

# Dispersal of the Hudson River Plume in the New York Bight

Synthesis of Observational and Numerical Studies During LaTTE

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**ABSTRACT.** Observations and modeling during the Lagrangian Transport and Transformation Experiment (LaTTE) characterized the variability of the Hudson River discharge and identified several freshwater transport pathways that lead to cross-shelf mixing of the Hudson plume. The plume's variability is comprised of several different outflow configurations that are related to wind forcing, river discharge, and shelf circulation. The modes are characterized by coastal current formation and unsteady bulge recirculation. Coastal currents are favored during low-discharge conditions and downwelling winds, and represent a rapid downshelf transport pathway. Bulge formation is favored during high-discharge conditions and upwelling winds. The bulge is characterized by clockwise rotating fluid and results in freshwater transport that is to the left of the outflow and opposed to classical coastal current theory. Upwelling winds augment this eastward flow and rapidly drive the freshwater along the Long Island coast. Upwelling winds also favor a midshelf transport pathway that advects fluid from the bulge region rapidly across the shelf on the inshore side of the Hudson Shelf Valley. A clockwise bulgelike recirculation also occurs along the New Jersey coast, to the south of the river mouth, and is characterized by an offshore veering of the coastal current. Modeling results indicate that the coastal transport pathways dominate during the winter months while the midshelf transport pathway dominates during summer months. Finally, because the time scales of biogeochemical transformations in the plume range from hours to weeks or longer, the details of both the near- and far-field plume dynamics play a central role in the fate of material transported from terrestrial to marine ecosystems.

## INTRODUCTION

River discharge into the coastal ocean represents a major link between terrestrial and marine systems. Moreover, with over half of the world's human population located within coastal watersheds, this discharge is an important pathway that extends anthropogenic impacts into the ocean. Although biogeochemical processes can significantly modify this transport pathway, understanding the processes that determine freshwater transport pathways is essential in determining the fate and transport of material fluxing across the land-sea interface. River outflows are less dense than the

saline ocean waters and this density difference produces a buoyancy force that drives the plume's circulation. The classic model of plume dynamics balances this buoyancy force with the Coriolis force that causes the outflow to turn to the right (in the northern hemisphere) and form a narrow coastal current trapped within a few internal Rossby radii (the ratio of internal wave speed to the local Coriolis frequency) of the coast (Garvine, 1987, 1999). The coastal current may be confined to a thin surface layer or may be attached to the bottom (Yankovsky and Chapman, 1997). In general, the classic model emphasizes

that, in the absence of winds, coastal current dynamics severely limit the cross-shelf transport of river plumes.

Buoyant outflows may also contain a bulge-like region in the vicinity of the outflow, and the cross-shelf extent of these bulges can be many times the width of the downstream coastal current. Yankovsky and Chapman (1997) incorporated a bulge in a steady-state model that they closed by equating the freshwater flux in the coastal current to the freshwater flux exiting the estuary. With this steady-state assumption, they developed an elegant theory that related coastal current structure to the



estuarine discharge and the cross-shore slope of the seafloor.

Recent modeling and laboratory studies of buoyant outflows provide a more detailed characterization of bulge structure (Fong and Geyer, 2002; Avicola and Huq, 2003; Horner-Devine et al., 2006) and emphasize that a bulge may be *unsteady* and grow in time. Consequently, the freshwater flux out of the estuary may be greater than the freshwater flux in the coastal current, with the remainder going into bulge formation. Based on laboratory experiments in a rotating tank, Avicola and Huq (2003) reported that approximately one-third of the outflow became incorporated in a coastal current. More detailed analysis afforded by numerical modeling indicated that the fraction of freshwater from the river that is incorporated in the coastal current depends on the outflow parameters. Specifically, as the flow becomes increasingly nonlinear,

less of the discharge goes into the coastal current and more into bulge growth. The nonlinearity is characterized by the Rossby number, which is the ratio of inertial to rotational forces. Fong and Geyer (2002) discuss the mechanisms by which the bulge feeds the coastal current by invoking a model by Nof (1988), whereby the amount of freshwater entering the coastal current is determined by the amount of the eddy (bulge) pinched off at the coastal wall. As the Rossby number increases, the eddy's center moves increasingly further from the coastal wall and reduces the fraction of the eddy that is pinched off, thus diminishing the freshwater transport into the coastal current. Laboratory experiments by Horner-Devine et al. (2006) show even more dramatic shunting of the coastal current by bulge formation as the recirculation completely pinches off the coastal current, and the entire outflow goes into bulge formation. Note that

although laboratory and modeling studies often produced such bulges, the lack of observational evidence caused some to suggest that bulge formation may in fact be an artifact of models. Indeed, Fong and Geyer (2002) note that bulge formation in models is more pronounced than in nature.

Wind forcing also plays a critical role in the cross-shelf transport of river plumes (Whitney and Garvine, 2005). Modeling studies reveal that upwelling winds are effective in both transporting river plumes offshore and mixing the plume with the coastal ocean (Fong and Geyer, 2001). Observational studies of coastal currents reveal that the structure of the flow and salt fields (Rennie and Lentz, 1999) and of the diapycnal fluxes (Houghton et al., 2004) appear to be consistent with numerical studies (Fong and Geyer, 2001). Despite this consistency, there has been little research on the effect of wind forcing on bulge dynamics, with the notable exception of Choi and Wilkin (2007).

In this paper, we discuss the character of the Hudson River's discharge into the coastal ocean based on observations and modeling efforts during the Lagrangian Transport and Transformation Experiment (LaTTE). The major objective of LaTTE was to elucidate the transport and transformation of dissolved and suspended material as it exits New York Harbor onto the continental shelf of the Middle Atlantic Bight; hence, it was imperative to characterize freshwater transport pathways. This highly urbanized watershed (Figure 1) is among the most industrialized in the world; thus, our objectives included tracking contaminant metals along with nutrients and organic matter, as well as aspects of the

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phytoplankton and zooplankton assemblages. A project emphasis was to investigate interactions between the plume's physical structure and biogeochemical processes. For example, we hypothesized that biogeochemical processes that are mediated by photochemistry, such as primary production, colored dissolved organic matter (CDOM) degradation, and production of dissolved gaseous mercury, would fundamentally differ between upwelling and downwelling events because light levels in a thin upwelling plume would be elevated relative to light fields in a thick, and potentially more turbid (if bottom attached), downwelling plume.

These objectives were founded on a classic view of a buoyant discharge (i.e., coastal current formation and the response of the coastal current to along-shore wind stress). Results from LaTTE revealed, however, a much more complex

plume structure not adequately captured by the classic model. In particular, results emphasized that the plume's outflow was in fact susceptible to bulge formation, that the outflow was highly sensitive to meteorological forcing, and that the plume, even though it was surface advected, appeared to be influenced by the underlying topography. The major topographic feature on the shelf, the Hudson Shelf Valley (HSV) bisects the entire 150-km-wide shelf from near the shelf break to within 10 km of the Hudson outflow (Figure 1). The HSV, the ancestral channel of the Hudson, is ~ 50–70 meters deep. Together, coastal currents, bulge formation, sensitivity to wind forcing, and interaction with shelf topography and circulation produce distinct “modes” of freshwater transport that in aggregate drive a rapid cross-shelf mixing of freshwater (Castelao et al., 2008a; Zhang et al., in review-a).

Because the biogeochemical transformations of interest in LaTTE occur over a range of time scales (Moline et al., this issue), describing the details of both the near-field plume dynamics and broader shelfwide dispersal of freshwater are critical to understanding the fate and transport of riverborne materials.

## FIELD OBSERVATIONS

The LaTTE field effort included a series of 2004–2006 cruises and mooring deployments in the New York Bight (Figure 1). Each field campaign featured dye studies whereby rhodamine dye was injected into plume water to provide a Lagrangian framework from which to interpret physical, biological, and chemical data. Drifters were deployed with the dye to guide in tracking the dye and provided additional Lagrangian data to characterize plume trajectories. Details of the dye studies can be found in

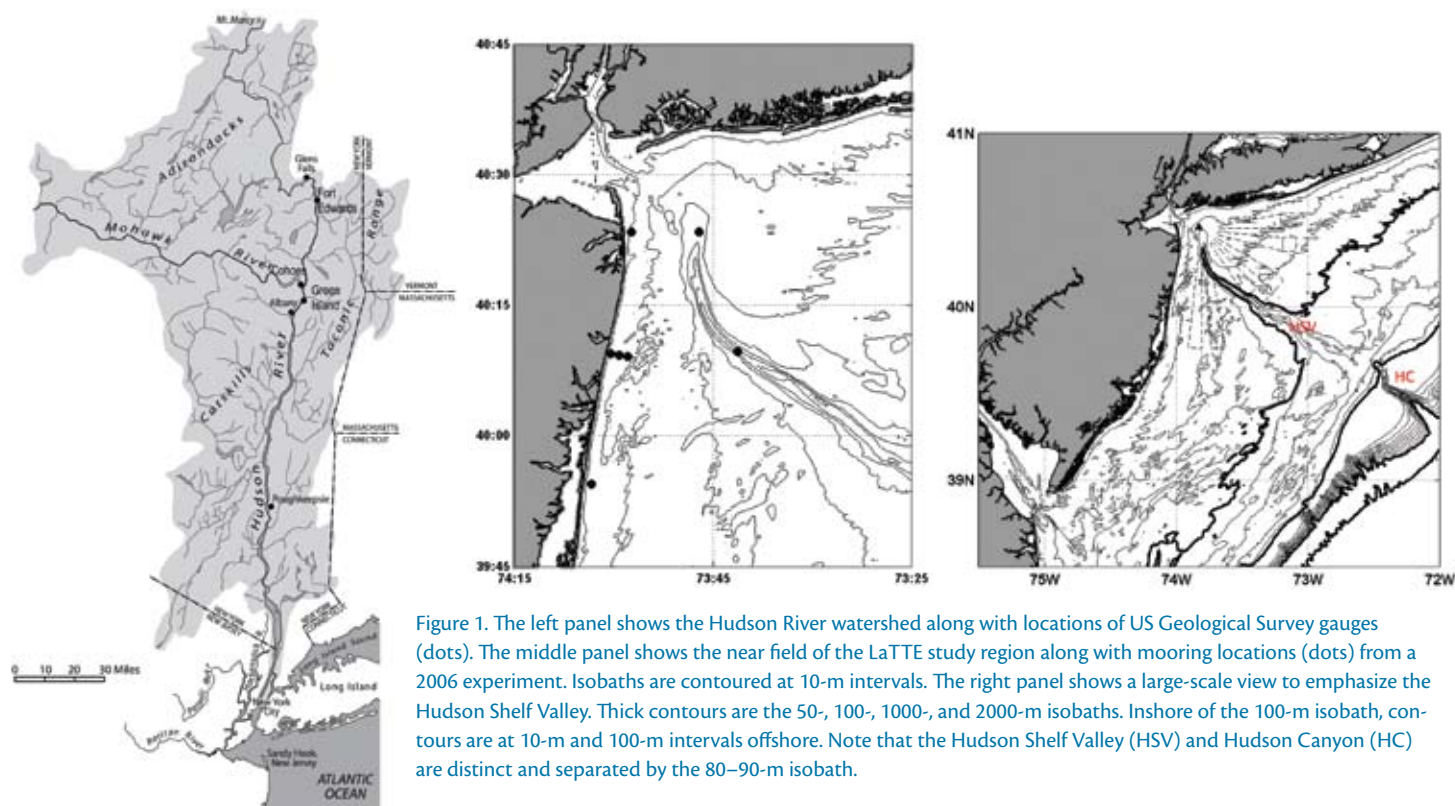


Figure 1. The left panel shows the Hudson River watershed along with locations of US Geological Survey gauges (dots). The middle panel shows the near field of the LaTTE study region along with mooring locations (dots) from a 2006 experiment. Isobaths are contoured at 10-m intervals. The right panel shows a large-scale view to emphasize the Hudson Shelf Valley. Thick contours are the 50-, 100-, 1000-, and 2000-m isobaths. Inshore of the 100-m isobath, contours are at 10-m and 100-m intervals offshore. Note that the Hudson Shelf Valley (HSV) and Hudson Canyon (HC) are distinct and separated by the 80–90-m isobath.

Houghton et al. (in review). All observations were conducted within the Rutgers University Coastal Ocean Observing Laboratory (RU COOL), which facilitated the field effort by providing real-time data from gliders, Coastal Ocean Dynamics Applications Radar (or CODAR, a high-frequency radar system used to measure the surface currents of the coastal ocean), and satellite imagery to guide ship operations. The observatory also provided large-scale context to interpret the shipboard and moored observations by extending the observations in both space and time, such as described in Castelao et al. (2008a, b). Finally, LaTTE included physical and biogeochemical modeling (Choi and Wilkin, 2007; Cahill et al., 2008; Zhang et al., in review–a, b), which was essential in providing a coherent framework to characterize annual variability in the plume’s structure and transport pathways. Modeling efforts used the Regional Ocean Modeling System (ROMS; [http://](http://www.myroms.org)

[www.myroms.org](http://www.myroms.org)) that was forced by tides, winds, and remotely forced flows at the offshore boundaries as specified by Lentz (2008). Horizontal resolution in the model was approximately 1 km and covers the New Jersey coastal area from eastern Long Island south to Delaware Bay, and offshore to approximately the 70-m isobath. Details of the model setup and numerics within can be found in Zhang et al. (in review–a, b) and Choi and Wilkin (2007).

The three-year field effort emphasized significant yet coherent variability of the structure and trajectory of the Hudson outflow. Variability was characterized by various modes of the plume’s structure that were comprised of a blend of surface-advected coastal currents, bulge formation, and the response of these features to wind forcing.

In 2004, we conducted two dye studies. In one of the studies, we injected dye in a surface-advected coastal current that formed along the New Jersey

coast (Figure 2a). The behavior of this current was largely consistent with classic theory. The downshelf speed of the current, drifter, and dye was close to the internal wave speed,  $c = \sqrt{g'h}$ , where  $h$  is the thickness of the coastal current and  $g'$  is reduced gravity and equal to  $g\Delta\rho/\rho$ , where  $g$  is gravity,  $\Delta\rho$  is the density difference between the plume and ambient shelf waters, and  $\rho$  is the density of the shelf waters. Also consistent with theory, the plume’s width was approximately one internal Rossby ( $R=c/f$ ) radius wide, where  $f$  is the local Coriolis frequency. The coastal current formed in response to downwelling-favorable winds. During subsequent upwelling winds, the plume was arrested, advected offshore, and eventually mixed away into the coastal ocean. This reversal is evident in the drifter trajectory (Figure 2a). Note that discontinuity in drifter trajectory occurred because we moved the drifter back toward the center of the dye. In general, the response of

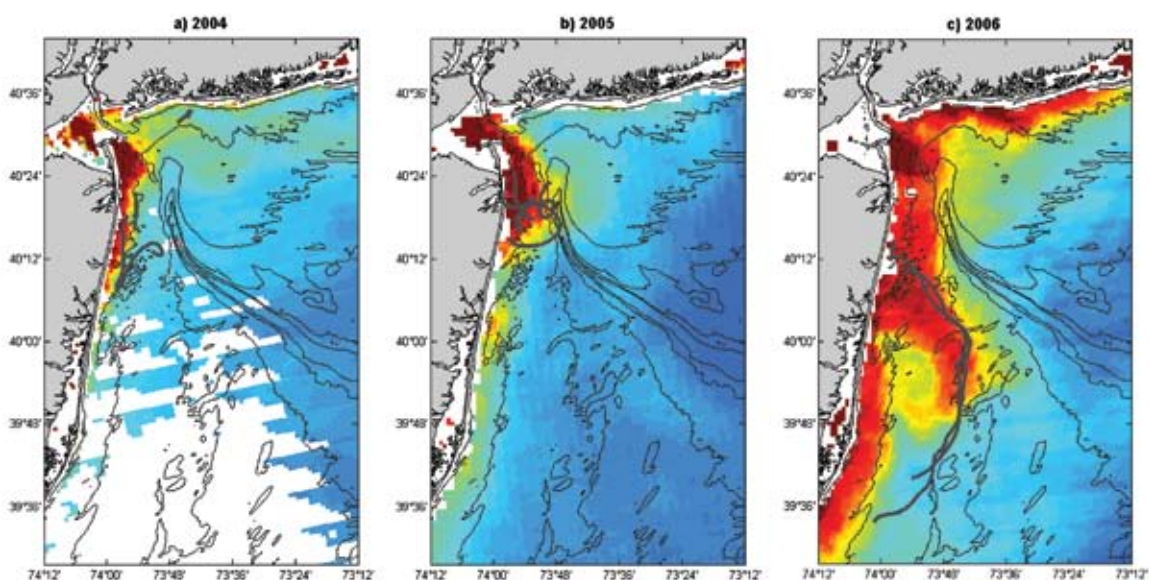


Figure 2. Sea-surface temperature (SST) images from each of the three LaTTE field seasons along with drifter trajectories (thick dark lines). Plume water is warmer (red) relative to cool (blue) offshore waters. Isobaths (thin contours) are at 10-m intervals.



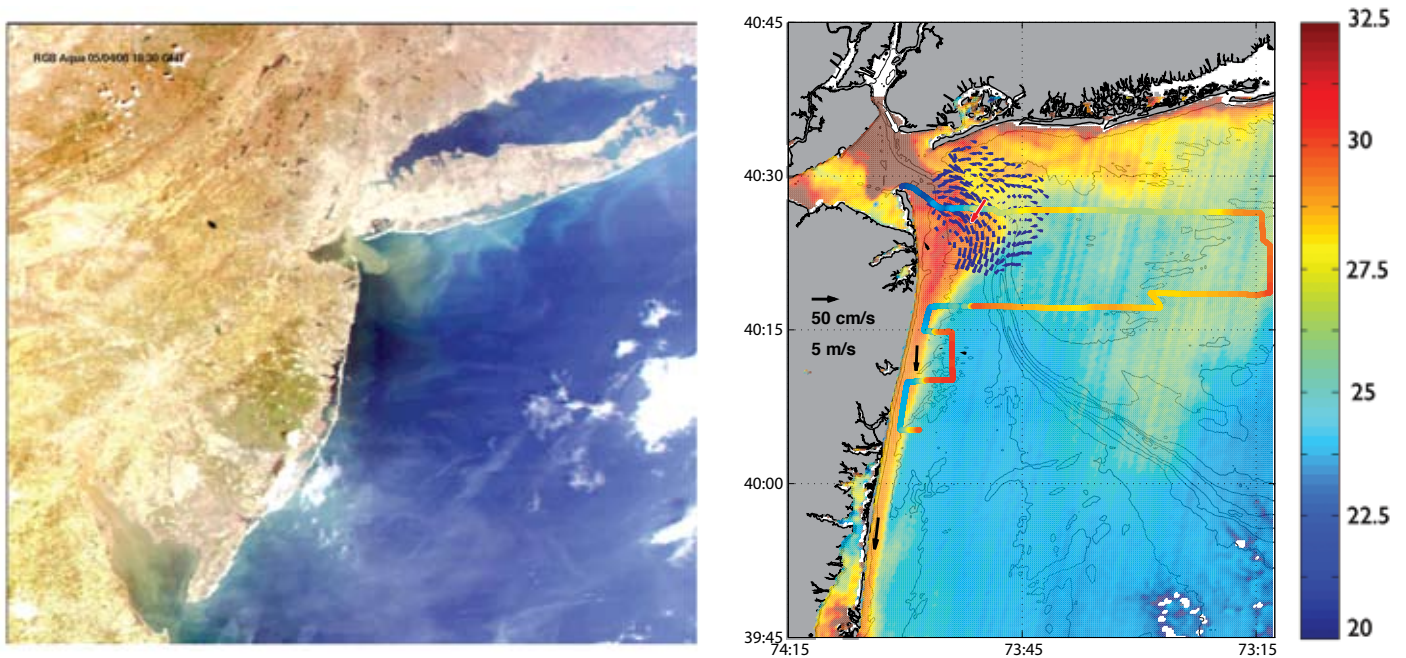


Figure 3. (Left panel) RGB (red-green-blue) image from April 5, 2005, during peak river discharge. Note that the plume is exiting the estuary and heading to the east toward Long Island. (Right panel) Image obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on April 9 for absorption at 448 nm; the color scale is relative, with red representing high absorption and blue representing low absorption. Blue arrows (top left in colored area) show the Coastal Ocean Dynamics Applications Radar (CODAR) field, black arrows (near coast) from shelf moorings, white arrow (in outflow region) from NOAA mooring at the Narrows; the red vector (roughly middle of blue arrows) represents winds from Ambrose. The color bar is for surface salinity from the ship track shown in the figure. All current data have been low-pass filtered.

the plume to upwelling winds was consistent with Fong and Geyer (2001) and is discussed in more detail in Houghton et al. (in review).

In 2005, we conducted a field effort immediately following a 10-year flood in the Hudson River Basin, with shipboard surveys commencing four days after the peak in river discharge on April 5 at just under  $8000 \text{ m}^3 \text{ s}^{-1}$ . The plume's behavior during the 2005 field effort was radically different than in 2004 and was characterized primarily by bulge formation, although both coastal currents and plumes driven eastward by wind along the Long Island shore were also evident. For example, immediately following the peak discharge on April 5, 2005, winds were strongly upwelling favorable and the plume was advected eastward and

toward the Long Island coast (Figure 3a). A CTD survey on April 9 revealed that a lens of brackish water extended 70 km east of the outflow and along Long Island's south shore; the lens is also evident in satellite imagery (Figure 3b). A series of satellite images and shipboard surveys indicated that this plume eventually moved south and was found to reside along the western side of the HSV on April 13 (Figure 4). The April 9–10 survey also revealed that a bolus of freshwater extended out of the Hudson and that a surface-advected coastal current emanated from it and flowed along the New Jersey coast (Figure 3b). As was the case in 2004, the downshelf propagation speed of the front, as inferred from consecutive satellite imagery and moored data, was close to the internal

wave speed. Moreover, the cross-shore dynamics were largely geostrophic, which implies that the freshwater transport is proportional to  $(g'h)^2$  (Fong and Geyer, 2002).

The transport of freshwater in the coastal current, however, was only one-third to one-half of the transport of freshwater to the coastal ocean (Chant et al., 2008). Subsequently, most of the freshwater entering the coastal ocean recirculated in a growing bulge at the mouth of the estuary. The retention of estuarine fluid in the bulge region was confirmed by dye releases and drifters that were deployed in new plume water and remained in the vicinity of the outflow for approximately one week (Figure 2b). The growth of this bulge was apparent in the April 13–14

survey, which showed a thin bolus of chlorophyll-rich brackish water extending eastward (Figure 4). Estimates of the freshwater volume of this bolus indicate that most of the discharge that had occurred since its inception on April 9 remained in the bulge with only a small fraction transported away in the coastal current (Chant et al., 2008). Moreover, chemical tracers suggest that the fluid in the coastal current is fed by aged fluid in the bulge that has undergone significant biogeochemical processing. For example, while nitrate levels remained elevated in the outflow during this event, nitrate levels quickly fell to less than 2  $\mu\text{M}$  in the coastal current. Moline et al. (this issue) discuss the biological and chemical consequences of this bolus and conceptualize the bulge as a chemostat fed by estuarine waters that in turn feed biogeochemically processed waters to the coastal current.

The bulge's structure was also modified by shelf circulation as suggested by

Fong and Geyer (2002). In particular, during upwelling-favorable winds, a jet develops that transfers freshwater from the bulge toward the shelf break along the inshore side of the HSV. This rapid cross-shelf advection of the plume was documented following a second "10-year flood event" during summer 2006 (Castelao et al., 2008a). Glider data revealed that following the flood event, freshwater was transported over 100 km from the coast in fewer than two weeks. Analysis of surface current data revealed a transport pathway that advected the outflow cross-shelf. This pathway was associated with a cross-shelf jet that resides along the 40–50-m isobath on the inshore side of the HSV. The timing of this jet was correlated with persistent upwelling winds and was evident in overlaid surface velocity data, satellite imagery, and drifter trajectories (Figure 5) that show cool water from the Long Island coast extending offshore in a jet

that resides along the 40–50-m isobath (Figure 5, left panel). Note that the drifter trajectory was from July 26–30 while the satellite and CODAR images are from August 11. Nevertheless, both show the jet originates along the 40–50-m isobath on the inshore side of the HSV. Chlorophyll-*a* imagery suggests that the jet entrained biomass from the bulge region and advected it cross shelf along the inshore side of the jet (Figure 5b). Late spring/early summer shelfwide freshening was also observed in glider data from previous years (Castelao et al., 2008a; Chant et al., 2008); this seasonal shelfwide freshening is driven by the seasonal transition from downwelling- to upwelling-favorable winds (Castelao et al., 2008b) associated with springtime development of the Bermuda high. These springtime southerly winds warm the continent and melt the watershed's snow-pack; thus, the seasonal wind reversal tends to coincide with the spring freshet.

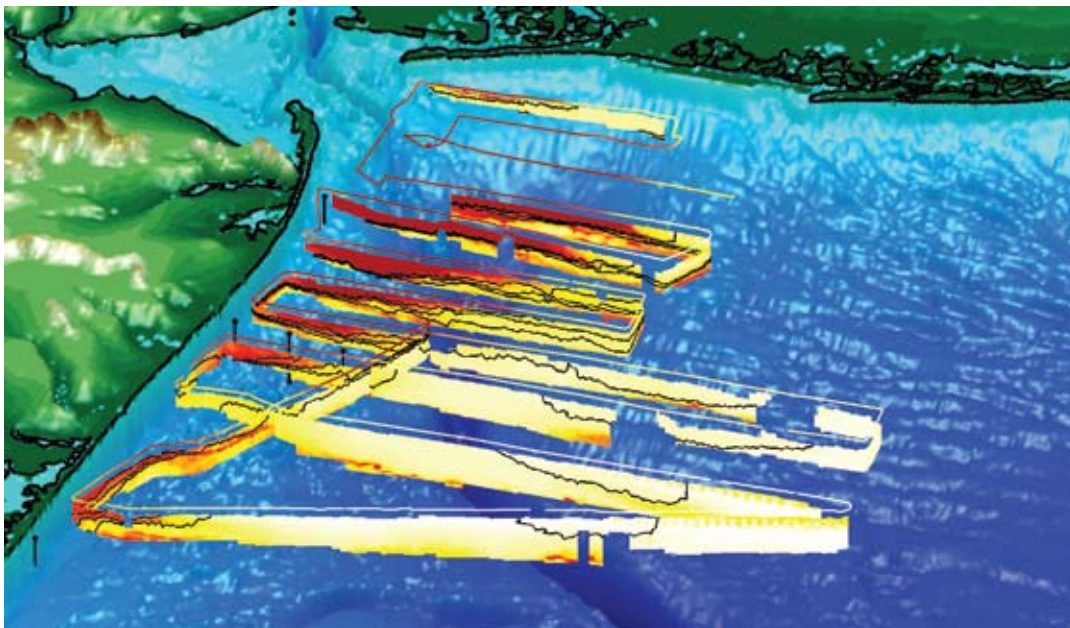


Figure 4. Contours are the 27, 28, and 29 isohalines. Color is chlorophyll *a* on a relative scale, with red representing high values; the bulge is characterized by high chlorophyll *a* values. The old plume over the Hudson Shelf Valley is devoid of plankton but less than 29. Note that the single isohaline on the offshore side of the last four sections is the 29 isohaline.



Consequently, the midshelf freshwater pathway likely represents a robust mechanism that rapidly transports the spring freshet water across the continental shelf to the shelfbreak. We note that climate models are sensitive to the details of how freshwater mixes into the deep ocean (Garvine and Whitney, 2006); the timing between a watershed's freshet and seasonal wind patterns likely plays an important role in this process.

Although the summer 2006 event described above occurred during a high-discharge event, the major LaTTE field efforts in 2006 followed a moderate-discharge event, with flows peaking at  $1500 \text{ m}^3 \text{ s}^{-1}$ . The plume structure was again different from previous years and characterized by a remarkably steady feature that consisted of a coastal current extending from Sandy Hook approximately 30 km south. However, this coastal current veered offshore (bypassing our central mooring array!)

and flowed downshelf as a detached jet of freshwater (Figure 2c). Mean current velocities in the jet were to the south at  $25\text{--}30 \text{ cm s}^{-1}$ , while surface currents at the inshore mooring were to the north at speeds up to  $\sim 20 \text{ cm s}^{-1}$  and salinities of  $28\text{--}29$  (Figure 6c). A more detailed view of the flow structure is apparent in shipboard ADCP data (Figure 6a) and satellite imagery (Figure 2c), which indicated that the flow structure involved recirculation of plume water. This feature's stability was apparent in a suite of satellite imagery and shipboard surveys. For example, the satellite image in Figure 2c taken on April 28 shows a clear separation of plume waters (red in the image) just north of the mooring array and a recirculation to the south and offshore. An ADCP survey on May 2–3 (Figure 6a) picked up this jet, and indicated that its offshore veering was in approximately the same location as the satellite imagery four days earlier.

Moreover, the drifter trajectories between May 4 and 8 closely followed this jet, further emphasizing its steadiness. Although current speed in the jet, as indicated by the speed of the drifters, modulated with wind forcing (Figure 6c), the offshore jet remained evident in a final ADCP survey on May 10 (not shown).

In summary, the LaTTE field studies revealed significant variability in the structure of the Hudson outflow. We classify this variability into three distinct modes. The first mode is the classic surface-advected coastal current that propagated down the New Jersey coast at the internal wave speed. The coastal-current mode tends to occur during low to moderate discharge with downwelling-favorable winds. Although we never observed a bottom-attached coastal current, we suspect that one would develop under strong northerly winds. Upwelling winds of  $5 \text{ m s}^{-1}$  easily arrested this plume, advected it offshore, and mixed

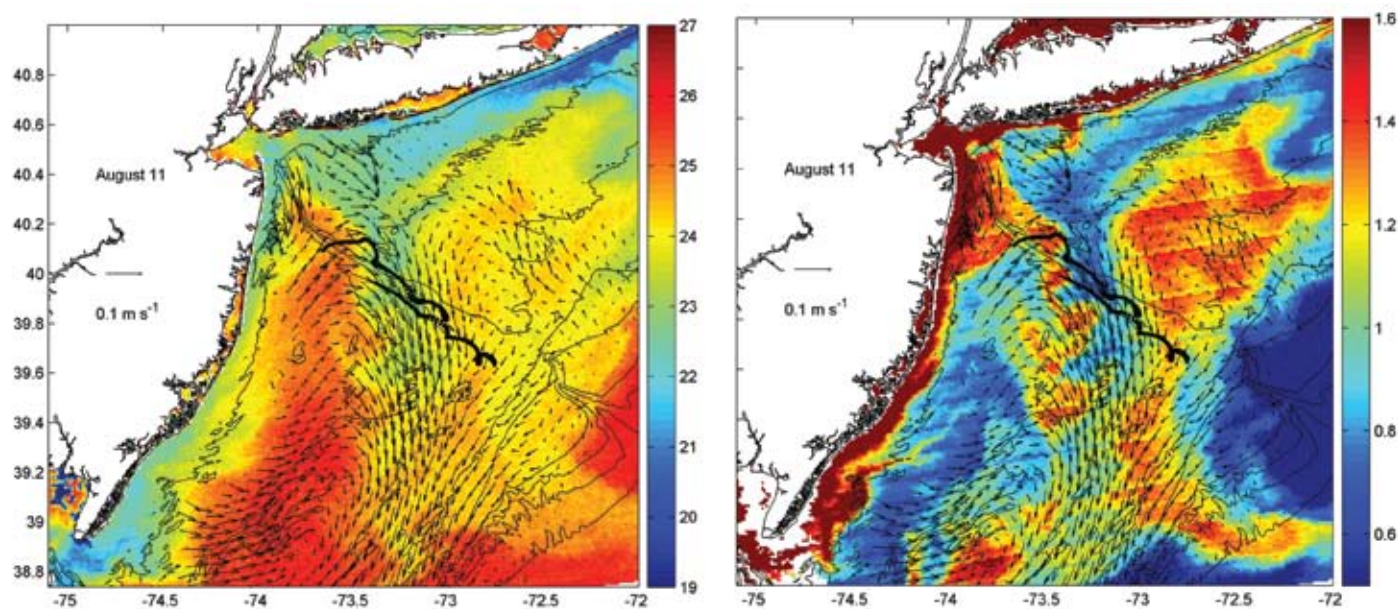


Figure 5. Both panels show surface currents weighted with a one-sided exponential filter as described in Castelao et al. (2008a). Left panel shows SST while the right panel shows chlorophyll *a* ( $\text{gm C m}^{-3}$ ). Both images are from August 11, 2006. Also shown are drifter trajectories from July 26–28, 2006. Together, the images suggest an offshore transport of cold water and high chlorophyll *a* by the midshelf jet just inshore of the Hudson Shelf Valley.



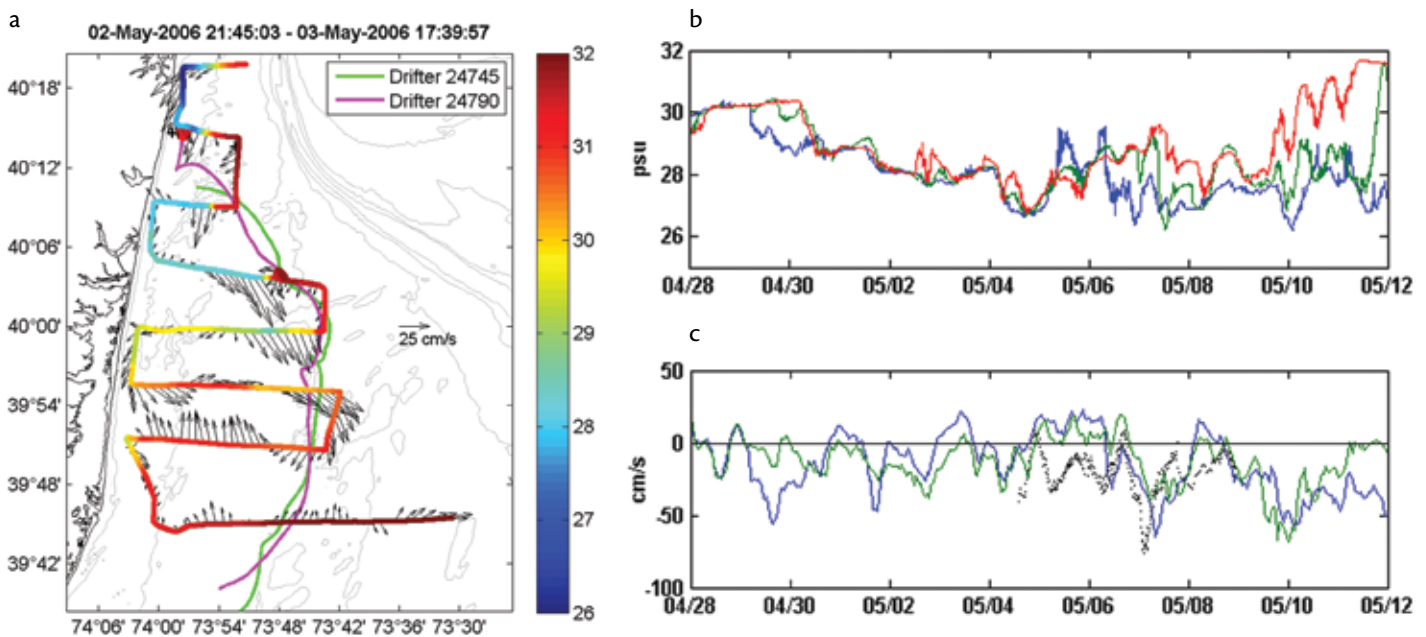


Figure 6. (a) Currents 3.5 m below surface from the May 2–3 shipboard survey along with a drifter trajectory between May 4–8. Note that the drifter track is the same as shown in Figure 2c. (b) Surface salinity from the central mooring array. Top surface salinity from inshore (blue), middle (green), offshore (red). (c) Alongshore surface velocities from inshore (blue) and offshore moorings (green) and alongshore velocity of drifters (dashed). Positive velocities are to the north.

it into the coastal ocean as suggested by the modeling studies of Fong and Geyer (2001) and Choi and Wilkin (2007). A second mode of outflow was characterized by bulge formation, which occurred during moderate to high discharge and weak or upwelling-favorable wind forcing. With upwelling winds, the bulge became compressed along the Long Island coast and extended eastward. Once formed, the bulge's structure was strongly modified by wind forcing and shelf circulation with a particularly rapid cross-shelf transport pathway associated with a midshelf jet. Finally, a third mode was observed that consisted of a coastal current with a downstream recirculating region. Next, we present numerical simulations of the Hudson outflow to provide a more detailed characterization of the spatial and temporal structure of the plume, of the processes that control this structure, and ultimately the freshwater transport pathways.

## NUMERICAL MODELING OF THE PLUME

The variability we observed in the plume's structure raises the following questions: To what extent is the observed variability representative of its typical behavior? Alternatively expressed: What is the relative importance of each "mode" of outflow and what is the seasonal variability of these modes and of these transport pathways? To address these questions in greater detail, we ran numerical simulations, first in a process study (Choi and Wilkin, 2007) and later with realistic forcings (Zhang et al., in review–a, b). The process study related variability in the model plume's structure to variations in river discharge and wind forcing and focused on the near-field plume dynamics while the realistic simulations characterized the plume's seasonal climatology based on a three-year simulation.

Choi and Wilkin (2007) explored

the sensitivity of the plume structure to variations in river discharge with a set of simulations with low ( $500 \text{ m}^3 \text{ s}^{-1}$ ) and high ( $3000 \text{ m}^3 \text{ s}^{-1}$ ) river discharge. Sensitivity to winds was assessed by forcing each of the discharge cases with constant winds from each of the four compass directions. Details of the forcing and model setup can be found in Choi and Wilkin (2007). In general, these simulations emphasized the tendency for bulge formation to occur under high discharge, and the tendency for sensitivity of the plume to wind forcing under both high and low flow conditions. Moreover, the simulations revealed that in addition to the direct action of the wind on the plume, the ability of the estuary to store and release freshwater under variable wind forcing modified plume structure. For example, for the low (and constant) river discharge case, more freshwater exited the estuary when winds blew from the west

than from the east for several days after the onset of steady winds. Although the estuary's outflow must eventually match the prescribed freshwater fluxes on a 2–5-day time scale, there can be significant mismatch because the estuary tends to store water while winds blow from the east and release water when winds blow from the west. This was noted by Lerczak et al. (2006), who found that freshwater flux measured by a mooring array in the lower Hudson River varied between  $200 \text{ m}^3 \text{ s}^{-1}$  upstream and  $2000 \text{ m}^3 \text{ s}^{-1}$  downstream during a time period when river flow was relatively constant at  $\sim 500 \text{ m}^3 \text{ s}^{-1}$ . Subsequently, the transport of freshwater from the estuary to the coastal ocean is strongly modified by meteorological forcing, and has two implications. First, because bulge formation tends to increase with discharge, pumping of the outflow by meteorological forcing will augment bulge formation. Second, it emphasizes

the necessity for models to resolve both estuarine and coastal geometry in modeling river plumes because the ability of the estuary to store freshwater is a function of the estuary's geometry.

Choi and Wilkin's (2007) model results emphasized that bulge formation became more prominent during high-discharge events as anticipated by Fong and Geyer (2002). Choi and Wilkin (2007) also demonstrated the sensitivity of the plume to winds under high-discharge events. Moreover, the modeled plume structure was similar to the outflow structure we observed in 2005. For example, upwelling winds transport freshwater along the Long Island coast while onshore and/or downwelling winds compress the bulge against the New Jersey coast, causing a coastal current to leak out. Choi and Wilkin's (2007) simulations also show the estuarine outflow forming a clockwise jet around the outer edge of the bulge (Figure 7).

When the jet reaches the coastal wall, it bifurcates, with a fraction of the jet feeding the coastal current and the remaining fluid feeding bulge formation. Implications of the model predictions are that in the absence of variable wind forcing, the coastal current would be essentially fed with new estuarine waters while the bulge would contain a mixture of new and old estuarine waters.

The aforementioned model runs were forced with steady winds; thus, while the bulge may be unsteady (i.e., growing in time), its growth is monotonic. In contrast, variable wind forcing would cause the bulge's structure to fluctuate, moving to the east during upwelling and/or eastward winds, and then compressing it along the New Jersey coast during downwelling and/or westward winds. As this fluctuation occurs, the bulge would be filled with fluid during its eastward expansion in response to upwelling winds, while downwelling winds would

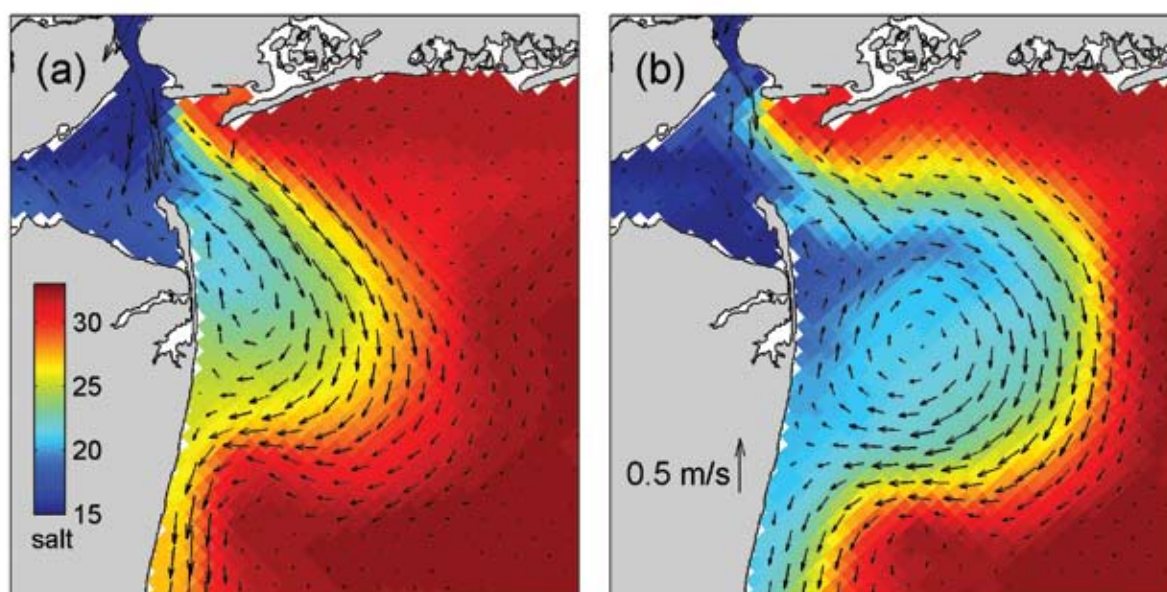


Figure 7. Surface salinity (color) and velocity from a model run without wind forcing and a discharge at  $3000 \text{ m}^3 \text{ s}^{-1}$ . Panel (a) is at mode day 13, and panel (b) is day 20.



compress the bulge against the coast causing a coastal current to leak out of it. Chant et al. (2008) clearly identified such fluctuations in coastal current transport in moored data both at the 2–5-day time scale and at the diurnal frequency. Therefore, this variable wind forcing, and thus bulge structure, will supply the coastal current with biogeochemically processed water from the bulge rather than new estuarine waters that circulate around the bulge's perimeter. The tendency for the coastal current to be supplied by aged bulge water was apparent in biogeochemical data as noted by Moline et al. (this issue).

Multiyear numerical simulations by Zhang et al. (in review–a, b) characterized both shelfwide and seasonal freshwater transport pathways. These simulations also captured the modes of plume structure that we observed in the field and in observatory data (i.e., coastal current formation and unsteady bulge formation). Moreover, these model runs characterized the modes' seasonal variability and placed them in context with the shelfwide dispersal of freshwater that is accomplished by the three freshwater transport pathways: the New Jersey coastal current pathway, the Long Island upwelling/bulge pathway, and the

midshelf pathway. These results are concisely described by Figure 8a–c, which depicts the freshwater transport during model year 2005 and 2006 across an arc 100 km south of the Hudson outflow that runs between the New Jersey (km 0) and the Long Island (km 200) coasts (arc 5 on Figure 8d and e). A clear seasonality to the pathway is evident, with freshwater pathways largely confined to the New Jersey coast during the winter months, and with a smaller pathway along the Long Island coast. In contrast, during the summer months, freshwater transport is focused along the midshelf pathway westward of the HSV. This temporal

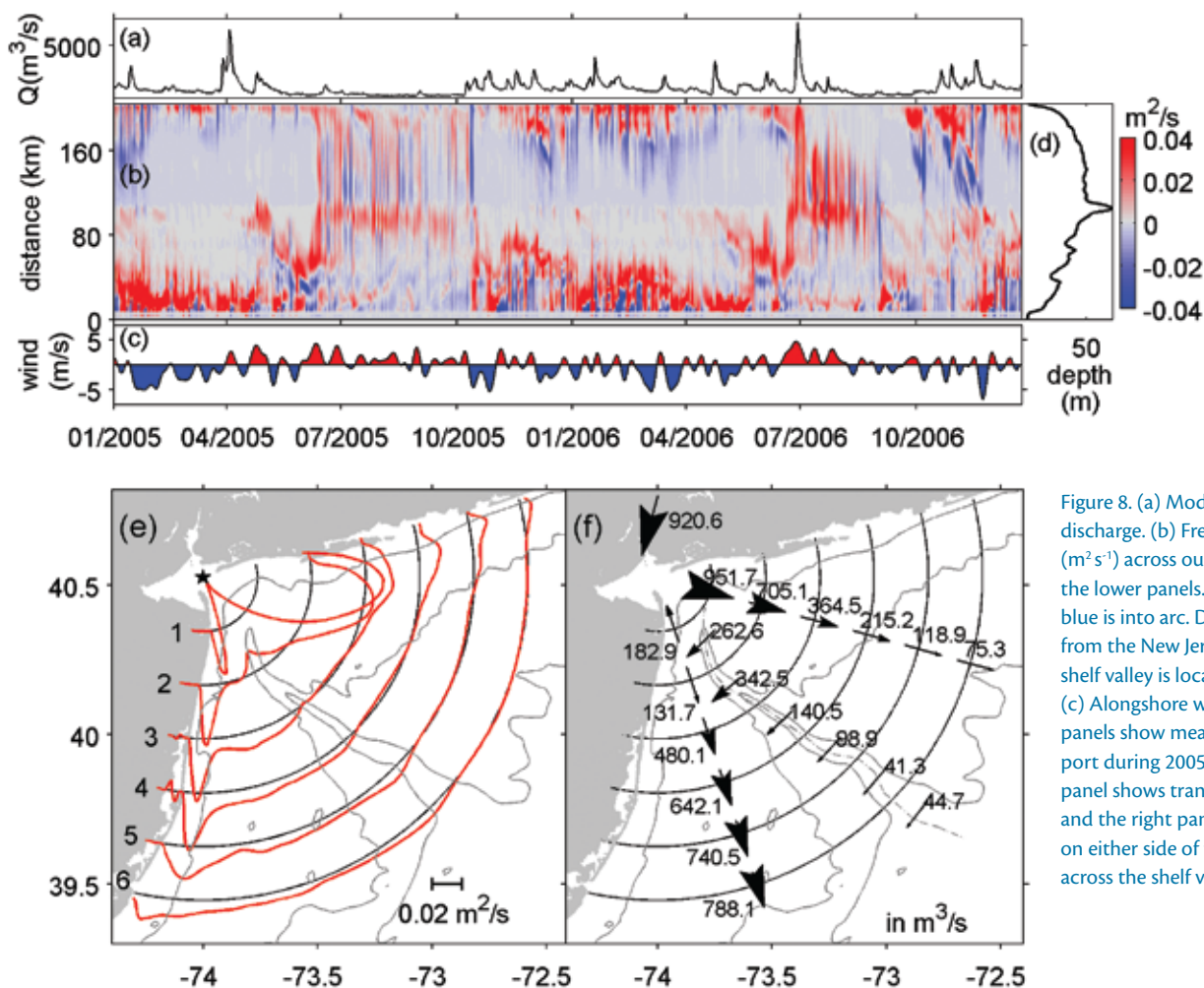


Figure 8. (a) Model-prescribed river discharge. (b) Freshwater transport ( $\text{m}^2/\text{s}$ ) across outer arc 5 shown in the lower panels. Red is out of arc and blue is into arc. Distance is kilometers from the New Jersey shore. The shelf valley is located around km 90. (c) Alongshore winds. The lower two panels show mean freshwater transport during 2005 and 2006. The left panel shows transport per unit width, and the right panel shows transport on either side of the shelf valley and across the shelf valley.

transition between the coastal pathways and the midshelf pathway coincides with the seasonal change in wind from downwelling favorable during the winter months to upwelling favorable during the summer months, and is similar to results obtained from observatory data described in Castelao et al. (2008a).

In addition, the modeled Long Island and New Jersey coastal currents are frequently associated with both upshelf and downshelf freshwater fluxes, as indicated by the red/blue banding in Figure 8b, such as along the New Jersey coastline (km 0–20) early in 2006. These fluxes are indicative of a clockwise recirculation of freshwater along both coasts. Along the New Jersey coast, this recirculation is consistent with observations, such as the quasi-stationary eddy we observed in 2006 (Figures 2c and 6a), with freshwater moving downshelf on the offshore side and freshwater moving upshelf on the inshore side.

Recirculation along the Long Island coast transports freshwater to the east at the coast and recirculates it back to the west offshore. Although this recirculation is consistent with bulge formation, it is also related to an interaction of the bulge with remotely forced downshelf flows on the shelf that increase in strength with distance from the bight apex (Zhang, et al., in review–a, b). The mechanism driving recirculation along the New Jersey coast is unclear and is currently under investigation. However, one important consequence of New Jersey coastal recirculation is that it appears to significantly reduce the speed of freshwater transport downshelf, which, when coupled to a range of time scales associated with biogeochemical processing of material in the plume, is

likely to impact the fate and transport of riverborne material. This slow downshelf propagation of the recirculation may explain the 40-day lag observed by Yankovsky and Garvine (1998) between river discharge and the appearance of freshwater 100 km to the south because coastal currents, traveling at the internal wave speed, would arrive in a few days. We further note that while many of these recirculation events along the New Jersey coast appear to be initiated by upwelling, some of them are not. For example, the New Jersey recirculation event that we observed in 2006 (Figure 6) occurred during persistent downwelling winds and did not appear to be initiated by upwelling winds. It may be related to impulsive discharge (Yankovsky et al., 2004) or associated with lateral shears that develop across the HSV (Harris, et al., 2003).

Together, these transport pathways disperse freshwater across the New York Bight. This dispersal is characterized by model estimates of the mean freshwater flux across a series of concentric arcs centered at Sandy Hook (Figure 8d, e). The mean freshwater transport structure emphasizes the importance of bulge formation. For example, the time-mean freshwater transport along the New Jersey coast at Sandy Hook is actually upshelf and opposed to the expected downshelf transport (Figure 8e). Model simulations indicate that while tides augment this recirculation, recirculation persists even in the absence of tides. To the east, the freshwater flux along the Long Island coast weakens and recirculates back westward and over the shelf valley before heading cross-shelf along the 40–50-m isobath. Freshwater transport along the New Jersey coast occurs

through a rapid jet; however, the maximum value is distinctly off the coast due to the frequent coastal recirculation that drives upshelf freshwater transport near the coast. Freshwater transport across the outer arcs is relatively evenly distributed west of the HSV. However, this distribution is likely due to ensemble averaging rather than a blending of coastal and midshelf pathways. Interestingly, the freshwater transport is sharply cut off at the shelf valley and appears to be related to remotely forced flows (Zhang et al., in review–a, b). This cutoff also suggests that dissolved material exiting the Hudson River, with reactive time scales of a week or longer, will be distributed primarily to the west of the HSV.

## SUMMARY

There were several surprising physical results from the LaTTE field and modeling efforts. First, although coastal currents were frequently observed in the near field, freshwater dispersal was largely accomplished through bulge formation. Indeed, modeling efforts revealed that freshwater transport in a section ~ 10 km from the mouth was *toward* the estuary and fed a mean freshwater recirculation that takes place over a 50–100 km region near the mouth. This recirculation tends to drive the new estuarine discharge toward Long Island and thus water quality in these inland bays may frequently be more impacted by the harbor's discharge, perhaps even more so than the communities along New Jersey's northern shore. We also found that the outflow appeared to be influenced by the underlying bathymetry, which is dominated by the HSV. This interaction is not direct, but rather the plume is interacting with barotropic shelf flows that are



directly steered by bathymetry, such as strong lateral shears that develop across the HSV (Harris et al., 2003).


Although many of the aspects of the Hudson's outflow are consistent with modeling investigations (Fong and Geyer, 2002; Choi and Wilkin, 2007), results from this study together with recent results from the River Influences on Shelf Ecosystems (RISE) project (Kudela et al., this issue; Hickey et al., this issue; Samelson et al., this issue) provide perhaps the most direct observational evidence of bulge formation that heretofore was studied primarily with numerical models and laboratory experiments. Results also emphasized the important role of bulge formation in driving cross-shelf transport of freshwater. We note that in the far field, plume structure appears as a wide coastal current. Indeed, the distribution of freshwater transport in the outer arc in Figure 8d is characterized by broad features as is the cross-shore structure of the annual mean salinity based on glider data (Castelao et al., 2008b). However, the freshwater pathway that produced the broadly distributed freshwater transport pathway was not solely the result of upwelling winds acting on a coastal current but also was significantly influenced by bulge formation and rapid cross-shelf advection associated with a cross-shelf jet along the 40–50-m isobath (Castelao et al., 2008a). Although the dynamics that underlie this cross-shelf jet remain elusive, it appears to be initiated by persistent upwelling winds (Castelao et al., 2008a). Several other studies have noted frontal systems in this region (Bumpus, 1973; Biscaye et al., 1994; Ullman and Cornillon, 1999), and analysis of long-term hydrographic data from the Mid-

Atlantic Bight also revealed a shelfwide freshening that was localized in the New York Bight region (Mountain, 2003).

Finally, the tendency for the Hudson's outflow to recirculate near the apex rather than rapidly advect away in a coastal current has significant implications for biogeochemical pathways. For example, nutrient uptake and primary production was so rapid in this region (Moline et al., this issue) that by the time the outflow reached the coastal current, primary production was nutrient limited, and high phytoplankton biomass in the bulge crashed and settled to the bottom. Furthermore, temporary retention of material in the apex region also appears to impact the fate and transport of contaminant metals (Moline, this issue). Thus, material that is rapidly cycled in the plume may quickly settle out into the landward-flowing lower layer where it may be transported back into the estuary, increasing the estuary's trapping efficiency of both terrestrial and biogenic particulate matter. On the other hand, material that remains dissolved in the plume for weeks will be rapidly mixed across the shelf.

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*Editor's Note: Oceanography does not usually permit citation of articles that are in review; however, because of the rapidly advancing nature of this issue's topics, we are making an exception. Updates on the status of manuscripts cited as in review here will be posted on the CoOP Web site (<http://www.skio.usg.edu/coop>).*

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