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Remote forcing contribution to storm-induced sea level rise during Hurricane Dennis

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[1] Numerical model experiments are conducted to address the previously unexplained anomalously high storm surge along the Florida coast of Apalachee Bay during Hurricane Dennis (2005). The 2–3 m surge observed during this storm cannot be obviously explained by the relatively weak local winds over this bay 275 km east of the storm center. Realistic and idealized numerical experiments demonstrate that the along-shore winds to the east of the storm center built a high sea level anomaly along the coast which traveled northward to Apalachee Bay as a topographic Rossby wave. The wave was amplified as the storm moved nearly parallel to the shelf and at comparable speed to the wave phase speed. These results suggest that enlarging the domain of the storm surge forecasting models can improve the surge forecast for a storm moving along a similar track, and have now been applied to operational use. **Citation:** Morey, S. L., S. Baig, M. A. Bourassa, D. S. Dukhovskoy, and J. J. O'Brien (2006), Remote forcing contribution to storm-induced sea level rise during Hurricane Dennis, *Geophys. Res. Lett.*, *33*, L19603, doi:10.1029/2006GL027021.

1. Introduction

[2] On July 10, 2005, Hurricane Dennis made landfall just eastward of Pensacola, FL (Figure 1). About 275 km to the east, Shell Point, and other coastal communities of Apalachee Bay experienced a devastating storm surge locally 2 to 3 m above normal tide levels (Figure 1) [*Beven*, 2005]. Although this surge was not near the height seen with the more publicized Hurricane Katrina in Mississippi and Louisiana the following month, it caused extensive damage to private property and local infrastructure, effectively isolating several communities. The last Public Advisory issued by the National Hurricane Center (NHC) prior to Dennis making landfall warned of a storm surge potential of only 4 to 6 feet (approximately 1.5 to 2 m) for this area, as the local winds this far east of the storm center were not strong. The extreme sea level rise is not obviously explained by the surge anticipated from the relatively weak winds measured along the coast and over the bay. This discrepancy naturally leads to the question of the source of the additional 1 meter sea level rise along the coast of Apalachee Bay.

[3] In this paper, it is hypothesized that as the region of strong southerly winds (to the east of the storm center) traveled northward along the Florida Peninsula, a high sea level anomaly developed along the coast which traveled as a barotropic shelf wave to Apalachee Bay. This wave was locally modified by the storm's along-shore wind as the storm tracked nearly parallel to the shelf, and was amplified to approximately 1 meter prior to arriving at Apalachee Bay. Surge models, such as the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model [*Jelesnianksi et al.*, 1992], when configured for local domains near the coast, cannot simulate this remote mechanism for storm-induced sea level rise. For this study, a suite of barotropic, nonlinear numerical ocean simulations are run using the Navy Coastal Ocean Model and analyzed to isolate the effects of local and remote wind forcing on the sea level in Apalachee Bay. The numerical simulations show that a forced barotropic topographic wave solution explains the additional 1 m sea level rise along the northwest Florida coast. The results from these experiments suggest that either coupling the local storm surge models to a larger domain ocean forecast model, or using a larger domain for the storm surge model, could greatly improve the surge predictions for storms that travel along a continental shelf in the downcoast (with the coast to the right in the northern hemisphere) direction as did Hurricane Dennis.

2. Storm History and Observations

[4] Hurricane Dennis formed from a tropical depression that originated near the southern Windward Islands on July 4, 2005. It strengthened as it traveled northwestward through the Caribbean Sea until it made landfall in Cuba as a Category 4 hurricane on July 8. The storm emerged into the Gulf of Mexico at 0900 UTC on July 9 as a minimal hurricane. The storm then tracked north-northwestward just west of the West Florida Shelf (WFS) break intensifying to a maximum sustained wind of 64 m/s at 1200 UTC on July 10 (Figure 1). The storm's maximum sustained winds then weakened to 54 m/s before it made landfall on the western Florida Panhandle at 1930 UTC on July 10.

[5] While in the Gulf of Mexico, the hurricane force winds in Dennis were localized to near the eye, however tropical storm force (1-minute sustained winds greater than 17.5 m/s) winds extended far eastward over much of the WFS. Although some of the data records are incomplete, the Apalachicola NOS (National Ocean Service) station recorded a maximum 6-minute average wind speed of 21 m/s, the COMPS (Coastal Ocean Monitoring and Prediction System, University of South Florida) buoy 42013 recorded a maximum 8-minute sustained wind speed of 23 m/s, and the coastal C-MAN station at Shell Point recorded a maximum 2-minute sustained wind speed of 16.5 m/s. Despite the fact

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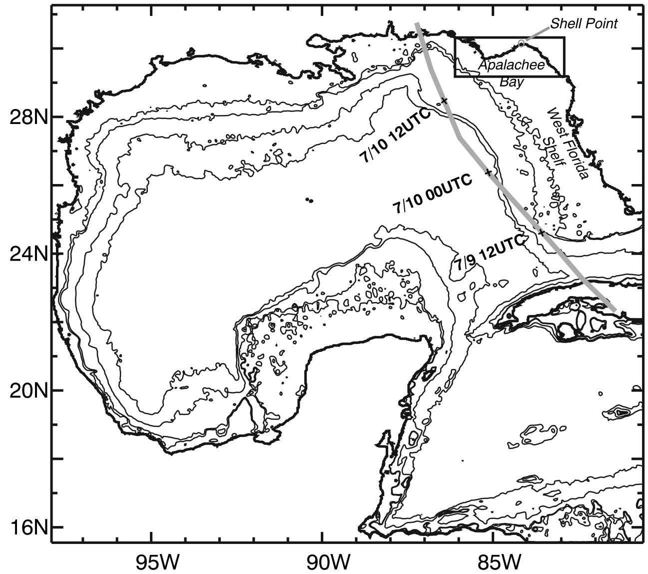

Figure 1. Map of GOM region with the NEGOM region overlaid as a black box. The Hurricane Dennis track is shown with a thick grey line. The 50 m, 100 m, 1000 m, and 2000 m isobaths are contoured.

that maximum sustained wind speed recorded at Shell Point remained less than tropical storm strength, a storm surge of 2.19 m was recorded.

3. Numerical Experiments

[6] The Navy Coastal Ocean Model (NCOM) [*Martin*, 2000] is used for numerical simulations of the sea level response to a moving hurricane in this study. The NCOM has a hybrid sigma/z-level vertical coordinate system that can be configured by the user with great flexibility. In these simulations, the NCOM is run with one sigma level and a homogeneous temperature and salinity field resulting in a nonlinear barotropic model.

[7] To demonstrate the remote forcing mechanism contributing to the hurricane induced sea level rise, an idealized shelf simulation is configured using the NCOM. In this experiment, an analytically derived wind field representative of Hurricane Dennis is translated along the coast at 8.3 m/s. The wind field is computed from the gradient wind balance applied to the analytical pressure field $P(r) = P_0 + (P_n - P_0)e^{-R/r}$ [*O'Brien and Reid*, 1967] where P_0 = 955 hPa is the minimum central pressure, P_n = 1015 hPa is the ambient pressure at the periphery of the wind field, r is the radial distance from the storm center, and R = 30 km is the radius of maximum wind speed. The idealized hurricane is located 430 km offshore. The model domain consists of a long (1200 km) shelf with a linear slope from the coast to the shelf break at 100 m 200 km from the coast, and a steeply sloping continental rise to 800 m 400 km from the coast. An offshore open boundary is located 500 km from the coast and radiation open boundary conditions are applied at the three open boundaries. The model horizontal grid spacing is 5 km and an *f* plane is assumed at latitude 30°N.

[8] For more realistic simulations of the sea level response to Hurricane Dennis, the NCOM is configured for a domain encompassing the Gulf of Mexico from 97°55′W to 80°36′W, 15°33′N to 31°16′N (Figure 1) with an open eastern boundary along which the *Orlanski* [1976] radiation open boundary condition is applied. The model horizontal resolution is 1/60° and the bathymetry is interpolated from the NOAA ETOPO2 data set. A second model domain is similarly configured except that the domain is limited to the northeastern Gulf of Mexico from 85°54′W to 82°37′W and 29°N to 30°15′N (Figure 1) with open southern and western boundaries. These two simulations are termed the GOM (Gulf of Mexico) and NEGOM (Northeastern Gulf of Mexico) simulations respectively. Both simulations are initialized from rest with an undisturbed free surface, and a semi-implicit time integration scheme is used. No tidal forcing is included in these simulations.

[9] Wind fields are constructed for the time period July 8 0:00 UTC – July 11 0:00 UTC, 2005, using the NOAA AOML Hurricane Research Division Wind Analyses (H*Wind fields) and the National Centers for Environmental Prediction Reanalysis II (NCEPR2) winds [*Kanamitsu et al.*, 2002]. H*Wind fields are objectively produced from all available surface weather observations for tropical cyclones [*Powell et al.*, 1998]. The 1-minute maximum sustained winds are provided on a 6 km grid roughly 960 km by 960 km. The NCEPR2 winds are used to complete the field over the GOM domain with an objective gridding method derived from that described by *Morey et al.* [2005] for producing gridded satellite scatterometer wind fields. In this method, the NCEPR2 winds are linearly interpolated in time to match the H*Wind times. A 1/8° wind field is then constructed by minimizing the functional given by *Morey et al.* [2005] treating the H*Wind data as "observations" and the NCEPR2 temporally interpolated winds as the background field. These fields are then interpolated to the model grid using bicubic splines. Wind stress is calculated from the interpolated wind fields using the wind stress bulk transfer coefficient given by *Large et al.* [1994]. The ocean model linearly interpolates the wind stress fields (at the H*Wind analyses times, typically three hours) in time to the ocean model time step (240 s).

[10] The GOM barotropic model is integrated from rest applying the wind fields from July 8, 2005 0:00 UTC to July 11, 2005 0:00 UTC. Two additional experiments are conducted using the NEGOM domain. First, the limited-area model is integrated from rest with wind forcing. The radiation boundary condition is used along the western and southern open boundaries. Second, this NEGOM domain is nested within the GOM domain, so that open boundary conditions are obtained from the large scale model. No local wind forcing is applied to the northeastern GOM nested model in this case. These experiments are designed to isolate the impacts of local forcing (in the first case) and remote forcing (in the latter case).

4. Results

4.1. Idealized Shelf Simulation

[11] The idealized shelf simulation is integrated for five days, beginning when the storm is outside of the domain. No significant sea level anomalies have appeared until the storm is within the domain (centered approximately 100 km downcoast) at the beginning of the third day of model integration.

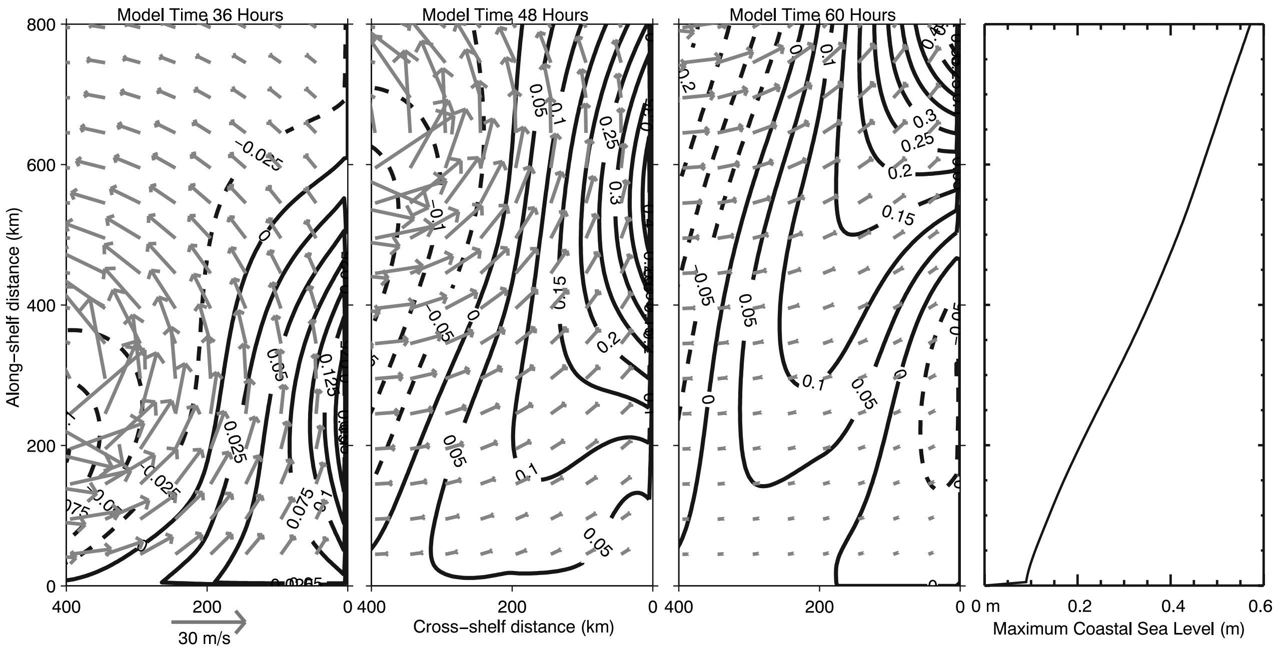

Figure 2. Sea level contours (m) for the idealized shelf simulation at model integration times 36, 48, and 60 hours (first, second, and third panels). Wind vectors are overlaid and $x = 0$ km is the coastline. Maximum sea level along the coastline during the model integration (fourth panel).

If the boundary at y = 0 km approximates the southern edge of the WFS at the Florida Keys, then y = 700 km approximately represents the distance along the WFS to Apalachee Bay. The maximum sea level calculated at each point along the coast during the simulation increases in the downcoast direction (northward when the WFS analogy is applied) reaching a maximum of 52 cm 700 km down the coastline (Figure 2). Synoptic maps of sea level show the high pressure anomaly propagating along the shelf with the storm. After initial adjustment to the application of the winds, an onshore Ekman mass flux is generated by the along-shore winds creating the high sea level anomaly along the coast. On a barotropic wide shelf, this pressure anomaly travels downcoast as a topographic Rossby wave at a speed of

$$c = \frac{\alpha g}{f\left(1 + R^2\left(k_x^2 + k_y^2\right)\right)}$$

where α is the bottom slope, g is acceleration due to gravity, f is the Coriolis parameter, R is the external Rossby deformation radius, and (k_x, k_y) are the cross-shelf and along-shelf wave numbers [*Cushman-Roisin*, 1994]. Although the wave numbers are difficult to estimate for this simulation, and R varies with depth, taking R = 215km over the inner shelf (using a depth of 25 m) and estimating the wavelength in both directions as 800 km yields c = 10.0 m/s. Thus, the high sea level signal generated by the storm travels at a speed comparable to the storm translation speed (8.3 m/s) and the wave continues to be amplified by the winds as it propagates along the coast. For a similar case, *Clarke* [1977] develops a solution for wind-forced coastally trapped waves. Essentially, the wave equation under along-shore wind forcing is solved by the method of characteristics. Changing to a storm-relative frame of reference, the wave phase speed would be replaced with a difference between the phase speed and the storm translation speed, yielding a maximum amplification when the storm translation speed equals the topographic Rossby wave propagation speed. This simple model can be extended to accommodate other effects such as stratification, bottom friction, higher order modes, etc., as in the work by *Clarke and Van Gorder* [1986], but it nevertheless provides an explanation for the unexpectedly high storm surge that accompanied Hurricane Dennis. It should be noted that *Mitchum and Clarke* [1986] estimated the first mode wave speed to be 8.2 m/s when they applied the *Clarke and Van Gorder* [1986] model to the WFS.

4.2. Barotropic Gulf of Mexico Simulations

[12] The barotropic 1/60° resolution GOM simulation produces a maximum storm surge in Apalachee Bay of 1.4 m at Shell Point, FL at 18:00 UTC on July 10 (Figure 3).

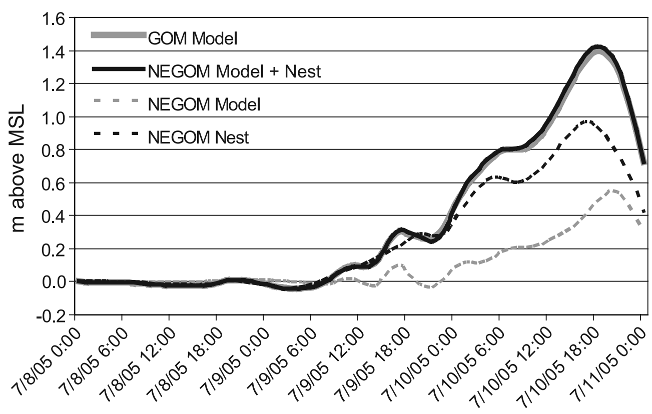

Figure 3. Time series of model sea level at Shell Point for the full GOM model (grey line), the NEGOM model (grey dashed line), and the NEGOM model with no wind forcing nested within the GOM model (black dashed line). The wind-forced NEGOM model solution is added to the unforced nested NEGOM model solution (black line).

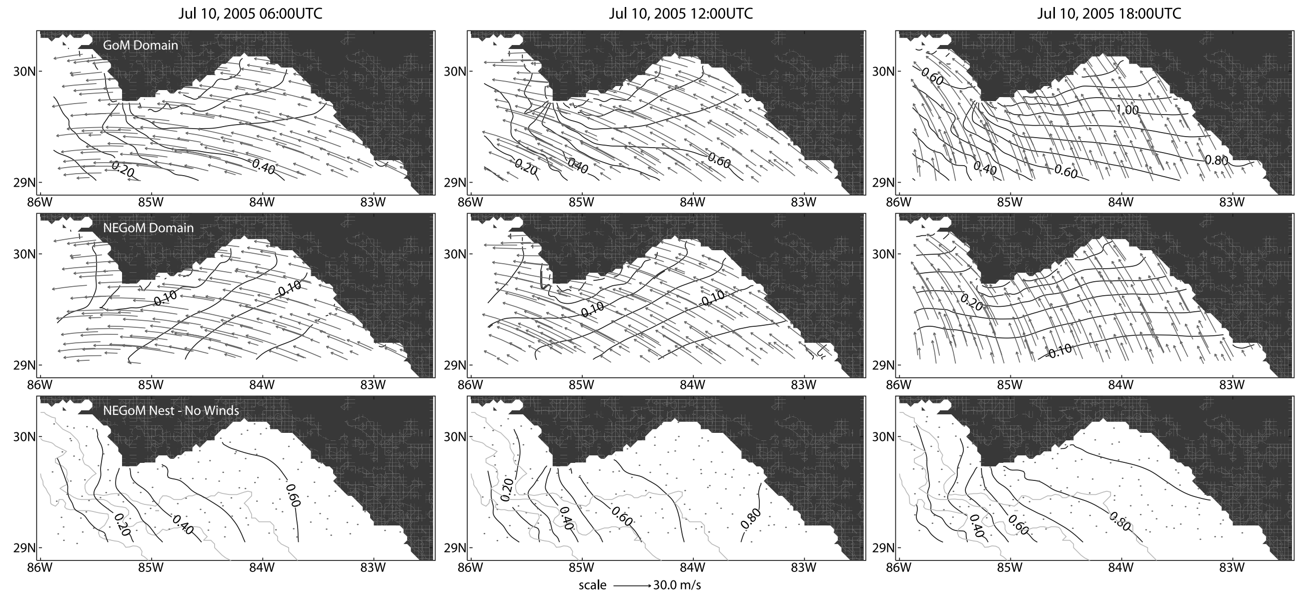

Figure 4. Model sea level contours from the (top) GOM, (middle) NEGOM, and (bottom) NEGOM Nest models. Wind trajectories are overlaid. The 20 m, 30 m, and 50 m isobaths are contoured in the bottom panels.

The storm surge (observed sea level – predicted tide) maximum observed at this location was 2.19 m at 16:48 UTC on July 10. Although the simulated sea level maximum is lower than observed, this model configuration is not intended to simulate local topographic effects, wind-wave setup, or atmospheric pressure effects (estimated at 7 cm for this location) that can locally add to the sea level.

[13] To simulate the sea level response to local wind forcing during the hurricane, the NEGOM simulation is run with surface wind stress but no forcing at its open boundaries. The locally forced sea level response in the NEGOM model is small compared to the sea level rise modeled in the full GOM simulation, with a maximum of only 0.55 m at Shell Point. This domain is comparable in size to the regional SLOSH models used for storm surge prediction.

[14] The model configured for the NEGOM domain is then integrated from rest with no local wind forcing but with sea level and barotropic transport at the open boundaries derived by nesting within the GOM domain. A high sea level anomaly can be seen propagating into the domain from the southern boundary and along the shelf (Figure 4), and reaches a maximum of nearly 0.96 m at Shell Point (Figure 3).

[15] This suite of numerical simulations is designed to explain the roles of local wind forcing on the storm surge in region, and of the remotely forced component to the local sea level rise in Apalachee Bay. In the model, a high sea level anomaly propagates northward as a shelf wave (topographic Rossby Wave), and is reinforced by eastward Ekman transport toward the coast under the along-shore winds at the eastern side of the storm. Because the region of along-shore winds is moving with the shelf wave as the storm translates in nearly the same direction, the high sea level anomaly is amplified as the wave travels, similar to the ocean response seen in the idealized shelf simulation. Inspection of the sea level time series at Shell Point reveals that the sea level responds as a linear combination of the remotely generated sea level and the locally forced sea level (Figure 3), which is consistent with the forced wave mechanism demonstrated by the idealized shelf model.

4.3. Application to SLOSH

[16] The SLOSH model is the primary storm surge forecasting model used by the NHC. This forecasting system usually predicts the maximum storm surge height within 20%, but dramatically underpredicted the surge in Apalachee Bay for Hurricane Dennis. Several model domains have been configured around the coast of the United States. The curvilinear grids do not conform to the latitude/longitude grid system used by the NCOM simulations in this study, but the northeastern Gulf of Mexico domain has similar bounds as the NEGOM model; that is, it cannot account for the remotely generated sea level anomalies. After reconfiguring SLOSH for the Gulf of Mexico basin, the model produces a maximum storm surge at Shell Point of 2.10 m, within 5% of the observed 2.19 m maximum.

5. Conclusions

[17] Relatively weak winds and a mild storm surge were anticipated along the Florida coast of Apalachee Bay during Hurricane Dennis; however, an unexpectedly high surge caught residents and forecasters by surprise and complicated evacuation efforts by County Emergency Managers. The winds observed over the bay and along the coast during the hurricane cannot, on their own, produce the observed storm surge of 2–3 meters. The additional sea level rise of approximately one meter is explained by a remotely forced shelf wave. The hurricane traveled from Cuba to the western Florida Panhandle over the course of 34 hours, during which along-shore winds persisted over the WFS. These along-shore winds forced Ekman transport toward the Florida Peninsula coast building a high sea level anomaly that propagated downcoast (northward) as a topographic Rossby wave. The storm traveled nearly parallel to the shelf in the same direction of the wave, resulting in amplification of the sea level signal along the coast. This high sea level anomaly reached its maximum amplitude at the northernmost bounds of the WFS (Apalachee Bay) and combined with the surge

driven by the local onshore winds to produce the extreme coastal inundation.

[18] An idealized shelf model demonstrates that a coastally trapped wave generated by a storm's winds is amplified when the storm translates in the same direction as the wave propagation. Experiments conducted with a Gulf of Mexico basin model and a smaller domain northeastern Gulf of Mexico model demonstrate that for storms traveling along a coast in the direction of the shelf wave propagation, remotely generated sea level anomalies can contribute significantly to coastal sea level rise during a storm. Application of these findings to the NHC operational SLOSH model where the domain has been expanded to include the entire WFS dramatically improved the model solution for the storm surge during Hurricane Dennis. Based on these results, operational storm surge forecasting activities at the NHC henceforth will include simulations using a full Gulf of Mexico basin SLOSH model domain to account for remotely generated coastal sea level anomalies.

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