Characterizing Mesoscale Physical Oceanography on the New Jersey Shelf
Non-Linear Internal Wave Initiative

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LONG-TERM GOALS

Develop and demonstrate in a Regional-scale Coastal Ocean Observatory a coupled observation and data assimilative modeling capability that contributes to our understanding of continental shelf processes, provides societal benefits, is relocatable worldwide in both collaborative and non-collaborative environments, and serves as an educational training ground for students and Navy personnel. Our approach will leverage the complementary capabilities of academic, industry and government groups through NOPP-style partnerships to develop new satellite remote sensing algorithms, new HF radar hardware and processing software, and new autonomous underwater vehicles and sensors for subsurface adaptive sampling. We will use the new technologies to sustain a continuous long-term presence in the Mid-Atlantic with enhanced coverage during an ongoing series of scientific process studies that include advanced data assimilation in coupled atmosphere/ocean physical, biological, biogeochemical, and sediment transport models. We will simultaneously develop and demonstrate the capability of a reach back cell to operate sustained autonomous ocean observing systems in remote locations world-wide. We will entrain students in the process, starting as early as their freshman undergraduate year, and we will provide training opportunities for in-service personnel from multiple agencies.

OBJECTIVES

Our primary objective of this data analysis project is to characterize the hydrography and stratification of the New Jersey Shelf during NLIWI/SW06 to provide a temporal and spatial context for internal wave evolution and dissipation studies. A secondary objective is to better understand the dynamical forcing responsible for the variability observed in cross-shelf transport and shelf-slope exchange during the experiment. The variability occurs on seasonal to supertidal time scales, and each can potentially affect the internal wave environment. In the end we seek connections between the shelf transport processes and the nonlinear internal waves. These science objectives can be grouped into four specific topics:

1) To characterize the hydrography and stratification of the NLIWI/SW06 sampling area, especially along the main mooring line as accurately as possible for the duration of the experiment. This result will feed into the internal wave analysis in collaboration with others.

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14. ABSTRACT
Develop and demonstrate in a Regional-scale Coastal Ocean Observatory a coupled observation and data assimilative modeling capability that contributes to our understanding of continental shelf processes, provides societal benefits, is relocatable worldwide in both collaborative and noncollaborative environments, and serves as an educational training ground for students and Navy personnel. Our approach will leverage the complementary capabilities of academic, industry and government groups through NOPP-style partnerships to develop new satellite remote sensing algorithms, new HF radar hardware and processing software, and new autonomous underwater vehicles and sensors for subsurface adaptive sampling. We will use the new technologies to sustain a continuous long-term presence in the Mid-Atlantic with enhanced coverage during an ongoing series of scientific process studies that include advanced data assimilation in coupled atmosphere/ocean physical, biological, biogeochemical, and sediment transport models. We will simultaneously develop and demonstrate the capability of a reach back cell to operate sustained autonomous ocean observing systems in remote locations world-wide. We will entrain students in the process, starting as early as their freshman undergraduate year, and we will provide training opportunities for in-service personnel from multiple agencies

15. SUBJECT TERMS

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2) To characterize the slope water intrusion process during the stratified season and to better understand its driving dynamics.

3) To characterize spatial and temporal variability of cross-shelf transport, and to quantify the dynamical role of wind, stratification, topography and ambient flow in the transport.

4) To characterize the nonlinear internal wave events seen in the glider data and compare with internal wave observations from other platforms.

APPROACH

Hydrographic data from the SW06 glider fleet, current data from the SW06 moorings and surface current data from the coastal HF Radars are used together to understand the mesoscale physical oceanographic processes at the outer NJ Shelf during the stratified season. ROMS numerical model will be used to study the dynamics of observed processes. Analysis of SW06 glider hydrographic data shows intense intrusion of slope water onto the shelf during the summer stratified season. Repeated sampling of the SW06 region by multiple gliders shows the temporal evolution of the intrusion features and allows one to characterize the spatial and temporal variability of these features. The glider CTD data for the outershelf will be combined with towed Scanifsh CTD data for the shelfbreak from Gawarkiewicz et al. to build a coherent picture of different watermasses extending across the shelfbreak. Current data from SW06 oceanographic moorings will be added to the analysis to understand the advection of these observed features. Existing multi-year HF Radar data are used to construct seasonal climatology of wind-driven circulation and surface cross-shelf transport. Finally the dynamics of cross-shelf exchange will be examined using ROMS numerical model in collaboration with Rutgers Ocean Modeling group. A set of three papers are planned for publication. The first two will focus on the observation results from SW06 gliders and CODAR, both near the final stage of completion. A third paper will focus on using numerical model to understand the dynamics of cross-shelf exchange at the outer NJ Shelf. Donglai Gong's dissertation will be based on the work that went into these publications. He plans to graduate by summer 2009.

WORK COMPLETED

Two science papers are being written, one focusing on outershelf hydrography and another focusing on climatology of shelf-wide surface flow. Different components of these studies have been presented in the past year at Ocean Sciences (March 2008) and Middle Atlantic Bight Physical Oceanography and Meteorology meeting (September 2008). The first study was completed in late 2007 and a manuscript was prepared for publication. The second study is near completion and the manuscript is being prepared. Work on the technical issue of glider CTD's thermal-inertia lag is progressing as well. Our initial approach of using velocity independent thermal-lag correction coefficients combined with stability enforcement was effective for realtime operations and sufficient for initial analysis independent of other observational platforms. Accurate characterization of watermass behavior near the pycnocline require us to tackle the fundamental problem of delayed response of glider CTD conductivity cell going through a sharp thermocline. A velocity dependent approach was outlined at Glider TTI meeting in January 2007 by Glenn & Kerfoot. Further study of the problem using different thermal inertia lag model was initiated by Gong & Shapiro during summer 2008. Despite continuing challenges of glider data QA/QC, we feel confident enough with the current version of the data to do science analysis. The initial study of mesoscale hydrographic interactions at the outer NJ Shelf during the 2006 stratified season incorporated glider CTD, SLBMD drifters, CODAR surface current, and satellite SST data (Gong et al. 2007). That study identified major watermasses at the outershelf and characterized the temporal and spatial variability of mesoscale hydrographic features in the SW06 sampling domain. A follow-up study is now underway focusing on characterizing the advection and dynamics of observed hydrographic features. The two studies will be integrated into one publication (Gong et al. 2008). Gong et al. is working on another paper characterizing the subtidal and seasonal variability of wind-driven circulation on the NJ Shelf using 6 years of Long Range CODAR data. The SW06 glider hydrographic analysis and CODAR surface current analysis form the first half of Donglai Gong's Ph.D. thesis.

RESULTS

The mean and subtidal surface circulation in the central region of MAB are characterized using six years of CODAR Long Range HF Radar data. The mean surface flow is 3-7 cm/s downshelf and offshore to the southwest. Subtidal variability on the NJ Shelf is on the order of the mean offshore but several times that of the mean inshore. The response of the surface current to wind depends on the stratification and exhibits significant seasonal patterns.

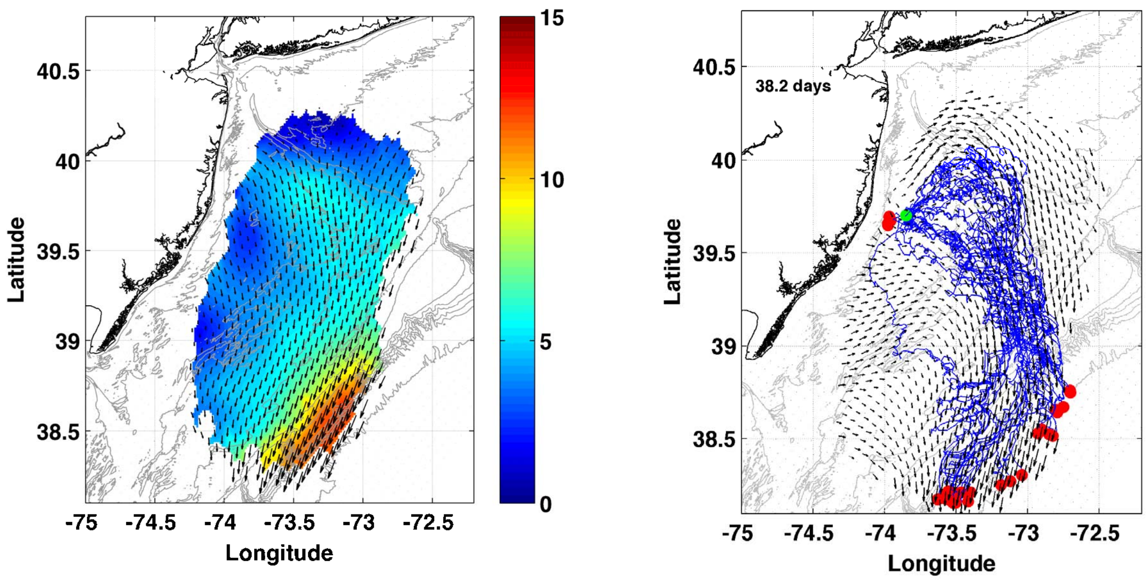

Figure 1: a) Mean Surface Flow on the NJ Shelf (2002 to 2007). Colorbar indicate flow speed. Mean flow shows both alongshelf and cross-shelf variability. b) Virtual Lagrangian drifter during summer 2006 shows offshore cross-shelf transport of surface drifters.

The flow tends to be either along-shelf or cross-shelf dominated. The seasonal climatology of the wind driven circulation for the NJ Shelf shows that (1) the alongshore wind is correlated with cross-shelf current in the summer time, (2) the cross-shore wind is correlated with cross-shelf current in the winter time, and (3) the along-shore wind is correlated with along-shelf current in the transition seasons of spring and autumn. Cross-shore NW wind drives cross-shelf offshore flow in the unstratified winter season. Along-shore SW wind drives cross-shelf offshore flow in the stratified summer season. NE wind, often associated with storm events in the spring and fall, seems to drive downshelf alongshelf flow. The Hudson Shelf Valley acts as a dynamical boundary between the northern and southern NJ Shelf with the north consistently showing weaker flow than the south.

Analysis of virtual Lagrangian surface drifters show that the residence time of surface material ranges from 1 week to 8 weeks. The transport pathways are either cross-shelf or along-shelf dominated. The upstream source of surface water for the SW06 study area is often the innershelf upwelling regions as well as the mouth of the Hudson River.

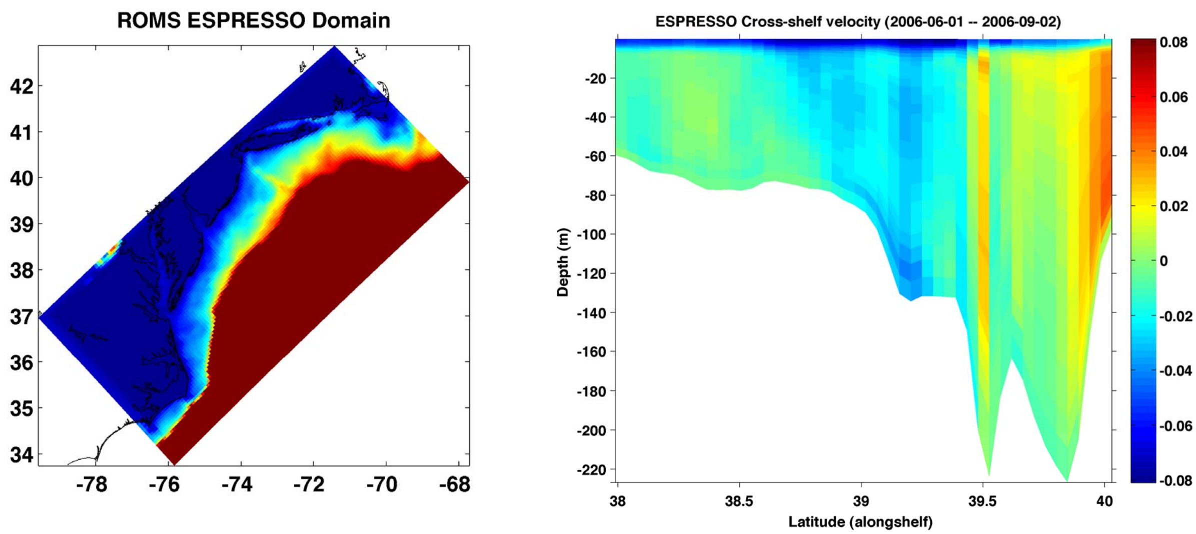

Figure 2: a) ROMS model domain used for seasonal cross-shelf transport analysis. Color indicates depths (red is 200+ meters). b) ROMS model output showing a summer 2006 mean cross-shelf velocity for an alongshelf section (black line in 2a). Surface flow is offshore (blue), Hudson Canyon and northern region flow is onshore (yellow/red). Region just south of the Hudson Canyon shows flow offshore from surface to bottom (blue).

Analysis of numerical model output using ROMS has shown that both summer and winter shows cross-shelf offshore flow in the surface layer while the interior flow is weak. Significant alongshelf variability is observed in the model with strong onshore flow focused in the Hudson Shelf Valley and area to the north. Areas to the south of the HSV shows offshore transport throughout the water column.

A fleet of autonomous Webb gliders that occupied six cross-shelf transects on the New Jersey outer shelf can be used to study salty slope water intrusions during the summer of 2006. Coordinated glider sweeps, between the 60 m and 100 m isobaths, crossed the climatological location of the foot of the shelf-slope front. Depth-averaged currents flowed 10 cm/sec along-shelf to the southwest, indicating a transit time of 7-10 days for the intrusions through the study site. Four types of slope water salinity intrusions were identified which were surface, pycnocline, sub-pycnocline, and bottom intrusions (Figure 3a). The pycnocline intrusions inshore were affected by shelf stratification which was especially strong due to remnant of low density Hudson River water associated with heavy June rainfall. Sub-pycnocline intrusions were possibly associated with the separation of the bottom boundary layer at the foot of the shelf-slope front with inshore diapycnal mixing below the seasonal pycnocline. The intrusions were persistent and highly variable in space and time, likely forced by offshore eddies. On average the pycnocline and the sub-pycnocline intrusions could each account for one-sixth of the slope water salt in the sampling volume, while bottom intrusions could account for half, with the remaining portions being surface intrusions and unclassified slope water.

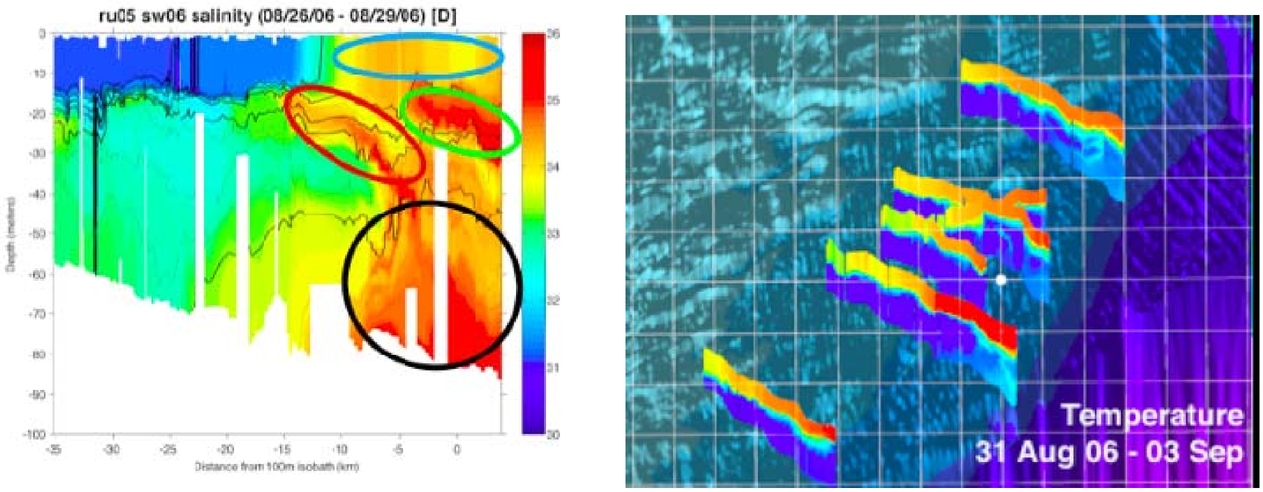

Figure 3: a) SW06 glider cross-shelf section of salinity. Four watermasses are identified based T-S properties. Salinity are colored ranging from 30 to 36 and density contours are overlayed. b) 3-D cross-section of glider temperature measurement during the passage of T.S. Ernesto in 2006. As the gliders flew inshore, the surface temperature dropped by 4-7 deg C.

Tropical Storm Ernesto dissipated and mixed away significant portions of the intrusions (Figure 3b). Slope water intrusions however re-established themselves within a week. The Webb Gliders enabled quantitative understanding of initiation, spatial distribution and dissipation of the highly dynamic shelf-slope exchange process.

IMPACT/APPLICATIONS

Previous studies of MAB watermasses on the continental shelf saw seasonal variability in the volume and the salinity of the shelf water (Manning 1991; Mountain et al. 2003). Shelfwater, defined to be water with salinity less than 34, reaches maximum southwestward extent during the summer and retreats to minimum volume during the winter (Figure 4, Mountain et al. 2003). Results from this analysis suggest that wind driven circulation could be a possible mechanism of seasonal alongshelf transport and cross-shelf exchange. The maximum change in the shelfwater volume in the central MAB occurs during the spring (increasing) and fall (decreasing). These are two periods when we observe predominantly alongshelf surface current flow. At the maximum and minimum extent of shelfwater during summer and winter, we observe the surface flow becomes predominantly cross-shelf. Indeed, sub-surface hydrographic observations during the summer at the outershelf often show fresh shelf water extending far offshore while salty slope intrudes onto the shelf below the surface layer. However, whereas little mixing is observed across the seasonal pycnocline during the summer, winter time cross-shelf surface flow driven by cross-shore wind occurs when the water column is unstratified and strong mixing is possible. If we assume there exists a two layer circulation during the unstratified season, with the surface layer going offshore and bottom layer going onshore (i.e., Lentz, 2003), the winter flow would also induce exchange with the slope at the shelfbreak. The increased cross-shelf flow of summer and winter would suggest the rate of leakage of shelf water into the slope sea is not constant and would be expected to exhibit a seasonal cycle.

The alongshelf variability of cross-shelf flow due to the presence of the Hudson Shelf Valley differs markedly from the two-dimensional circulation model proposed by Lentz (2008) which developed an interior onshore flow balancing the offshore surface flow on the MAB. Our observation and modeling suggest alongshelf variability in topography plays a crucial role in cross-shelf exchange. Long term Radar observations of surface cross-shelf flow driven by cross-shore wind for six winters are different from the subsurface mooring measurements (Ulman et al., 2008) that shows cross-shore wind driving alongshelf downshelf flow at the midshelf for 1 winter month. Detailed comparisons of the two results in conjunction with a modeling effort is necessary to address this key issue of wind-driven circulation on a shallow, wide continental shelf.

TRANSITIONS

The SW06 experiment itself resulted in several important transitions to NAVOCEANO related to glider operations. This includes the ability to fly fleets in coordinated sweeps across a region as a concept of operations to locally improve model hindcasts, the demonstrated need to send gliders upstream to improve forecasts, and the importance of 3-D visualization for human-in-the-loop coordination of large glider fleets. The concepts and 3-D visualization tools have been transferred to several NAVO glider pilots participating in three 1-week duration glider training sessions at Rutgers in 2008, and were used during Navy exercises in Valiant Shield in 2007, and BALTOPS, RIMPAC and NURFIT in 2008.

This follow-on study to SW06 focuses on the physical oceanography of the NJ Shelf using the combined SW06 and the Rutgers Coastal Observatory data. The most significant transition here is the continued work on the thermal inertia correction to the CTD data. SW06 occurred during a year with anomalously fresh surface waters and a warm summer that contributed to one of the strongest thermoclines and largest density difference we have ever operated gliders in. This tested the limits of our ballasting procedures and the buoyancy pumps ability to sample the full water column, successfully stretching ourselves beyond the quoted buoyancy limits for the glider. The result was significant differences in glider speeds above and below the thermocline, requiring development of a speed dependent correction to the glider thermal lag. The ability to obtain good CTD profiles through this most challenging of environments speaks well for our ability to produce high quality CTD data in other less challenging conditions. The thermal inertia corrections are now an integral part of the data processing in the proposed Littoral Battlespace Sensing and Fusion – Glider program.

RELATED PROJECTS

Analysis of SW06 data is proceeding in collaboration with similar analysis programs at Oregon State University, the University of Miami, and Woods Hole Oceanographic Institution. The physical analysis of SW06 data, in particular tropical storm Ernesto, has prompted two studies of turbulent mixing on continental shelves during storms. One study is a historical look back at previous storm data available in the region (Glenn et al, 2008). A second is a collaborative program with Oregon State University to build a pair of turbulence gliders designed to sample mixing events during storms. One will focus on west coast applications on narrow shelves, the other on east coast applications on wide, shallow shelves. The modified gliders will include ADCPs for current profiling, accelerometers for the turbulence measurements and waves, and an OSU Chipod turbulence sensor. A prototype with an externally mounted Chipod was flown during the 2008 hurricane season on the NJ shelf, collecting data during Tropical Storm Hanna, a series of northeasters, and waves from the offshore passage of Hurricane Kyle.

SW06 also inspired a research collaboration with Peter Rona other researchers on the hydrographic, methane gas and bathymetric study of the Hudson Canyon region using shipboard CTD and the Eagle Ray AUV in 2007 and 2008. One of the goals of this study is to understand the watermass interactions at the head of the Hudson Canyon. Comparison of water mass interactions inside the head of the Hudson Canyon will be compared with the in between canyon SW06 region. The data process is ongoing and parts of the result was presented at AGU Fall Meeting 2007.

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