1.64 m s^{-1} southeastward (Fig. 1), which is equivalent to wind stress of 0.02 N m⁻², given a drag coefficient of 0.005 (Yelland and Taylor 1996). The estimated drift current at 0.15-m depth (the average depth of the model surface layer) is about 3.8 cm s⁻¹, which is somewhat stronger than the mean surface residual current in FPS. The estimated deflection angle between the surface wind stress and the drift current at the corresponding depth is about 23°, which is smaller than the 33° deflection angle in FPS (Fig. 5e). These discrepancies are consistent with the linear increase of vertical viscosity

with depth in Madsen's theory being at about half the rate computed by the model turbulence closure.

d. Mean subsurface circulation

The mean current at 20-m depth for the different simulations is plotted in Figs. 4i–l. For the FPS case, southward flow is strongest offshore and this outer-shelf current deflects shoreward somewhat as it crosses over the Hudson shelf valley. On the mid- and inner shelf at this depth the Hudson shelf valley guides a significant flow toward the apex of the NYB. When the remotely forced along-shelf flow is removed (NAS, see Fig. 4j) the southward current from the mid- to outer shelf disappears, showing that the mean subsurface current in the NYB is driven primarily by large-scale shelf circulation. However, the shoreward flow intrusion at 20-m depth at the valley head remains in NAS. In Figs. 4i,k the subsurface circulation is much the same, except that the riverward intrusion at the valley head is weakened substantially in NWS. This indicates that the 2-yr mean up-valley flow at 20 m is, at least partially, the result of the prevailing westerly wind. This is consistent with wintertime observations of flow in the shelf valley by Harris et al. (2003). The mean current at 20 m in the NVS case (Fig. 41) differs from FPS in three respects: (i) not surprisingly, the slight shoreward detour of the outer-shelf current over the Hudson valley disappears, (ii) the abrupt increase of velocity magnitude over the valley is diminished, and (iii) the riverward water intrusion at the head of the Hudson shelf valley is weakened. Thus, from the mid- to outer shelf the valley steers the surface and subsurface currents in a similar way, while on the inner shelf it acts to funnel subsurface currents that flow shoreward to feed surface offshore transport that is driven by wind and river outflow.

The results from the NTS case (not shown), in which tides are omitted but all other forces and bottom drag coefficient are retained, are the same as those from FPS. This indicates that tidal processes in the NYB are mostly linear in the respect that there is no appreciable rectification of tidal currents into the mean circulation on the inner shelf or deeper waters. Moreover, we conclude that bottom friction is unimportant because the inclusion of tides dramatically increases bottom drag on the shelf, yet the mean flow patterns and freshwater pathways change little. The principal role of tides in this area is to influence mixing within the Hudson River estuary (Chant et al. 2007; Lerczak et al. 2006).

4. Mean freshwater dispersal

To examine the patterns of river-source freshwater spreading in the NYB, we consider flow across six arcs (thin lines in Fig. 6) centered at the entrance to New York Harbor. The arcs of radius 20, 40, 60, 80, 100, and 120 km are numbered arc 1 through 6, respectively. The 2-yr (2005–06) time-averaged, vertically integrated freshwater flux across each arc is depicted by the thick lines in Figs. 6a–d; the scale bar indicates freshwater transport per unit length of azimuth of arc. The 2-yr mean sea surface salinity is also given in Figs. 6a–d for reference. To quantify the budget of freshwater dispersal to the shelf, the freshwater fluxes across the segments of the arcs on either side of the valley and across the valley itself are presented in Figs. 6e–h.

In FPS three somewhat distinct freshwater transport pathways emerge in Fig. 6a: (i) southward along the New Jersey shore (which we name the New Jersey pathway), (ii) eastward along the Long Island coast (which we name the Long Island pathway), and (iii) along the southern flank of the Hudson valley (which we name the midshelf pathway). The Long Island pathway located on the inshore northeastern shelf has been observed episodically (Chant et al. 2008); it starts as a strong, broad feature that becomes thinner, weaker, and more coastally trapped as it moves eastward. On the offshore northeastern shelf there is virtually no freshwater flux across the arcs. The New Jersey pathway, located on the inshore southwestern shelf, has been noted in observations before and is consistent with the dynamics of a buoyancy-driven coastal current. It starts as a sharp and thin feature on arc 1 and gradually broadens as it propagates southward. On the offshore southwestern shelf the midshelf pathway becomes distinct at arc 3. At arc 6 it is almost evenly distributed between the 20-m isobath and the valley, with a local maximum on the southern flank of the valley. At arc 1 and 2 there is freshwater returning along a path over the Hudson valley as part of the freshwater recirculation identified in Fig. 4e. The freshwater budget in Fig. 6e shows that in the long-term mean almost all of the river discharge goes first to the northeastern shelf at arc 1, but the southwestern shelf is the eventual destination for more than 90% of the freshwater discharge. Recirculation processes on the northeastern shelf ultimately guide the freshwater across the Hudson shelf valley onto the southwestern shelf, with most of the crossing occurring within 80-km radial distance from the harbor mouth. Inside arc 2 there is northward transport between the New Jersey coast and the valley that creates a closed recirculation (Fig. 4e) of about one-fifth of the total freshwater discharge.

Comparing Figs. 6a,b we see that without the remotely forced along-shelf current (NAS), the freshwater dispersal pattern changes in several respects. On the northeastern shelf the Long Island pathway strengthens and a new, minor offshore pathway emerges along the northern flank of the valley; the freshwater return over the Hudson valley extends to arc 5, indicating an intensification of the bulge recirculation; and on the southwestern shelf the midshelf pathway splits into two lobes at arc 4. The New Jersey pathway remains the same as in FPS. Figures 6e,f quantify these differences. Compared to FPS, the NAS case has 50% stronger recirculation at the harbor mouth (cf. 267 and 183 $\text{m}^3 \text{s}^{-1}$) and a 40% weaker (355 versus $605 \text{ m}^3 \text{ s}^{-1}$) flow crossing the valley inside arc 3 (60-km radius). About one-third of the total freshwater exits the domain from the



FIG. 6. (a)–(d) Temporally averaged, vertically integrated freshwater flux (thick black lines) across thin black arcs of radius 20, 40, 60, 80, 100, and 120 km, respectively, and 2-yr mean surface salinity (color). The arcs are centered at the entrance to New York Harbor (star). (e)–(h) Temporally averaged, spatially integrated freshwater transport across the segments of the arcs on either side of the shelf valley (gray dashed–dotted line), and the valley itself. The size of the arrow heads along with the numbers indicates the freshwater transport. 20-, 40-, and 60-m isobaths (solid gray lines); (d),(h) corresponding isobaths after the valley is filled (dashed gray lines).

northeastern shelf at arc 6 in NAS compared to about one-tenth in FPS. These differences show that the remotely forced ambient current weakens the bulge recirculation, suppresses the Long Island pathway, and diminishes the net cross-shelf export of freshwater on the northern flank of the Hudson shelf valley. In terms of the eventual fate of material transported in the Hudson River discharge, the ambient current acts to direct water away from the Long Island coast and across the Hudson shelf valley toward the southwestern shelf.

When the effect of wind is removed (NWS, see Figs. 6c,g), the Long Island pathway along arc 1 and 2 grows substantially compared to FPS, and there is a commensurate increase in the freshwater recirculation on the offshore northeastern shelf, especially on the inner four arcs. On the southwestern shelf, a strong and broad pathway forms at arc 2 and flows cross-shore and then along shelf, bounded by the 20-40-m isobaths. This is the broad southward flow separated from the coast in Fig. 4g. Along the New Jersey coast there is no longer a coherent southward coastal current, but rather the flow direction is reversed consistent with the recirculation seen in Fig. 4g between the coast and the main pathway that turns offshore. Figure 6g shows that the net effect of these circulation changes when winds are absent is to first direct 35% more of the river discharge to the northeastern shelf; however, via a much stronger recirculation most of this flow crosses the Hudson valley within 80 km of the harbor mouth. Taking the result in section 3 into consideration, we conclude that by mixing the ocean surface layer, wind is a major force for the mean surface circulation on NYB and the freshwater pathways. It plays important roles in establishing the mean southward New Jersey coastal pathway, dispersing a portion of the discharge across the northeastern shelf, and suppressing the strength of the bulge recirculation.

Without the Hudson valley (Figs. 6d,h) the freshwater pathways differ from FPS such that the cross-shelf transport on the northeastern shelf is substantially weakened, the northward return flow in the Hudson valley at arc 1 and 2 disappears, the local maximum cross-shelf freshwater flux along the southern flank of the Hudson valley at arcs 5 and 6 is absent, and the New Jersey pathway is strengthened. These changes confirm the conclusions we reached in section 3; that is, the valley helps trap freshwater on the northern shelf in the NYB apex area, promotes formation of the closed freshwater recirculation loop there, and guides freshwater export on the southwestern outer shelf parallel to the valley. Comparing Figs. 6e,h we see that while in the NVS case less of the Hudson River discharge initially flows to the northeastern shelf across arc 1 (638 versus 952 $m^3 s^{-1}$ in FPS), the net export across northern portion of the arc 6 is 40% greater, and therefore relatively *less* freshwater crosses the Hudson valley from the north to the south when there is no shelf valley. This apparent paradox arises because by amplifying the recirculation in the NYB apex, the shelf valley fosters a stronger exchange from the north to the south between arcs 1 and 3 ($605 \text{ m}^3 \text{ s}^{-1}$ in FPS and 285 $\text{m}^3 \text{ s}^{-1}$ in NVS). In FPS this vigorous flow bifurcates at the New Jersey coast, feeding both the northward coastally trapped recirculation and the southward coastal current.

As was noted in section 3, there is little difference in the freshwater dispersal pattern in FPS and NTS.

5. Temporal variation of freshwater dispersal

The temporal variability of freshwater dispersal is presented in Fig. 7 in terms of the vertically integrated daily-averaged freshwater flux across arc 5 over the 2-yr period, along with the Hudson River discharge and the northward (parallel to the New Jersey coast) component of the wind. (The water depth as a function of azimuth along arc 5 is shown to the right of Fig. 7g.) Positive freshwater flux is defined as outgoing from the harbor. The time series of wind has been low-pass filtered with a cutoff period of 10 days.

In the FPS case (Fig. 7b) most of the outgoing freshwater flux occurs on the southern shelf and along the New Jersey coast, as was noted in the mean freshwater flux patterns described in section 4. A weak yet clearly discernible cutoff line over the valley distinguishes variability between the northern and southern shelves throughout the entire 2-yr period. Thus, the effect that the valley has on the freshwater flux at this outer-shelf (arc 5) location is also exerted at daily time scales. There is a noticeable seasonality in the freshwater dispersal patterns in FPS. Between October and May outgoing flux is predominantly found along the New Jersey coast, with a weaker eastward flux in a narrow current along the Long Island coast. In contrast, between June and September the outgoing flux is primarily across the midshelf portion of the arc. Comparing the freshwater flux with the time series of the alongshore wind (Fig. 7f), we see that the outgoing flux across the center portion of the arc coincides predominantly with periods of upwelling-favorable wind (southerly). This is consistent with the results of Castelao et al. (2008b) in CODAR and surface float observations in which a swift jet transports water from the NYB apex to the outer shelf in summer and is significantly correlated with upwelling-favorable winds. Moreover, this is also consistent with historical observations that reveal a freshening of the outer shelf during summer months (Mountain 2003). The offshore transport intensity differs between years, with the



FIG. 7. Time series of vertically integrated, daily averaged freshwater flux across arc 5 (Fig. 6) of different simulations: (b) FPS, (c) NAS, (d) NWS, and (e) NVS. (a) River discharge and (f) meridional component of the wind over the same period, and (g) bathymetry along arc 5: original depth (black solid line), depth after the valley is filled (blue dashed line).

summertime direct offshore freshwater transport being stronger in 2006 than that in 2005. It appears this is caused by the peak in Hudson River discharge in 2006 coinciding with the beginning of the upwelling season (the end of June), whereas the peak discharge in 2005 occurs some 2 months before the upwelling season. All of these features of the flow variability are similar at arc 3, 4, and 6 (not shown).

To examine the relationship of freshwater transport to winds more quantitatively, we consider correlations between time series of the wind at the New Jersey coast (northward positive) and freshwater flux across 5° azimuth intervals of each arc. Using a similar analysis approach as that of Castelao et al. (2008b), applied to CODAR surface velocity in this region, a weighted running mean filter is first applied to the time series using the equation $f_k(t) = k^{-1} \int_{-\infty}^t f(t') e^{(t'-t)/k} dt'$, where f(t) is the wind stress or freshwater flux at time t, and $f_k(t)$ is the resulting convolution with weights that decay exponentially with time scale k (Austin and Barth 0.8



FIG. 8. Correlation (dark lines) between the filtered meridional component of the wind (southerly as positive) and the filtered freshwater flux across four arcs in the full physics simulation. The correlation is plotted only where it is significant at the 95% confidence level. Bathymetry along the arcs (gray lines).

2002). By doing this, the time history of the wind and the freshwater advection is considered. Here, k is chosen to be 4 days, which is a time scale reflecting the 2-5-day variability in the synoptic wind field in the NYB and thereby is appropriate to the duration of wind events that could displace waters on the order of 70 km, at 20 cm s⁻¹, from the New Jersey coast to arc 4-6. Of all of the wind directions, the component along the New Jersey shore has the highest correlation with the freshwater flux over the Hudson shelf valley area. The correlation between filtered alongshore wind and freshwater flux for the four outer arcs is presented in Fig. 8. The correlation is plotted only where it is significant at the 95% confidence level. The results are similar for all four arcs; the negative correlation on the shelf adjacent to the New Jersey coast indicates that southward (negative) wind favors the export of freshwater in the coastal current, while the positive correlation from the 40-m isobath on the south (New Jersey) side of the valley to approximately the 30-m isobath north of the valley indicates that the northward wind favors the offshore freshwater advection in the midshelf pathway and the weak eastward freshwater advection on much the northern shelf. Similar conclusions were drawn by Choi and Wilkin (2007) using idealized simulations.

To depict the seasonal variation of the freshwater pathways clearly, Fig. 9 shows the mean vertically integrated freshwater fluxes as a vector field on the model grid during the spring (March-May), summer (June-August), fall (September-November), and winter (December-February) months. Offshore freshwater transport along the midshelf pathway dominates the summer period, eastward freshwater transport along the Long Island coast is the most obvious pathway in the fall period, and southward freshwater transport along the New Jersey coast dominates the winter-spring period. In all seasons, freshwater first moves eastward after it exits New York Harbor. In summer, part of the outflow turns to the south and forms a weak freshwater recirculation at the river mouth, but the majority of it turns seaward at the 40-m isobath and crosses the Hudson shelf valley about 100 km from the harbor mouth, whereupon it moves offshore following the 60-m isobath. This path is similar to the episodic jet transport that Castelao et al. (2008b) found in CODAR surface current observations. There is little freshwater movement along the New Jersey coast in summer. In fall, a relatively strong flow in the Long Island pathway, weak recirculation at the harbor mouth, and a weak New Jersey pathway transport are present. In winter-spring months, a strong New Jersey pathway and a



FIG. 9. Temporally averaged, vertically integrated freshwater transport within 140 km from the estuary entrance for (a) spring (March–May), (b) summer (June–August), (c) fall (September–November), and (d) winter (December–February). Transport magnitude (color) and direction (vectors) are depicted. The 20-, 40-, and 60-m isobaths (black lines).

strong recirculation at the harbor mouth are distinctive features of the flow, and there is modest transport of freshwater eastward along the Long Island coast in the winter. There is little transport to the northern and central mid- and outer shelf at this time.

We now return to consideration of the forces that influence variability in the freshwater spreading on short time scales. Time series of the freshwater flux across arc 5 in the NAS, NWS, and NVS cases are shown in Figs. 7c–e, respectively, to complement the FPS results discussed previously. The temporal variability of FPS and NAS are very similar, but in NAS (Fig. 7c) the Hudson shelf valley appears clearly as a conduit for onshore transport for much of the time, especially from October through May when winds tend to have a southward along-coast component (negative in Fig. 7f). In summer, when the wind is predominantly upwelling favorable (positive in Fig. 7f), the NAS case shows stronger offshore transport on the southern flank of the valley that then spreads over the entire northern shelf.

The pattern in NWS (Fig. 7d) is very different from FPS and NAS, clearly showing that wind is the primary driving force for the daily time-scale variability of the freshwater flux and the spreading of freshwater onto the mid- and outer shelf. Without wind, the freshwater only crosses the arc on either end, in coastal currents, leaving the middle of the shelf free of freshwater flux. Both of the coastal currents have recirculations that grow and decay in step with the respective outflows, indicating that the freshwater movement largely follows the static path in Fig. 4g.

Case NVS (Fig. 7e) shows variability similar to the full physics simulation (Fig. 7b) on time scales from days to seasons, but the boundary at the valley that delineates the northern and southern shelf regimes in FPS vanishes. This indicates that the valley plays its role in blocking freshwater movement at all time scales. The boundary at the valley between the two regimes is evident, even in the absence of any wind forcing (Fig. 7d). Moreover, without the Hudson valley, it appears that the southward freshwater transport on the New Jersey coast is more coastally trapped, consistent with the results in section 4.

The time variability of freshwater flux across arc 5 in the NTS case (not shown) is the same as FPS, which shows that tides have no real effect on the freshwater transport to the mid- and outer shelf, even on daily time scales.

6. Summary and conclusions

We have conducted a study of the processes that influence the dispersal of the Hudson River discharge as it enters the New York Bight and spreads across the New Jersey shelf. Two-year simulations with ROMS were used to analyze the mean momentum dynamics and freshwater transport pathways. To investigate the influences of remotely forced along-shelf current, wind, the topographic control of the Hudson Shelf Valley, and tides, reduced physics simulations were conducted in which each of these respective factors was individually withdrawn from the model configuration.

In all simulations, the mean sea surface current follows the isobaths on the mid- and outer shelf, and a freshwater recirculation occurs in the apex of the New York Bight near the harbor mouth. Analysis of the surface current identifies Ekman dynamics and geostrophic balance as the two major processes governing the mean surface circulation. The reduced physics simulations show that the large scale remotely-forced shelf circulation is the major driver for the surface geostrophic balance. Below the surface mixed layer most of the circulation, except on the inner shelf where bathymetry funnels subsurface flow toward the head of the Hudson Valley. Tides have almost no influence on the mean shelf circulation.

The freshwater entering New York Bight from the Hudson estuary disperses along three principal transport pathways: (i) along the New Jersey coast, (ii) along the Long Island coast, and (iii) along a midshelf pathway that proceeds offshore guided by the southern flank of the Hudson shelf valley, consistent with recent analyses of CODAR surface current observations (Castelao et al. 2008b). In all cases a freshwater recirculation forms near the harbor mouth within the 40-km arc. In terms of the freshwater budget, all of the simulations show that the majority of the river-source freshwater flows first onto the shelf north of the shelf valley, but then crosses the valley within 80 km of the harbor mouth. In the simulation with all of the physics included, more than 90% of the freshwater flux eventually exits the region on the south side of the Hudson valley.

From the reduced physics simulations, we found that the role of the remotely forced large-scale shelf circulation is to decrease the volume of recirculating freshwater, and to push freshwater from the northern shelf across the Hudson valley, subsequently dispersing it more evenly over the southern shelf. Wind is the most significant force pushing freshwater from the inner shelf onto the mid- and outer shelf. Winds also reduce the recirculation intensity at the river mouth but do little to change the ultimate fate of the freshwater. The bathymetry of the Hudson shelf valley is shown to have a significant role in forming the strong and closed recirculation at the harbor mouth and promotes cross-shelf transport of freshwater farther down shelf. Tides have minor impact on the freshwater pathways.

There is seasonal variability in freshwater flux across the 100-km arc over the simulated 2-yr period. In the winter-spring period, the New Jersey coastal pathway dominates. During fall, the Long Island pathway is relatively strong. During summer, the midshelf pathway that directly transports river discharge to the mid- and outer shelf dominates. The midshelf pathway is active when the wind is upwelling favorable, which supports the tentative conclusion drawn by Castelao et al. (2008b) that upwelling wind is the main driver of offshore transport. The cross correlation between a 4-day-weighted temporal average of along-coast wind and freshwater flux across the four outer arcs considered shows significant positive correlation between the upwelling wind and midshelf outgoing freshwater flux. This result agrees with Choi and Wilkin's (2007) conclusion that southward wind favors the New Jersey pathway.

The comparison of the differing reduced physics simulations identifies wind as the primary source for the daily scale variability of freshwater transport and the major force pushing the freshwater onto the mid- and outer shelf. Ambient current is shown to be a suppressive force for the outgoing freshwater flux on the northern shelf. These results have implications for biogeochemical processes in the New York Bight because the Hudson River is a significant source of nutrients, organic matter, and dissolved and suspended contaminants to the inner shelf. The patterns of freshwater dispersal revealed here indicate that the destination of material transported in the Hudson River discharge changes rapidly on the time scales of a few days, but also with longer-term seasonal differences. For river-borne material that is biologically or geochemically active on time scales from a few days to months, the transport pathways inferred here will influence deposition, availability to the regional marine ecosystem, and regions where material may be exported from the New York Bight by advection.

Acknowledgments. This work is funded by National Sciences Foundation Research Grant OCE-0238957. ROMS model development is funded by NSF and the Office of Naval Research Grant N00014-04-1-0382 and N00014-05-1-0366. We thank the Coastal Ocean Observation Laboratory of Rutgers University for providing the CODAR data.

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