Process-Driven Improvements to Hurricane Intensity and Storm Surge Forecasts in the Mid-Atlantic Bight:

Lessons Learned from Hurricanes Irene and Sandy

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***Abstract*— The coastal northeast United States was heavily impacted by hurricanes Irene and Sandy. Track forecasts for both hurricanes were quite accurate days in advance. Intensity forecasts, however, were less accurate, with the intensity of Irene significantly over-predicted, and the rapid acceleration and intensification of Sandy just before landfall under-predicted. By operating a regional component of the Integrated Ocean Observing System (IOOS), we observed each hurricane's impact on the ocean in real-time, and we studied the impacted ocean's influence on each hurricane's intensity.**

Summertime conditions on the wide Mid-Atlantic continental shelf consist of a stratified water column with a thin (10m-20m) warm surface layer (24-26C) covering bottom Cold Pool water (8-10C). As the leading edge of the Irene tracked along the coast, real-time temperature profiles from an underwater glider documented the mixing and broadening of the thermocline that rapidly cooled the surface by up to 8 C, well before the eye passed over. Atmospheric forecast sensitivity studies indicate that the over prediction of intensity in Irene could be reduced using the observed colder surface waters. In contrast, Hurricane Sandy arrived in the late Fall of 2012 after seasonal cooling had already deepened and decreased surface layer ocean temperatures by 8C. The thinner layer of cold bottom water still remaining before Sandy was forced offshore by

downwelling favorable winds, resulting in little change in ocean surface temperature as Sandy crossed and mixed the shelf waters. Atmospheric sensitivity studies indicate that because there was little ocean cooling, there was little reduction in hurricane intensity as Sandy came ashore. Results from Irene and Sandy illustrate the important role of the U.S. IOOS in providing the best estimate of the rapidly evolving ocean conditions to atmospheric modelers forecasting the intensity of hurricanes. Data from IOOS may enable improved hurricane forecasting in the future.

***Index Terms*—Hurricane Forecasting, U.S. IOOS, Underwater Gliders, HF Radar, Ocean Modeling, Atmospheric Modeling.**

I. Introduction

Tropical storms are some of the most destructive and deadly weather phenomena on Earth, and have killed more people than any other natural catastrophe (Keim et al. 2006). For example, in the United States during the 20th-century, ten times as many deaths and >three times as much damage occurred from these extreme weather events as compared with earthquakes (Gray, 2003). The impacts are magnified given the human population density found along the coastlines that are prone to hurricanes. Despite the potential devastation, advances in technology, communication, and forecasting have resulted in significant declines in hurricane-related mortalities between 1900 and present day (Walker et al. 2006). Most recently these declines reflect the developments in global atmospheric models and an ensemble forecasting approach that have successfully reduced hurricane track forecast errors by factors of 2-3 over the last two decades, allowing communities sufficient time to proactively prepare for the storms and evacuate prior to their arrival. Despite the progress in predicting hurricane tracks, the predictive skill for hurricane intensity forecasts has remained "flat" over the last twenty years (Pasch & Blake, 2012).

This current state of the science was illustrated by the two recent hurricanes Irene and Sandy that devastated many communities along the Mid-Atlantic coastline spread over dozen states. Hurricanes Irene and Sandy struck dense population centers, and as a result, the National Hurricane Center's list of costliest hurricanes in United States history ranks Sandy second with over $60 billion and Irene eighth with over $15 billion in damages. Despite the epic scale of devastation, the loss of life was greatly minimized due to accurate forecasts of the hurricane tracks days in advance. Unfortunately, forecasts of hurricane intensity were less accurate, impacting efforts to proactively mitigate the damage. For Irene, the intensity was significantly over predicted by many operational hurricane models and overforecast by the National Hurricane Center, and for Sandy, the rapid acceleration and intensification just before landfall were under predicted. The over prediction of Irene's intensity in 2011 led to skepticism of the storm surge warnings for Sandy in 2012. To further complicate matters, the under predicted intensity of Sandy resulted in an under predicted storm surge that in some cases led to insufficient preparation.

The Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS), one of eleven Regional Associations comprising the regional component of the U.S. Integrated Ocean Observing System (IOOS), operates a Regional-Scale Coastal Ocean Observatory that includes coastal weather mesonets, satellite data ground stations, a 1000 km long High Frequency (HF) Radar network (Roarty et al., 2010), and a distributed fleet of autonomous underwater gliders (Schofield et al., 2010). Observatory data is assimilated into global and regional-scale ocean models, and an ensemble of regional atmospheric models beginning to use the ocean surface conditions as a boundary condition. The Regional-Scale Coastal Ocean Observatory was fully operating during both hurricanes. In this paper, we discuss selected highlights of real-time ocean data acquired by the MARACOOS regional-scale network during Irene and Sandy, and how the ocean forecasts faired. Through a series of atmospheric model sensitivity studies, the potential impact of accurate real-time ocean data and forecasts on hurricane intensity forecasts in the Mid-Atlantic is demonstrated.

II. Hurricanes Irene & Sandy

The Mid Atlantic Bight of North America was recently struck by two hurricane landfalls that devastated dense population centers and communities spread over a dozen neighboring states (Figure 1). Hurricane Irene, a category 1 storm offshore, tracked rapidly northward along the eastern seaboard in August of 2011, resulting in significant flooding on inland waterways due to torrential rains. Fourteen months later, Hurricane Sandy, a much larger category 2 storm offshore, made an uncharacteristic left turn and approached perpendicular to the coast in October of 2012, causing significant damage to coastal communities due to the extreme storm surge.

Fig. 1. National Weather Service tracks for hurricanes Irene (purple) and Sandy (orange).

Data from the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS), one of eleven regional associations in the U.S. Integrated Ocean Observing System (IOOS), monitored the ocean response, and used that data to study the influence of the ocean on the intensity of both hurricanes.

Hurricane Irene approached the Mid Atlantic's regional ocean observatory from the south. The real-time observations of the evolving ocean are described in the MARACOOS blog (Glenn et al., 2011). Irene's size was similar to the 1,000 km length scale of the region's HF Radar network (Figure 2) Strong storm-related winds were experienced for only 1 day. Winds initially came from offshore, turned to an alongshore direction as the eye passed, and continued turning to come from the coast after the eye moved north into New England. Most atmospheric hurricane models in the ensemble converged on the track forecast days in advance, but unfortunately, the intensity was over-predicted by the tropical model ensemble. Dire warnings of severe storm surges and damage at the beach were not realized. Because of the short duration of hurricane-forced winds, the relative timing between the high tide and the time of the most severe onshore currents for this rapidly moving storm were critical to determine the severity and location of the maximum storm surge. The severe damage from Irene instead occurred inland, where winds that picked up moisture over the warm ocean resulted in heavy rains and flood conditions along the Delaware, Hudson and Connecticut Rivers.

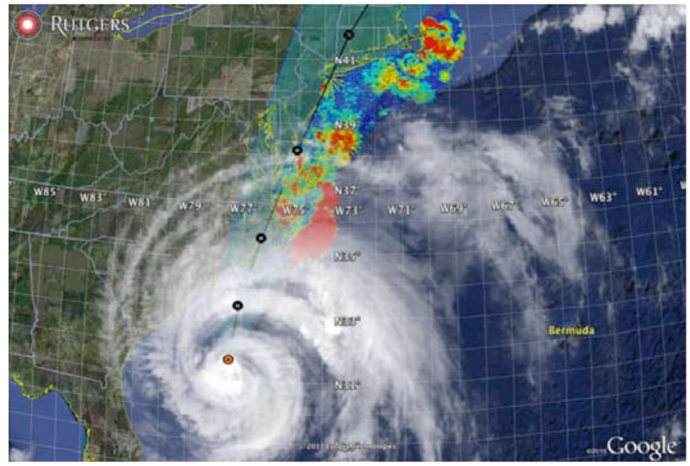

Fig. 2. Spatial extent of Hurricane Irene, August 27, 2011.

Hurricane Sandy approached the Mid-Atlantic's ocean observatory from offshore, perpendicular to the alongshore track of Irene. Real-time ocean observations were again described in the MARACOOS blog. The diameter of Sandy was twice as large as Irene, larger than the scale of the observatory (Figure 3). The approach direction had a significant impact on the areas with severe storm surge damage. North of the eye on the right hand side of the track, the counterclockwise circulation is in the same direction as the propagation. Here sustained winds from offshore that transported water towards the coast were experienced for multiple tidal cycles. South of the eye, winds blew from the coast and water was transported offshore. Compared to Irene, Sandy's size and slower movement over the continental shelf meant that several high tides were expected as Sandy came ashore. More important for Sandy was your location north or south of the eye, as damage was widespread in space and time.

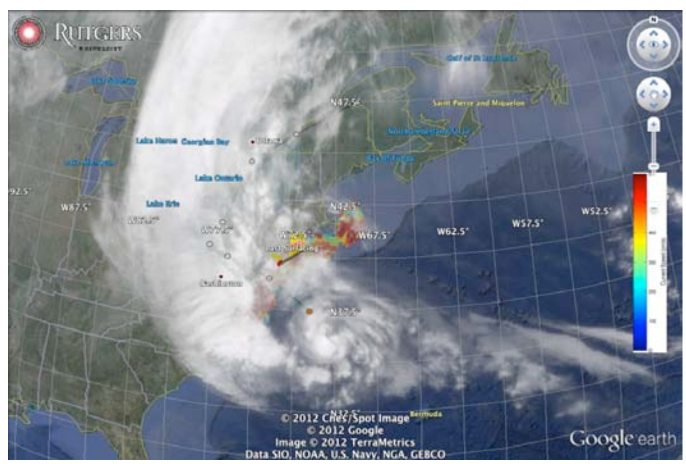

Fig. 3. Spatial extent of Hurricane Sandy, October 28, 2012.

III. WATER COLUMN MIXING IN IRENE

The eye of Hurricane Irene made landfall in southern New Jersey near Atlantic City about 0935 UTC on August 28, 2011. Irene was moving rapidly northward, fully crossing the state of

New Jersey in about 6 hours. The rapidly evolving surface current response as Irene propagated along the New Jersey coast was observed (Figure 4) using the Mid-Atlantic's High Frequency (HF) Radar network (Roarty et al., 2010). At 0600 GMT, Irene's eye is still over water, with its location observed in the CODAR currents offshore southern New Jersey. Strong onshore currents over the entire width of the shelf are observed north of the eye. At 1200 GMT, the eye is over land in central New Jersey. The ocean currents have rotated to be along the coast to the northeast, and are reduced in speed. By 1800 GMT, the eye is over northern New Jersey. Currents behind the eye are again strong and offshore. The transition from strong onshore flow to strong offshore flow occurred over a short 6 hour period.

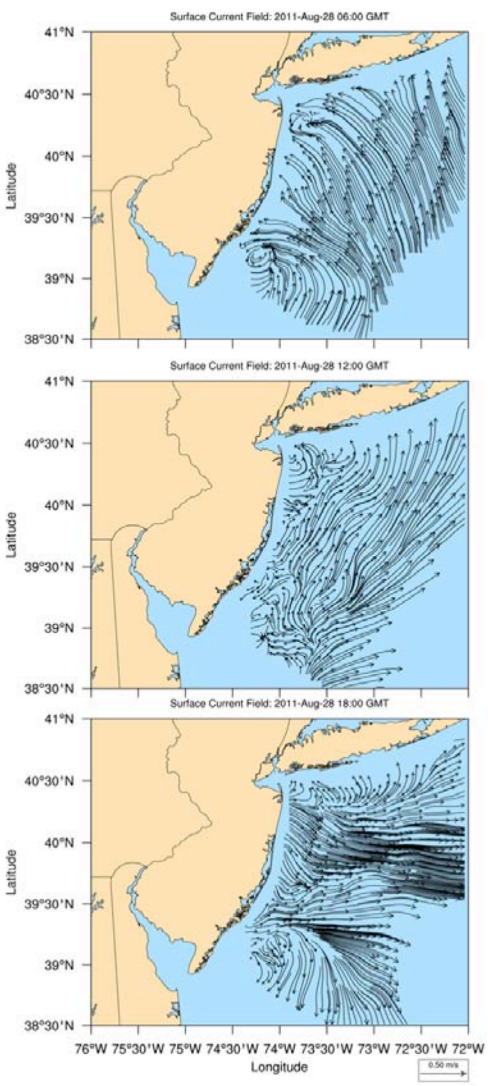

Fig. 4. CODAR-derived surface current spatial response as Irene tracks along the New Jersey coast.

Glider RU16 was deployed on the New Jersey shelf on a coastal survey mission well ahead of and independent of the hurricane. As Irene approached, the glider was purposely left at sea, but was moved offshore to the 40 m isobath to ride out the storm (Figure 5a) The 40 m isobath is an area of relatively uniform sandy sediment, and was considered far enough offshore that even strong hurricane currents faster than the glider's flight speed would not blow the glider onto the beach.

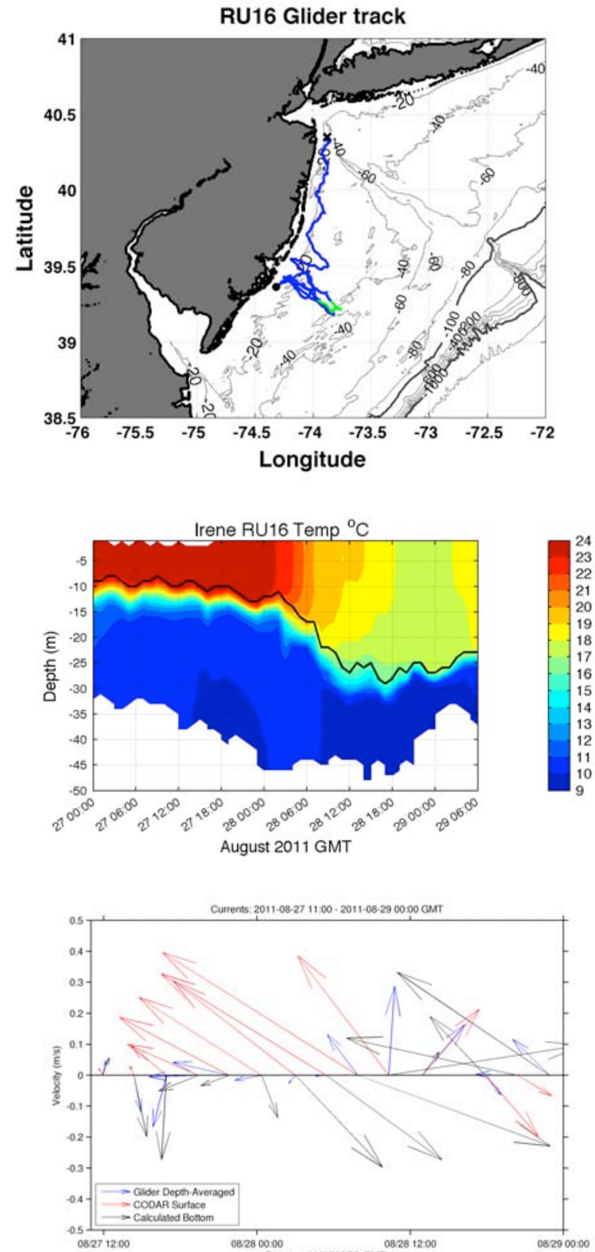

Fig. 5. (a) Glider track in Hurricane Irene. (b) Glider temperature section for the portion of the glider track marked in green. Black line is the depth of the surface mixed layer. (c) Glider depth averaged currents (blue), CODAR surface currents along the glider track (red), and inferred bottom layer currents (black).

The temperature section collected by the glider near the 40 m isobath during Irene (Figure 5b) indicates that on

August 27, the Mid Atlantic shelf was near its peak summer stratification, with a thin 10 m thick layer of warm surface water near 22-25C, and a thicker layer of bottom "Cold Pool" water near 8-10C. The summer thermocline was typically sharp, with the transition from warm surface waters to bottom Cold Pool waters occuring in a few meters. As Irene approached, mixing within each of the surface and bottom layers made each layer more uniform and tightened the thermocline. On August 28, between 0000 GMT and 1200 GMT, as the northern edge of Irene passed over the location of the glider, the thermocline broadened (from less than 5 m to over 15 m) and deepened (from 10 m to 28 m), and the surface layer cooled (from 24C to 18C). After 1200 GMT, as the backside of the hurricane passed over the glider, the deeper thermocline remained near 25 m. Both the surface and bottom layers continued to cool independent of each other as the thermocline reintensified.

Gliders report the depth averaged current over the previous segment with each surfacing. The depth averaged current is estimated by comparing the dead reckoned surface location with the actual surfacing location, and assuming the difference is due to advection of the glider by the depth averaged current. During the hurricane, depth averaged currents are initially southward at 20 cm/sec before the storm, drop to near zero during the approach of the storm, and transition to northward at 30 cm/sec on the backside of the storm (Figure 5c). The important observation is that the depth averaged current is near zero between 0000 GMT and 1200 GMT on August 28 when the thermocline deepening and surface layer cooling is observed. Plotting the CODAR surface currents at the location of the glider, shows how the surface layer is being forced directly onshore to the northwest by the hurricane winds starting on August 27 and peaking during the deepening event. After 1200 GMT on August 28, the CODAR surface currents rotate clockwise to alongshore and then to offshore as noted in the spatial maps (Figure 4). Using the observed CODAR surface current to represent the average current above the thermocline, the average current below the thermocline was estimated based on the requirement that the weighted average of the surface and bottom layers equal the observed glider depth averaged current. Based on the estimated bottom layer current, the onshore transport in the surface layer begins midday on August 27 and for the first 12 hours, there is little response in the bottom layer. During this time the storm surge is expected to grow. Between 0600 GMT and 1200 GMT, as the onshore currents in the surface peak, the offshore currents in the bottom layer accelerate, resulting in zero net transport towards the coast. This time interval when the greatest shear between the surface and bottom layers is expected is precisely the time when the thermocline is observed to deepen. The zero net transport also implies that the storm surge that would have resulted from the shoreward transport of surface water is compensated by the offshore transport of bottom water.

The Regional Ocean Modeling System (ROMS) was operated in forecast mode during the storm. The model was rerun here using the same forecast parameters for more in depth studies. The ROMS forecast/hindcast of the ocean response has several features consistent with these observations that enable further definition of the physical processes responsible for the surface layer cooling. But there are also several differences between the observations and the model. The initial state of the ocean in the ROMS model (Figure 6a) has a 10 m thick surface warm surface layer near 24 C, and bottom Cold Pool layer near 9C, but the initial thermocline is wider than observed, extending over 15 m thick instead of less than 5 m. So the initial condition has a less extreme thermocline that would be more easily mixed than observed. Despite the weaker thermocline, significant mixing does not begin in the model until 6 hours later than the observations. The initial response is an acceleration of the alongshore currents to over 60 cm/sec to the northwest at 0000 GMT on August 28 (Figure 6c). The cross-shore currents, in the onshore direction at the surface and the offshore direction in the bottom, spin up simultaneously and peak at 0600 GMT. At this peak in shear, the thermocline starts deepening and the surface water starts cooling. In the model, this process ends in 6 hours, with the surface water cooling 5C and the bottom water warming 1C. At 1200 GMT, the alongshore surface current reverses direction consistent with the CODAR observations, the bottom jet relaxes in the cross-shore current but remains present in the alongshore current. The glider observations indicate that the bottom jet should have remained in the cross-shore direction.

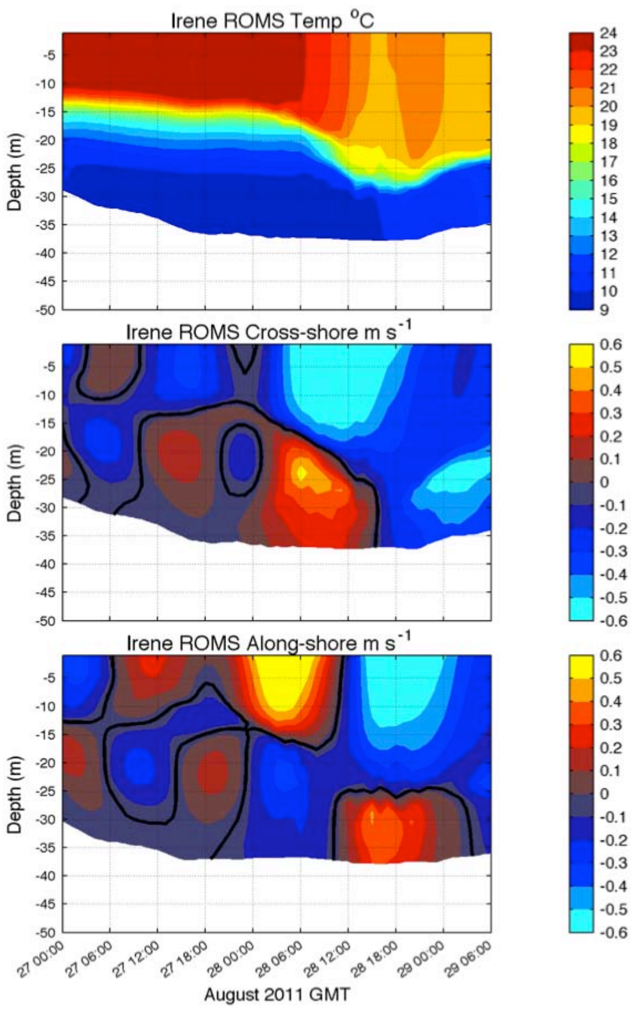

Fig. 6. Regional Ocean Modeling System (ROMS) hindcast of temperature, cross-shore (+offshore) and alongshore (+northeast) current sections along the green portion of the glider track in Figure 5a. Black lines indicate 0 cross and alongshore currents.

While the exact details of the deepening of the thermocline and the cooling of the surface layer do not exactly match those observed, model diagnostics indicate that the vertical diffusion in the surface layer dominate advective changes in the model. This points to improvements in the mixing parameterizations as a place to look to improve the model. Even with a weaker thermocline, the mixing is insufficient to cool the upper layer as much as observed.

Satellite-derived Sea Surface Temperature (SST) maps of the Mid-Atlantic Bight just after Irene indicate that the cooling was widespread (Figure 7). The locally generated SST product (Figure 7a) indicates that surface temperatures dropped to as low as 14C on the shelf, with the greatest cooling observed over the historical location of the Cold Pool and concentrated on the mid to outer shelf, shoreward of the shelfbreak. The cooling was so significant, even though skies were clear after the storm, the cloud detection algorithms rejected the data as being too cold, removing it from the Real Time Global (RTG) SST updates (Figure 7b). As a result, the RTG SST map is essentially unchanged before and after Irene. Since the RTG map is the SST used by several atmospheric forecast models as a bottom boundary condition, the ocean used in the Irene forecasts was too warm. The difference between the RTG and the actual sea surface temperatures after the storm is as large as 10C (Figure 7c).

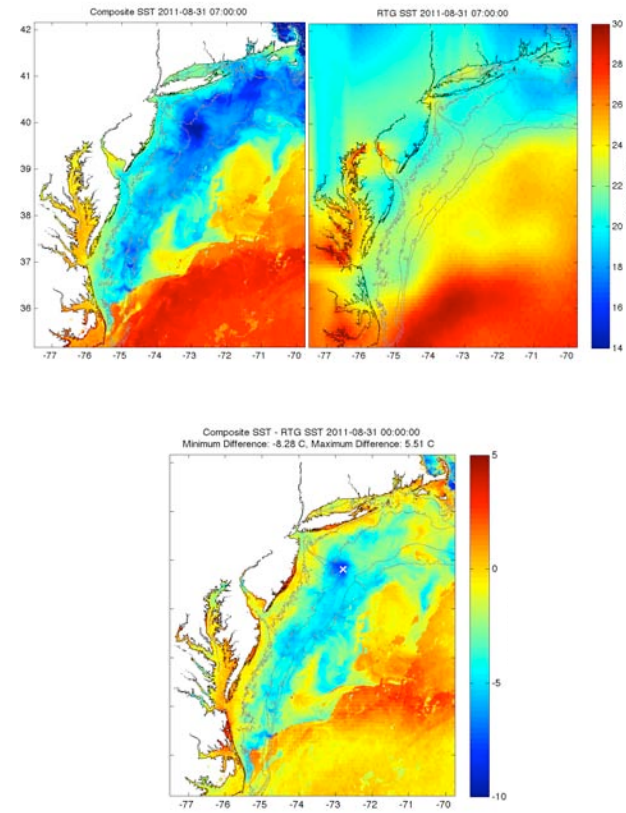

Fig. 7. Post-Hurricane Irene Satellite-derived Sea Surface Temperature (SST) products for August 31, 2011. (a) Locally composited SST showing the surface cooling. (b) Operational global SST product with the cool pixels incorrectly identified as clouds. (c) Difference.

The impact of the rapidly cooling SST on the Weather Research and Forecasting (WRF) model hindcast sensitivity studies of Hurricane Irene illustrates the significant impact of the cooler water. The glider data indicates that the cooling occurred ahead of the eye as the high winds of the outer wind bands approached. Thus the eye of the hurricane passed over cool water as it propagated northward. Since the RTG SST does not cool, it was used as the base case for comparison (Figure 8a). Since the ROMS model cools late and insufficiently, the locally composited SST product was used to simulate the change in SST as the storm passed. Starting with the warm pre-storm SST, the cold post-storm SST was applied everywhere at the time of peak mixing observed in the glider transect. The resulting WRF forecast is lower by 5-10 knots. (Figure 8b).

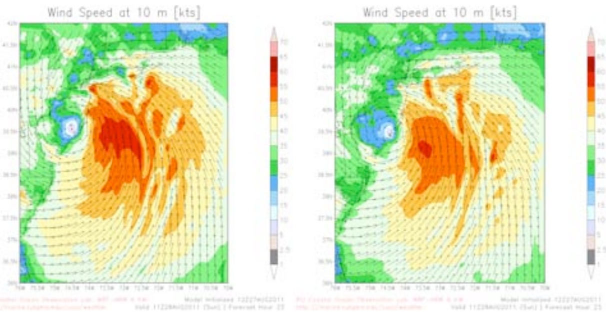

Fig. 8. Weather Research Forecast (WRF) atmospheric hindcasts of Hurricane Irene with different ocean boundary conditions. (a) Using the warm SST throughout the run. (b) Switching to the cold SST in Figure 7a when the cooling is observed in the glider data.

IV. Sandy

Hurricane Sandy followed Hurricane Irene by 14 months. Forecasts made by the European Center for Medium-range Weather Forecasting (ECMWF) alerted researchers to the possibility of a signficant storm hitting New Jersey a full week in advance. The importance of the glider observations in Irene prompted the deployment of glider RU23. Based on the lessons learned in Irene, the glider payload bay with its standard CTD was further equiped with optical sensors to look at the sediment concentrations as a tracer for mixing. A Nortek Aquadopp Acoustic Doppler Current Profiler (ADCP) was attached externally to examine the shear across the thermocline during the event. The glider was deployed nearshore with a small boat, and, as in Irene, was directed to fly to the 40 m isobath to ride out the storm (Figure 9).

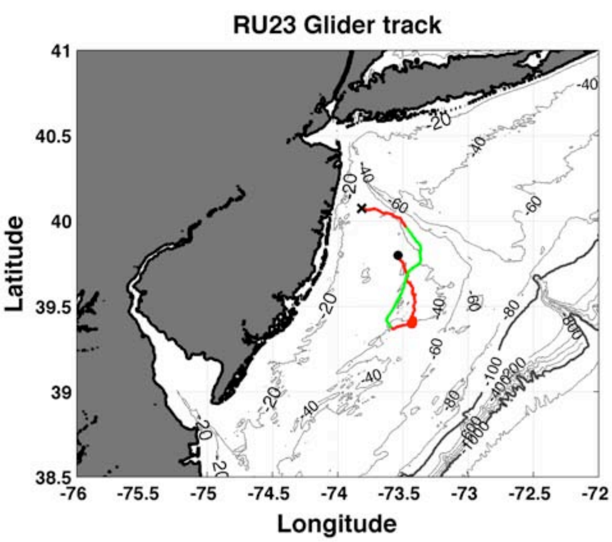

Fig. 9. Glider track during Hurricane Sandy.

Glider RU23 revealed that the initial ocean conditions for Hurricane Sandy were quite different than 14 months ago before Irene (Figure 10). The peak summer thermocline intensity observed in Irene was already 2 months into the fall transition. The two-layer structure was still present, but the surface layer had already cooled to 16C-17C, and thickened to a depth of 30 m. As usual, the bottom Cold Pool temperatures where observed to be around 9C-10C. Like Irene, the thermocline is again observed to be only a few meters thick. As Sandy approaches the coast, the increase in the thermocline depth is even more rapid than Irene, occuring within a few hours near 0600 GMT on October 29. After the deepening event, the water column is filled with a single surface layer, but the layer cooling is only 1 C from 16 C to 15 C. The glider data indicated that Sandy was going to make landfall propogating over SSTs that changed little from the pre-storm conditions. No ohterwise unobserved cooling to reduce intensity was expected.

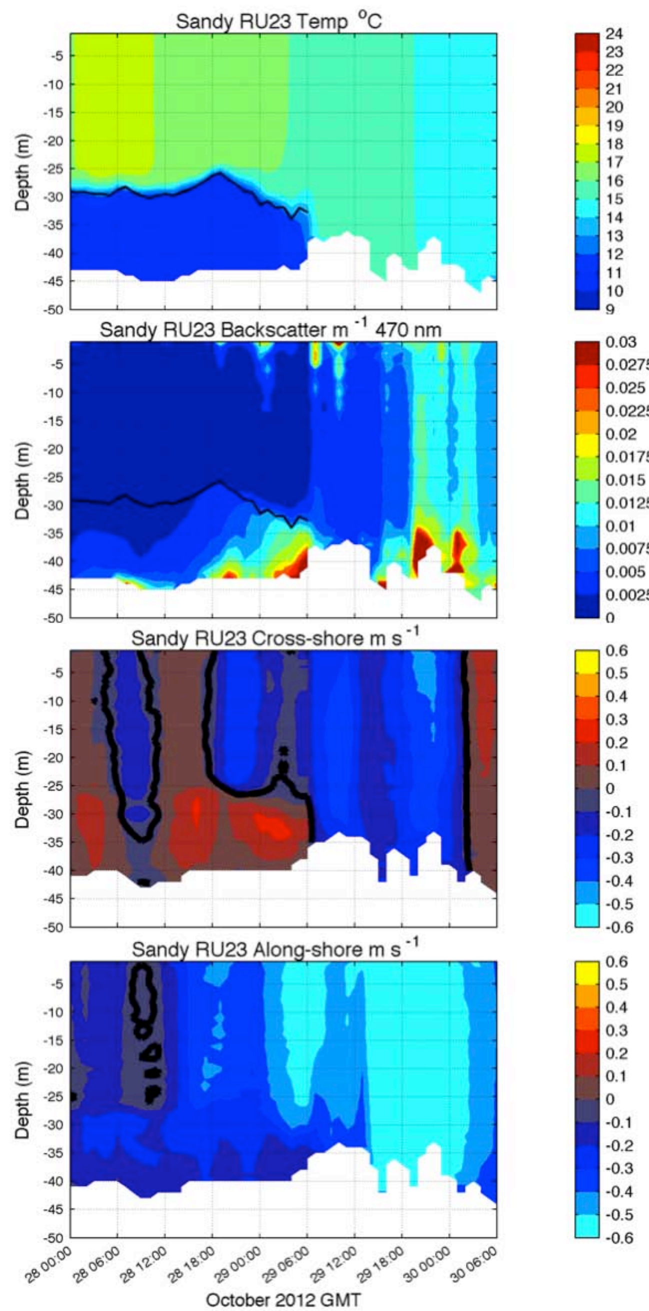

Fig. 10. Glider-derived temperature, backscatter, cross-shore (+offshore) and alongshore (+northeast currents for Hurricane Sandy.

The ocean model in Irene indicated the deepening and cooling of the surface layer, while inadequate, was dominated by a mixing processes. More extensive glider observations in Sandy indicate the layer deepening was likely dominated by an advective process. Optical backscatter in Sandy indicates that before the transition to a fully mixed water column, sediment suspended from the bottom did not cross the thermocline. After the transition to one layer, optical sensors indicate that sediment resuspension filled the water column, with a single mixed layer going from surface to bottom. Currents measured by the glider-mounted ADCP indicate that before the transition, a two layer flow was observered, especially in the cross-shore direction. A strong offshore jet formed in the bottom layer and persisted for over 18 hours before the transition as the water in the bottom layer thinned and moved offshore. Once the transition was complete, the water column responded as a single layer. Most significantly, the cross-shore current was onshore throughout the water column and persisted for two tidal cycles as the alongshore current accelerated to the southwest.

The same two SST products used in Irene were also examined in Sandy for August 27 (Figure 11). There is little pre-storm difference between the two SSTs, both maps have shelf temperatures in the 16C-18C range before the storm. Because Sandy was so extensive, and it was followed several days later by a northeaster that dropped snow on the damaged area, new SST products were not available for 11 days after the storm.

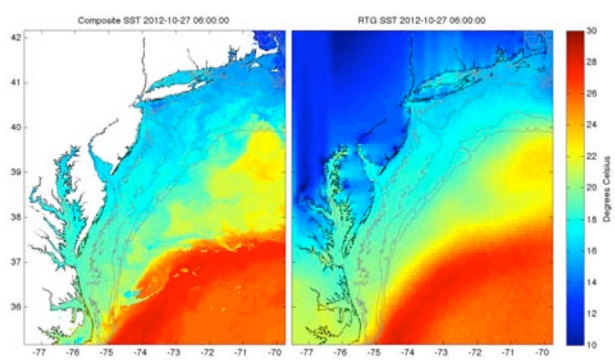

Fig. 11. Pre-Hurricane Sandy Satellite-derived Sea Surface Temperature (SST) products for October 27, 2012. (a) Locally composited SST. (b) Operational global SST product.

The Sandy observations indicated that there would be no significant cooling of the ocean surface layer as Sandy propagated shoreward. The WRF winds based on the conditions used in the real-time WRF forecasts, with atmospheric boundary conditions supplied by the National Centers for Atmospheric Prediction (NCEP) and ocean boundary conditions supplied by the locally composited SST are in Figure 12a. There is little sensitivity to the source of the SST, either the RTG or composite. Both result in an intensification of the storm as it makes landfall. The acceleration and intensification is significant, since the mean storm surge using operational products was under-predicted by 1 m in the hardest hit areas. Using the WRF model run in Figure 12a with the proper intensification and acceleration gains back significant portions of the missing meter in the mean storm surge as predicted by the New York Harbor Ocean Prediction System (NYHOPS) run by Stevens Institute of Technology.

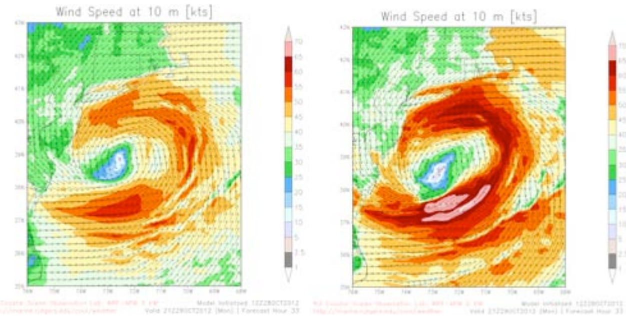

Fig. 12. Weather Research Forecast (WRF) atmospheric hindcasts of Hurricane Sandy with different ocean boundary conditions. (a) Using the cold SST from Figure 11a. (b) Using a warm SST characteristic of August conditions on the Mid-Atlantic continental shelf.

This series of model runs, while producing a hindcast that accurately recreates the observed storm surge, leaves unanswered the question of forecast sensitivity to SST in Sandy. If Sandy had hit earlier in the hurricane season during the peak summer stratification, would the forecast be sensitive to rapid changes in SST? As a test case, Sandy was rerun with typical August SSTs where, as in reality, it was assumed that no satellite updates to SST were available for over a week. The increase in forecast intensity at landfall is evident in Figure 12 b. Using these higher winds to force the NYHOPS storm surge model results in further increases in the predicted storm surge.

V. Conclusions

The back-to-back landfalls of hurricanes Irene and Sandy along the coast of New Jersey have hightened awareness of hurricanes and their potential impacts in the Mid-Atlantic. Irene's alongshelf track was accurately forecast but the intensity was over-predicted. Ocean observations by U.S. IOOS provide guidance as to why. Operational SST products did not pick up the 8-10C cooling caused by Irene even several days after the weather had cleared. An autonomous underwater glider that flew through the storm indicated that the cooling occurred rapidly as the leading edge of the hurricane approached and well ahead of the eye. Even if the operational SST products were reconfigured to pick up the cooling after the storm, they could not be applied in time to impact Irene. A more useful SST mapping product that accurately captures the timing and spatial extent of the cooling can only be supplied by an ocean forecast model. The ocean observations indicate what processes the ocean model must capture. Specifically, the initial thermocline must be better represented as the starting point. Second, the model must be 3-D, with a coast and a bottom. An infinitely deep 1-D model, one potential option for coupled atmosphere-ocean modes, will not capture the processes observed here. These include the initial onshore transport in the surface layer towards the coast, and the delayed response of the bottom layer to produce an offshore transport that limits the net shoreward transport. When there are two layers, the water transported onshore has an escape route through the bottom layer that appears to limit the storm surge. It also appears that the bottom layer also should be sufficiently thin for the offshore transport to produce a large shear across the interface. It is when this large shear is present that the mixing and cooling occurs.

Sandy occurred later in the year than Irene, after the fall transition was well on its way. Real time ocean observations during Sandy provided different guidance on what to expect when Sandy came ashore. The surface layer was already much thicker and cooler, so significant additional cooling was not expected. Advection moved what remained of the bottom Cold Pool offshore, removing the midshelf source of cool water. The water column responded as a single layer as Sandy came ashore, with mixing from surface to bottom, no cooling to reduce the intensity, and no bottom layer for the water in the growing storm surge to escape offshore.

The U.S. IOOS observations of hurricanes Irene and Sandy as implemented by MARACOOS for the Mid-Atlantic provided unprecedented real-time views of the evolving coastal ocean as the hurricanes made landfall in New Jersey. The observations led to new process studies in the ocean using numerical ocean models to examine the role of shallow topography, stratification and mixing that ultimately will lead to better ocean forecasts in extreme forcing conditions. New atmospheric sensitifivity studies further indicate that the rapid evolution of the ocean's surface layer temperature can have a significant impact on hurricane intensity. These results provide further evidence that one step towards improving hurricane intensity forecasting is to provide atmospheric modelers a better forecast of the rapidly changing coastal ocean beneath hurricanes.

Acknowledgment

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