Studying the Dynamics and Biological Significance of the Hudson River Using an Ocean Observatory

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***Abstract-* The Lagrangian Transport and Transformation Experiment (LaTTE) was designed to quantify how physical, biological and chemical processes transform material in a buoyant river plume and to link these processes to wind forced changes in the plume structure. The three LaTTE field programs included a May 2004 pilot, a full scale effort in April 2005, and a final study in May 2006. In each field study, dye was released and tracked by two vessels for physical, biological and chemical sampling of the tagged water mass. The field study and data assimilation segments of LaTTE relied on a research-based coastal ocean observatory to provide a temporal and spatial context for these intensive process studies. The observatory included a shelf-wide observational backbone (international satellites, nested HF Radars, and autonomous underwater gliders) that was locally enhanced with high-resolution relocatable moorings in the New York Bight apex for the process studies. During the experiments, a shore based operations center combined real-time datasets with forecasts from a high-resolution atmospheric model (WRF) and hindcasts from an ocean model (ROMS) to provide adaptive sampling guidance to the research vessels. Results from the April 2005 and the May 2006 process studyies will be reviewed. During the strong outflows of April 2005, the ebb tide squirts flowing onto the shelf were observed to respond to a strong sea breeze, forming a recirculating eddy just south of the Harbor entrance. The eddy served as an incubator for biological productivity, resulting in high phytoplankton concentrations leading to depleted bottom dissolved oxygen in a location consistent with historical observations. Only a portion of the fresh river water entering the recirculation zone exited as the expected coastal current along the New Jersey shelf. Most of the freshwater was observed to flow cross-shelf along the southern flank of the Hudson Shelf Valley, consistent with historical remote sensing data. This newly observed transport pathway can have potentially significant impacts on material transport from the Hudson River plume onto the continental shelf. In 2006, wind driven circulation resulted in the plume advecting south along New Jersey and eventually detaching into two pieces. In 2006, wind driven ROMS forecasts were successful at predicting the transport of the river as validated by the drifters and glider data.**

I. THE LATTE EXPERIMENT

Buoyant coastal currents fed by numerous rivers that are generally characterized by moderate flow rates extend along much of the US east coast. Despite these moderate flows, these buoyant plumes appear to dominate the transport of nutrients and chemical contaminants to the coastal ocean. This is especially true for the New York and New Jersey Harbor which arguably hold the grand distinction of being one of the most contaminated estuaries on the east coast. Therefore, understanding the transport of sediment and the associated material from the harbor to the coastal ocean is a fundamental problem for state and federal water quality managers. This is a difficult task considering how dynamic these plumes are in space and time. These plumes are modified by bottom

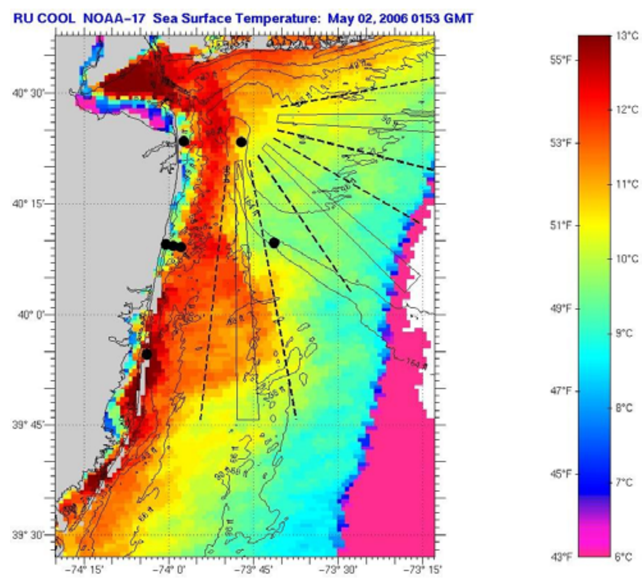

Figure 1. A sea surface temperature (SST) map off the New Jersey coast in May 2006. During this period the Lagragian Transport and Transformation Experiment (LaTTE) was conducted. As part of that field effort, a series of moorings (black circles) were deployed to capture the nearshore coastal and Hudson Canyon cross shore buoyant plume jets that are typical for this time of year. The deployment was based on several years of process studies prior to year of 2006. The currents and winds this year however resulted in the coastal jet detaching from the coast and passing between the fixed mooring arrays. The jet spread offshore after passing the offshore moorings. This illustrates the potential pitfalls relying on fixed Eulerian grids on continental shelves.

topography, shoreline geometry, atmospheric forcing, tides, and river outflow. This makes sampling a plume using moorings or fixed sampling grids impractical (Fig. 1). Therefore development of an adaptive sampling capability is a key need for coastal oceanography.

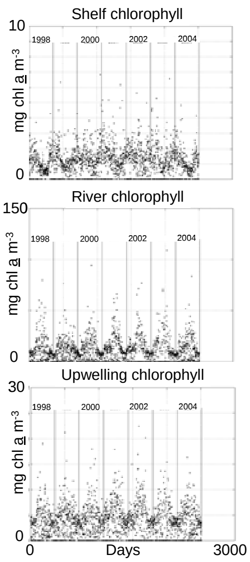

Fig. 2. The seasonal interannual chlorophyll a with the shelf (top panel), coastal upwelling (middle panel), and rivers (bottom panel)

The National Science Foundation's Lagrangian Transport and Transformation Experiment (LaTTE) program is focused on the physical circulation mechanisms that alter the transport and transformation of the chemistry and biology of the harbor plume as it flows into the coastal ocean. To monitor and adaptively sample the plume, this project relied on an ocean observatory. Rutgers University's Coastal Ocean Observation Lab provides real-time data from remote assets and the data is used to direct ship and gliders. The observatory is sustained allowing the river behavior to be placed in context of the entire MAB. Ocean color imagery and sea surface temperature provide maps that help define the spatial extent of the Hudson river plume. During field experiments, these daily composites are advected through time using the hourly data from the surface current radars. Data was compiled in real-time in the COOL room and transferred to ships at sea, using the nested communication network. This adaptive capacity allowed ships to adjust sampling strategies on the fly. Supplementing the ship data were Webb gliders that provide subsurface maps of the river plume. This data streams also allows model initialization and assimilation. *Here the scientist benefits from having a three dimensional picture of the plume and its contents over a time period sufficiently long to study the transformation of organic material. The environmental managers benefit from a real-time picture of the plume allowing adaptive sampling and increased understanding of potential deposit centers of pollutants, heavy metals, organic and inorganic particulates flowing out of the harbor. This paper will review the 1) biological significance of the Hudson River for the Mid-Atlantic Bight (MAB) and 2) the transport of biological material onto MAB using data from the 2005 and 2006 field seasons.*

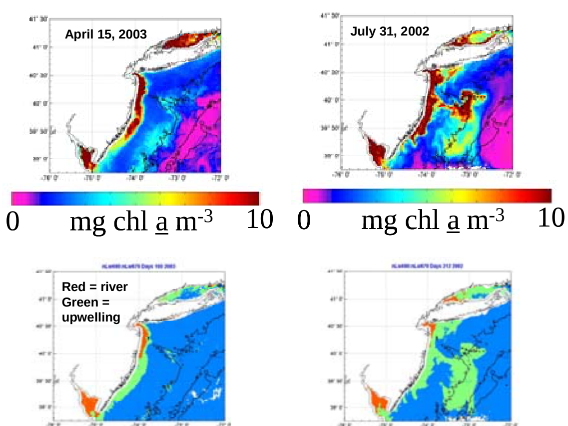

Figure 3. An example of the band ratio technique on two different satellite images. A statistically based value when the ratio was low, it indicates high CDOM water which on this shelf is associated with river water (delineated by red). The April 18th image of chlorophyll a is during heavy river outflow. As the river water ages as it flows along the NJ coast it mistakenly designates the river water as upwelling (green). Therefore the estimate of 25% of the chlorophyll a associated with rivers is a lower limit estimate. The July 31st image is during a large summer upwelling which was advected offshore.

II. THE BIOLOGICAL SIGNIFICANCE OF RIVERS TO THE PRODUCTIVITY OF THE MAB

The MAB is one of the most productive shelf ecosystems on Earth. It is characterized by relatively high mean chlorophyll a values (1-2 mg chl a m^{-3}) throughout the year with peak values found in late winter and early spring as the shelf waters begin to stratify (Fig. 2). Productivity values tend to be lowest during the highly stratified summer season when nutrients are low on the shelf. Superimposed on this is the productivity associated with rivers and summertime nearshore coastal upwelling. These different waters masses can be discriminated by the taking the ratio of blue to red wavelength satellite reflectances which is sensitive to the relative presence of colored dissolved organic matter (CDOM) and phytoplankton. The concentration of CDOM varies between river, shelf, and upwelling waters. This ratio allows the satellite derived chlorophyll a that is associated with upwelling, shelf waters, and rivers to be discriminated (Fig. 3). Using this discrimination technique, the annual budgets suggest that half of the chlorophyll a is associated with overall shelf productivity and the remaining 50% of the MAB chlorophyll is associated with rivers and upwelling. The rivers and coastal upwelling each contribute 25% of the total chlorophyll a. Therefore despite the relatively low outflow of the Hudson river it provides a disproportionately large contribution to the MAB productivity.

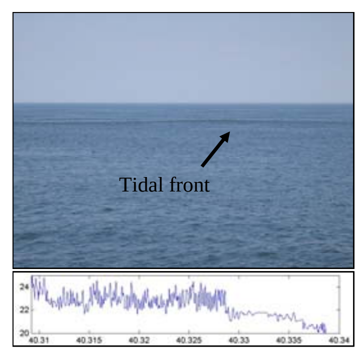

Fig. 4. The tidal front in Hudson Bay visible from the deck of the ship and in surface flow though data. Bottom panel is for salinity over time

II. THE NEARSHORE DYNAMICS OF THE HUDSON RIVER

During both 2005 and 2006 the outflow of the Hudson river was phased with the ebb tide. Within the estuary, the outflow front was clearly visible by eye and surface salinity data exhibited immediate changes after crossing over the tidal front (Fig. 4). The river water entered the ocean as a discrete "squirt" of fresh water with enhanced currents that are clearly visible in the HF radar. Associated with the enhanced outflow during the ebb tide is highly turbid water that is easily detected with visible satellite imagery (Fig. 5). The tidal squirting is visible on each tidal cycle in the CODAR radials that look south along the NJ coast (Fig. 6). The ability to visualize front in real-time allowed the pulse to identified which then allowed the ships to be placed on the leading edge of the plume as it exited the estuary and headed out to sea. During the dye injections, CODAR data was used to set the timing and location of the dye injection.

III. THE HUDSON RIVER DURING THE 2005 FIELD EFFORT

The LaTTE experiment was conducted 7 days after river outflow peaked (~4500 m3s-1) during spring 2005 following a period of substantial rains and subsequent snow melt. During the 2005 field effort, winds were variable and impacted the

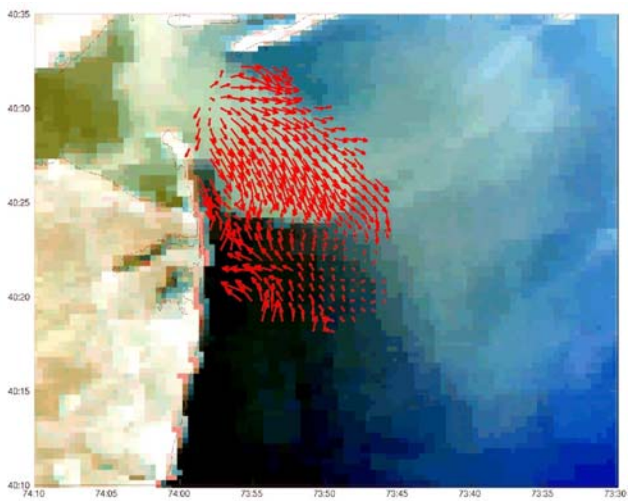

Figure 5. The mean currents (red arrows) during an ebb tide. The currents are overlaid on a visible image clearly delineating the turbid Hudson river water flowing out of the estuary.

dynamics of the river plume. During the first five days of the field effort, winds were largely from the north with periods of sustained winds of >10 ms^{-1}. Winds then reversed to south and were complemented with afternoon sea breezes. The southerly and sea breeze winds resulted in river waters forming a bulge of turbid freshwater at the mouth of the estuary that showed significant recirculation before it flowed to the south along the New Jersey coast. The bulge formation during this event was definitive because strong upwelling winds on April 6-8th cleared the region of a previous outflow by driving the freshwater to the east along the Long Island coast and upwelling saline water along New Jersey. The nutrient-laden water discharged from the Hudson River was retained nearshore in a recirculating eddy before moving southward along the New Jersey coast and mixing with relatively saline coastal water. This was confirmed from moorings and simulated drifters injected into the CODAR time series (Fig. 7).

Biological sampling of the recirculating zone and southward moving plume water was facilitated by a shelf-wide coastal observatory system. Rapid nutrient uptake and assimilation by

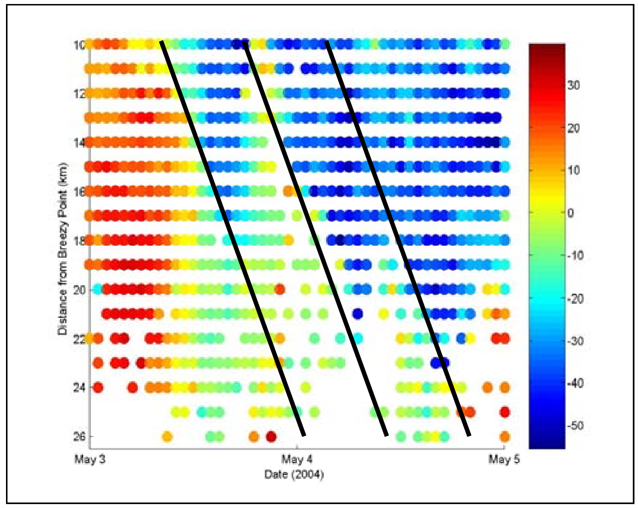

Figure 6. The southerly flowing radials over a series of tidal cycles. The black lines indicate the timing of the tides.

phytoplankton within the eddy resulted in extremely high rates of productivity (> 10 mg C m-3 h-1). Approximately 75% of the fixed carbon within the eddy could be attributed to phytoplankton in the > 20 um size class determined subsequently to be comprised primarily of large (~200 um) chain forming diatoms. Characterization of the zooplankton assemblage revealed a dominance of small copepods, approximately 200-400 um in size, and shipboard grazing

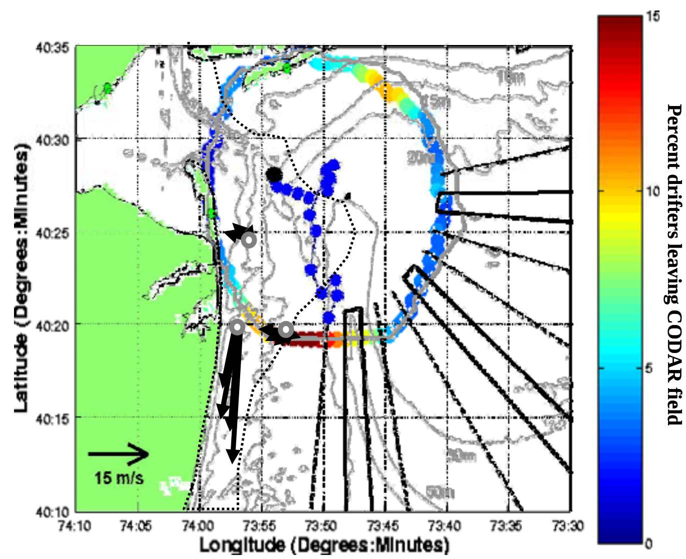

Figure 7. The drift of hypothetical drifters released at the black dot every hour during the LATTE experiment. The colors of the ring indicate where the drifters were advected outside the standard resolution CODAR field. The grey open circles indictae moorings and the arrows indocate the surface currents measured at the moorings during the LATTE experiment. The dotted line indicates the areal extent of the turbid plume.

experiments indicated a negligible feeding impact of these mesozooplankton on the phytoplankton. The apparent mismatch in size between producers and consumers, coupled with the high rates of primary production, resulted initially in a pronounced accumulation of phytoplankton biomass (> 25 ug L^{-1} chl a) within the recirculation zone with subsequent

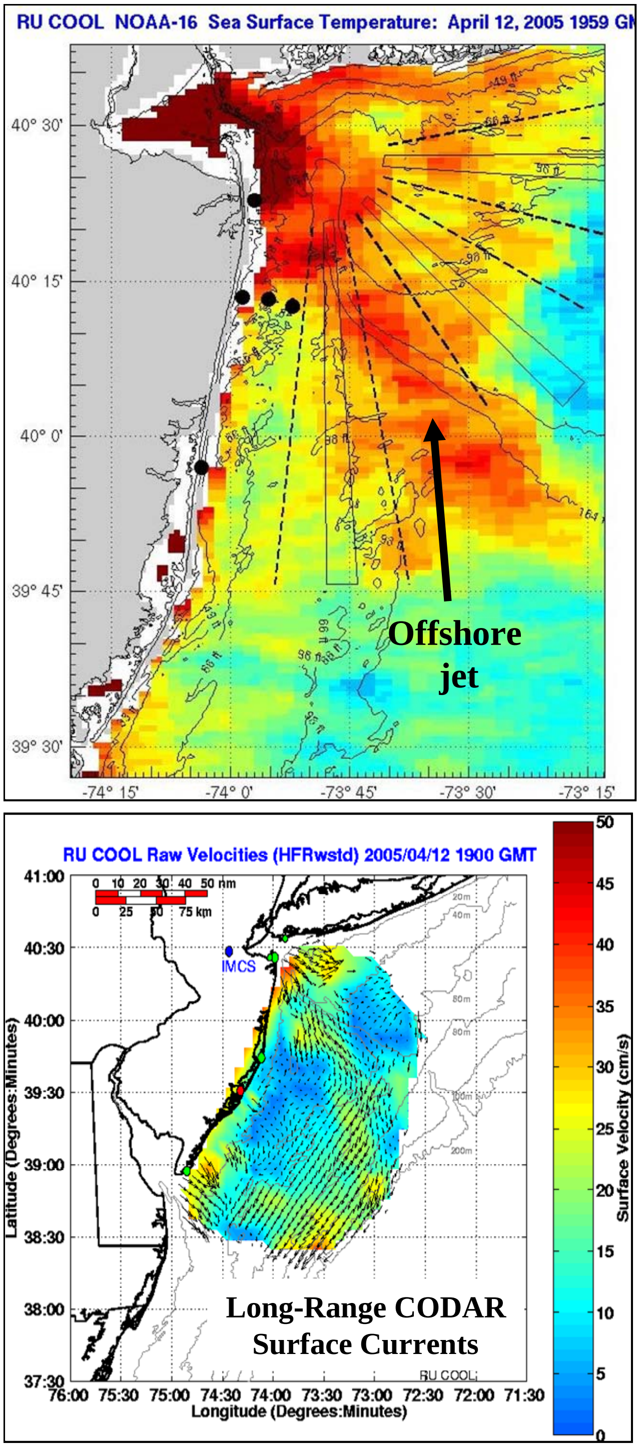

Figure 8. Images of the offshore jet of Hudson river water. The top panel is satellite sea surface temperature, and the offshore jet is visible as warm water. The bottom panel is long range CODAR surface currents. The offshore jet is also clearly visible.

declines in dissolved oxygen concentration in bottom waters coincident with nutrient reduction and bloom senescence. The waters in the bulge contributed to a southerly flowing nearshore jet that hugged the New Jersey coast and to a ribbon of water that ran out along the edge of the Hudson shelf valley.

Estimates of fresh water fluxes in the coastal current made with both the moored instruments and ships indicated that only approximately 1/3 of the outflow became incorporated into the

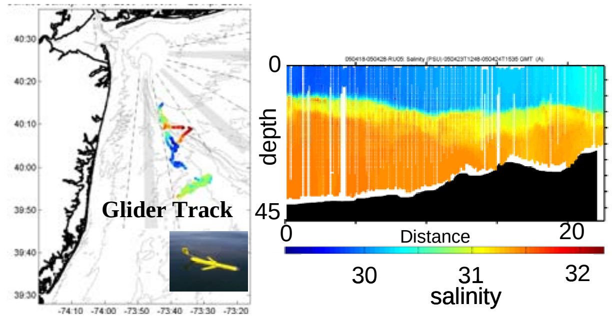

Figure 9. A glider cross section. The left panel shows the surface salinity values mapped by the glider. The right panel shows the subsurface transect.

coastal current, while the remaining 2/3 was transported out along the Hudson canyon. The offshore transport data was visible in satellite, CODAR, and glider data (Figs 8-9). This transport was not expected and it was the observatory that redirected ships which were initially focused on characterizing the southerly flowing coastal jet. Here the observatory was able to identify an unexpected feature and deliver to ship board scientists who could then adaptively sample a previously undiscovered feature (Fig. 10).

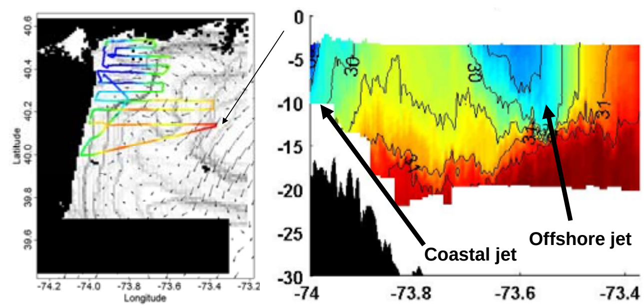

Figure 10. The left panel shows the ship track. The colors show surface salinity (red = high salinity). Right panel is one of the ships transects overlaid on satellite derived water mass boundaries. The offshore river containing 2/3 of the Hudson water is clearly visible.

The presence of this offshore jet has significant ecological and biogeochemical implications. As the Hudson river contributes a significant fraction of the shelf chlorophyll a, the jet then provides an efficient mechanism for transporting nearshore carbon to the shelf break. At the shelf break there is the potential to sequester carbon on the continental slope. Additionally, some species of fish of the MAB (black sea bass, summer flounder) are known to make on/offshore migrations. Some of these species are strongly associated with habitat types. Black seabass, for instance, are considered temperate reef species and may make use of strongly structured habitats such as boulder fields and hard bottoms. On/offshore migrations routes for theses species may require a network of suitable bottom types. The Hudson canyon region is well known as a hotspot for commercial and recreational fishing. Many fish species that spend summers inshore are routinely caught at the head of the Hudson canyon as temperatures decline nearshore in the fall. Finally ancillary evidence suggests that animals have migration corridors which may involve the topography of the Hudson canyon and the offshore may facilitate transport to offshore waters. The offshore jet may provide an effective to facilitate the migration, transport larval fish, and provide a food source. Therefore more research effort should be focused on this cross-shore jet.

IV. THE HUDSON RIVER DURING THE 2006 FIELD EFFORT

Similar to the 2005 field effort, the observatory structured ship sampling efforts in May 2006. River outflows were low during this field year and winds were variable. Wind forcing of the plume dynamics proved to be extremely important. Similar to the field efforts in 2005, the outflow of the plume exhibited significant tidal pulsing. The major addition for ship-based sampling strategy was the addition of using ocean forecasts generated by the ROMs modeling to adaptively sample the plume. Forcing of the ROMs include both standard weather models as well as a high resolution atmospheric forecast provided by the Weather Research and Forecasting

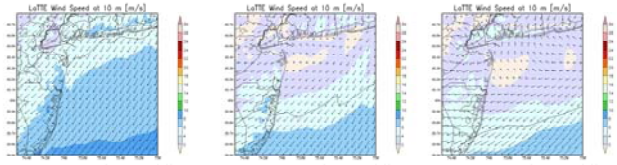

Figure 11. Model outputs from WRF showing the evolution of a sea breeze.

Model (WRF). The WRF model has sufficient resolution to resolve local sea breezes that been shown to be important for understanding Hudson plume dynamics.

This year the southerly current carried the plume to the south and offshore (Fig. 12). This was visible in both the sea surface temperature and in the ocean color estimates of chlorophyll a. As before the CODAR and satellite imagery directed the ship sampling and helped scientists at sea to determine where to dye label the plume. This year in addition to the observatory data, dye was added to the ROMs model allowing forecasts to be generated. ROMs forecasts predicted that initial dye patch was going to split into two discrete patches (Fig. 13). To follow both patches a glider was

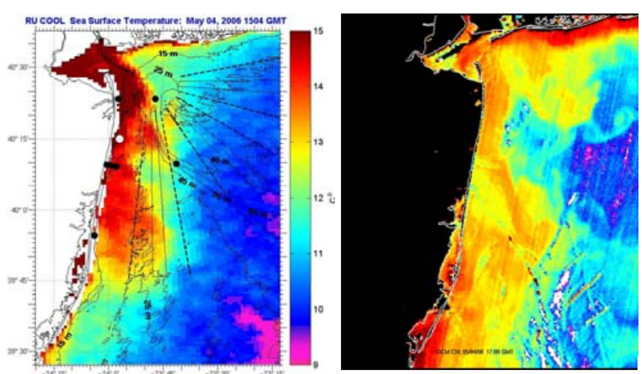

Figure 12. Satellite images of the Hudson river showing the southerly and offshore transport.

deposited in the predicted nearshore patch. The ship and two drifters followed the offshore patch. The presence of two distinct patches was confirmed. Additionally the skill of ROMS to forecast the location of the offshore transport of the dye was gratifying (Fig. 14).

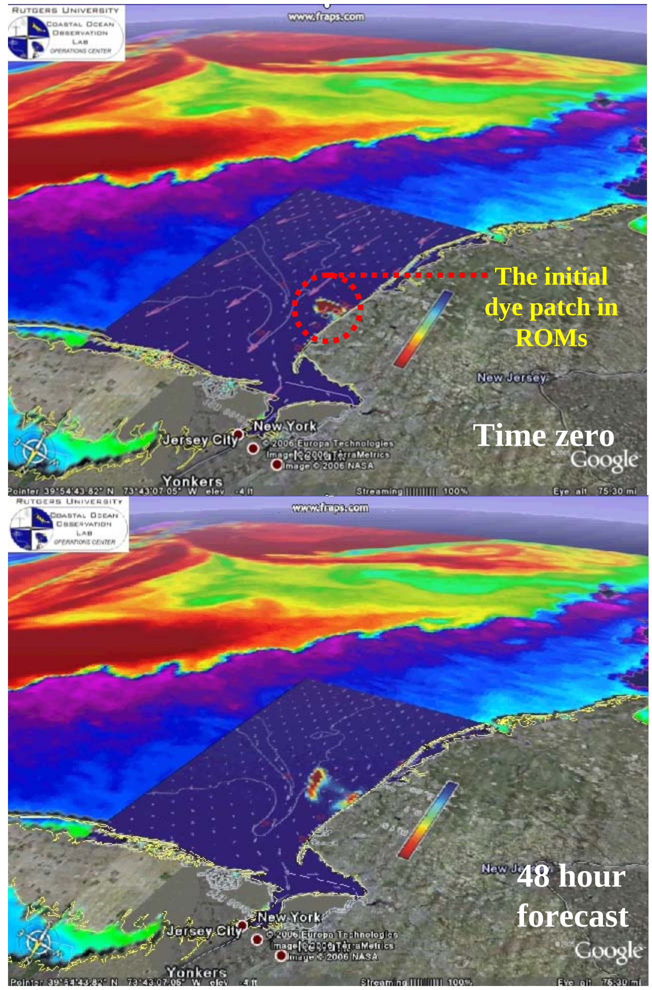

Figure 13. A ROMS 48 hour forecast. The dye (concentration is denoted by the color) patch was predicted to split into two distinct patches. The ROMs output is overlaid on a satellite sea surface temperature field. The sea surface temperature clearly shows the warm waters of a large warm core ring which impacted this region during the experiment.

V. CONCLUSIONS

The ocean is chronically undersampled. Driven by the need to address these limitations, the oceanographic community is poised to embark on a novel and revolutionary approach for studying the ocean by establishing interactive, globally distributed and integrated networks of sensors in the ocean. These networks will be coupled to numerical models. These ocean observatories will open a new door for oceanography. This network is part of a broader trend in the physical and natural sciences toward use of arrays of *in situ* sensors, real-time data, and multidisciplinary approaches to study complex natural systems. We believe our observatory is a prototype of such a system and based on our experience we believe the future is bright for marine science. The key however is that system provide real-time spatial data especially in the coastal waters where important features such as buoyant plumes are ephemeral and impossible sample using traditional approaches.

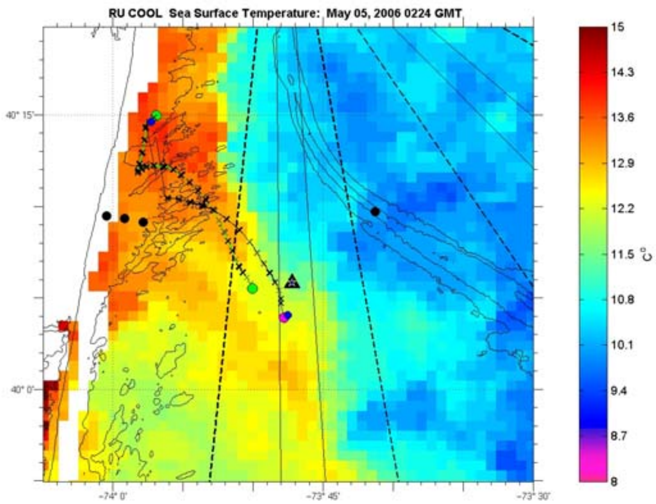

Figure 14. The ROMS forecasted dye to be transported to the triangle. The circles denote the path and final position of two drifters which were deposited into the ocean when the dye was injected.