Modeled Oceanic Response to Hurricane Katrina

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Abstract

The ocean response to hurricane Katrina is simulated using a 4th-order-accurate ocean model based on a collocated control volume grid. The surface winds are imposed by an atmospheric hurricane model. An intense nonlinear mesoscale eddy having Rossby number O(1) is generated. Its scale is 50-100 km and sustained top layer currents as fast as 5 m/sec occur in the northern Gulf of Mexico. The strong mesoscale response to Katrina winds is not surprising in view of its strong eyewall-concentrated winds. Further, the simulated currents and Gulf of Mexico internal wave speeds are comparable to Katrina's translation speed, which may lead to extra energy absorption by a given material element or by a propagating solitary internal wave in a kind of near-resonance with the atmosphere: structures with flow velocity or internal wave phase velocity close to Katrina's translation velocity are likely to amplify most. However, the flow is very nonlinear and time dependent, and cannot be analyzed using conventional linear theory. Nonlinearities can further focus and intensify the response.

1. Introduction

Ocean response to hurricane winds is important because the eyewall-scale wind-generated mesoscale currents can be fast enough to destroy oil rigs, as happened with Hurricane Katrina. The observed response and feedback include: significant cooling between the thermocline and ocean surface due to vertical mixing and upwelling, affecting hurricane path and intensity; and the ensuing upper layer recovery affecting the fate of possible future hurricanes following the same path (as in Rita which followed Katrina during 2005).

Sheng et al. (2006) modeled the ocean response to Hurricane Juan, which hit Halifax,

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Canada with category 2 winds during 2003. It was done using a nested grid adaptation of the CANDIE (CANadian version of DIEcast) ocean model. Although a free surface version exists, a rigid-lid approximation was used. To achieve high resolution near Halifax, a one-way nesting approach was applied. The surface winds were idealized, but patterned after the observed hurricane. Other results of CANDIE simulation of 1998 Caribbean Sea Hurricane Mitch are also presented recently (Sheng, 2007).

Hurricanes are highly time dependent, especially when growing "explosively" as did Katrina. Although accurate initialization is not possible in detail, dynamics similar to the real hurricane can be modeled once an adequate initialization is constructed (with similar scales and wind amplitudes). One can then explore the general nature of the response, as done here. In the case of Katrina, whose explosive growth involved interaction with an unusually warm Loop Current that was observed before Katrina arrived, an atmospheric hurricane model during and after its explosive growth may be more like the real hurricane than before it encountered the Loop Current.

Herein, hurricane Katrina winds simulated by an MM5-based atmospheric hurricane model (Yau et al., 2004) are applied to the MEDiNA (coupled MEDiterranean Sea and North Atlantic; Dietrich et al., 2007a) adaptation of the DieCAST ocean model, from which the aforementioned CANDIE ocean model was derived. The coupling was made possible using six grids. All adjacent grids are two-way-coupled, and are solved using a fourth-order-accurate, central difference, collocated control volume based primitive equations solver having small numerical dispersion and diffusion (Dietrich, 1997; Sanderson and Brassington, 1998). MEDiNA uses the hydrostatic version of DieCAST, although a nonhydrostatic version exists (Tseng, et al., 2005; Dietrich and Lin, 2002) that is equivalent in the limit of small vertical acceleration.

2. Model Setup

The maximum Katrina wind stress based on the atmospheric hurricane model (Yau et al., 2004) was about 13.3 Newtons/m^2. Rapid vertical mixing by subgrid-scale processes is parameterized using the empirical, wind stress dependent vertical eddy viscosity and diffusivity that was used for modeling the ocean response to extratropical hurricane Juan (Sheng et al., 2006). For the present case, it gives a maximum vertical eddy viscosity of 0.2 m^2/sec. If applied for two hours at a given location, that gives a scaled mixed layer thickness about 40 m. That is reasonable based on observations of 30 m thick mixed layers for weaker hurricanes. That implies a velocity change of about 12 m/sec for a well-mixed vertical column of water that is

40 m thick (mixed layer thickness) and is exposed to the maximum wind stress for one hour. Of course, whether a given material column is exposed to such stress for that long depends on how fast the hurricane moves relative to the water material, and the momentum mixed layer may be thicker than the material mixed layer due to the vertical exchanges of momentum by internal waves. Although the ocean model simulated surface cooling by vertical mixing and wind forced upwelling was generally 3-5°C, similar to observations, no feedback to the atmospheric hurricane model is included in this purely ocean response study.

The velocity response to the winds depends strongly on the vertical eddy viscosity. However, the 5 m/sec maximum currents simulated in the model (see Section 3) seem reasonable since indirect evidence suggests that such significant currents may have actually occurred. While a major oil rig was destroyed, it was thought that the winds could not have done that directly; and the observed scattering of its debris over tens of kilometers suggests currents of at least that magnitude (Dennis Lavoie, personal communication). Unfortunately, no direct current measurements exist; current meters in Katrina's path were removed in order to avoid them being destroyed or lost.

The present six-grid MEDiNA framework is the same as that used by Dietrich et al. (2007a), except the large vertical viscosity and diffusivity terms are solved using a time-split approach to avoid excessive computation. These terms include time scales less than one minute on the scale of one vertical grid interval (11 m for the top layer). This approach is valid because all other spatial terms are much smaller (Dietrich et al., 1987). The western North Atlantic, Gulf of Mexico and Caribbean Sea use a 1/8° resolution horizontal grid.

Herein, we focus on a major mesoscale eddy generated by Katrina winds. The DieCAST model is ideal for simulating mesoscale features: Cushman Roisin et al. (2007) show realistic meandering Po River plume in an Adriatic Sea implementation; Dietrich et al. (2007a) show accurate Mediterranean Overflow Water penetration and the associated density current; and Dietrich et al. (1997) show realistic mesoscale frontal eddies along the Loop Current front.

MEDiNA model is forced by annual cycle surface wind and watermass climatology for fourteen model years before applying Katrina winds. The model is initialized from Levitus'94 climatology (Dietrich, et al., 2007). Although MEDiNA had already reached beyond year 20 at the time of this simulation (now it has reached nearly 50 years running on a single processor Pentium 4 based personal computer), results from the summer of its 15th model year are used to initialize the model for Katrina wind forcing. This time was chosen because the Loop Current was unusually well extended into the Gulf of Mexico, similar to the conditions just before Katrina arrived, but with surface temperatures closer to climatology. The actual Loop Current surface temperatures were about 2°C warmer than climatology when Katrina arrived; based on this extremely warm water in its projected path, it was forecasted to grow explosively into a category 5 storm, which it did. Thus, during 30 days before we applied Katrina winds (starting with hurricane winds east of Florida), we nudged the surface layer toward satellite derived surface temperatures; also, the differences resulting from the surface layer nudging were distributed vertically with amplitude decreasing with increasing distance from the surface.

3. Results and Discussion

Figure 1 shows a time sequence, every eight hours, of top layer vorticity and velocity vectors, starting near the time Katrina grows over the Loop Current. The eye-wall winds drive a strongly-out-of balance cyclonic flow, as indicated by the vectors that reveal a big outward flow component of the cyclonicly spinning water. At hour 0, Katrina is centered over the southwest Florida shelf causing a single tight vortex on the shelf. At hour 8, Katrina is straddling the southwest shelfbreak, resulting in a splitting of the vortex into a deepwater one and one on the shelf. During hours 8-32, the deep vortex follows the Katrina eye across the eastern edge of the Loop Current, while the shelf vortex propagates northward and elongates before breaking up when it reaches the north Florida coast. After hour 32, as Katrina grows explosively over the Loop Current, the deep vortex also grows explosively. As Katrina passes over the northern shelfslope onto land, and decays starting about hour 56, so does the vortex, which also spreads longitudinally into the Mississippi Bight region in response to the steep northern Gulf of Mexico shelfslope.

The very intense nonlinear mesoscale vortex has scale 50-100 km and Rossby number O(1). As Katrina passes over the northern Gulf of Mexico, sustained top layer currents as fast as 5 m/sec occur (Figure 1, hour 56). Figure 2 shows the sub-surface layer flow at hour 56. Currents more than 4 m/sec extend down to about 50 m depth; currents nearly 2 m/sec extend down to almost 100 m depth; and currents over 1 m/sec extend down to nearly 200 m depth. Figure 2 also shows the developing deep resolved mesoscale turbulence, which reflects a combination of internal waves and directly wind forced flow. There is a strong downslope flow near the northern shelfslope soon after hour 56 as upwelled cold shelf water spills back into the deep (not shown).

Internal waves remain strong until the run is terminated at hour 96.

The model results also show the surface temperature decreases by up to 5° during the development of hurricane Katrina, and the depth of 22°C surface decreased from ~300 m to ~200 m as part of the upwelling response to Katrina (not shown). Although this may have significant effect on a slower moving storm, the direct effect on the ocean response is less.

The strong anticyclonic vorticity on the outer edge of the eye-wall results in near zero absolute vorticity, and strong vertical mixing decreases the near-surface stratification. This decreases rotation and buoyancy constraints, and allows significant wind-forced upwelling near the eye-wall and inside the eye as internal waves quickly spread the upwelling signal.

Without large vertical mixing (vertical viscosity up to 2 m^2/sec) to levels much deeper than the mixed layer (which reached 100 m depth for momentum and 50 m depth for watermass), the wind stress would result in even faster flow than 5 m/sec in the model results. The vertical mixing is no doubt enhanced by big amplitude external and internal gravity waves. Internal waves occur in the model response, but large pressure signals throughout the water column result from breaking surface waves and large clusters of surface water elements sheared off into the winds. These cannot be modeled explicitly even with a free surface model, because they involve very small time and space scales and two-phase flow, but their effects no doubt extend throughout the water column in nature due to their associated big pressure signals that generate big amplitude internal waves. These pressure signals propagate throughout the water column almost instantaneously in nature by extremely fast compression waves (in a hydrostatic model instantaneously). Internal waves transfer momentum vertically even when they are laminar (do not break). However, they mix very little watermass material in the laminar diffusion limit, unless they break.

The ocean surface during a hurricane is not well defined because of the clusters of watermass elements sheared off big waves. Thus, the use of a free surface model may have no advantage; a truly two-phase model would be ideal, but the cost would be prohibitive. An alternative approach may include partial parameterization of some of the two-phase flow effects by changing the density of the upper levels of the model to represent a time average vertical density distribution that depends on wind speed, having air density at its top and water density at its bottom, and having a vertical density discontinuity in the limit of low wind speed. This is not done in this study.

4. Final Remarks

The modeled strong response to Katrina winds is not surprising because the currents generated (3-5 m/sec) and Gulf of Mexico internal wave speeds are comparable to the Katrina translation speed, which may lead to big energy absorption by a given material element or by a propagating solitary internal wave, which may be viewed as a kind of resonance that is somewhat analogous to nonlinear critical layer dynamics. Vertical mode structures having signal propagation velocity (combined flow velocity and internal wave phase velocity) close to Katrina's translation velocity are especially likely to amplify. However, the flow is very nonlinear and time dependent, so cannot be easily analyzed. The response can be huge and big mesoscale nonlinearities can further focus and intensify the response. With higher resolution and better air-sea interface parameterization, the currents may have been even faster, but they were strong enough to destroy oil rigs and scatter their debris over tens of kilometers, as happened.

Thus, some of the water (at least near some upper level depth) may have closely followed the eye-wall. In such a case, strong momentum input from the winds IN ALMOST THE SAME DIRECTION may have occurred over an extended time. Time averaged location of lagrangian elements RELATIVE TO THE EYE WALL may suggest this, but that is beyond the scope of the present study; that would determine whether the watermass material that follows the eye wall most closely is the material that developed the biggest velocity, thus suggesting a kind of near-resonance with the hurricane wind forcing. Another kind of near-resonance may be that certain internal wave modes propagate at similar speeds, thus allowing reinforcement of internal wave structure. These possibilities are not addressable using conventional linear ocean dynamics theory; the Rossby number of the intense mesoscale eddy in the modeled ocean response is O(1).

Acknowledgements
Natural Science and Engineering Research Council of Canada; National Science Council of Taiwan; Jinyu Sheng for supplying the vertical mixing subroutine appropriate for hurricane force winds; Bob Haney and Ben Ash.

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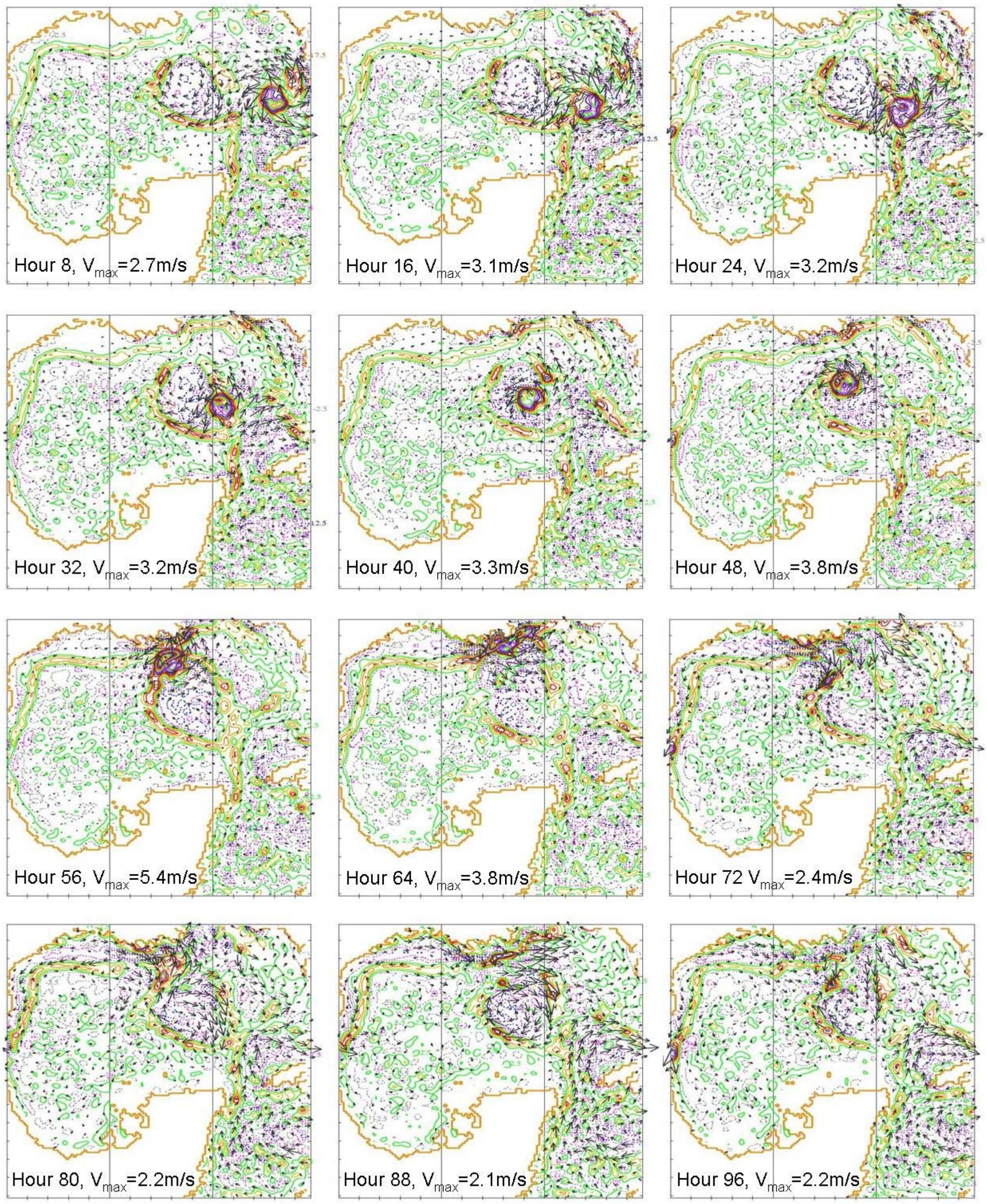

Figure 1: Time sequence (every eight hours) of top layer vorticity and velocity vectors, starting near the time Katrina grows over the Loop Current. Longitudinal grid spacing is 1° (Mercator grid, so the physical distance for latitudinal spacing matches the longitudinal ticks). The cross-grid lines are every 5° with the westernmost boundary 87.5°W.

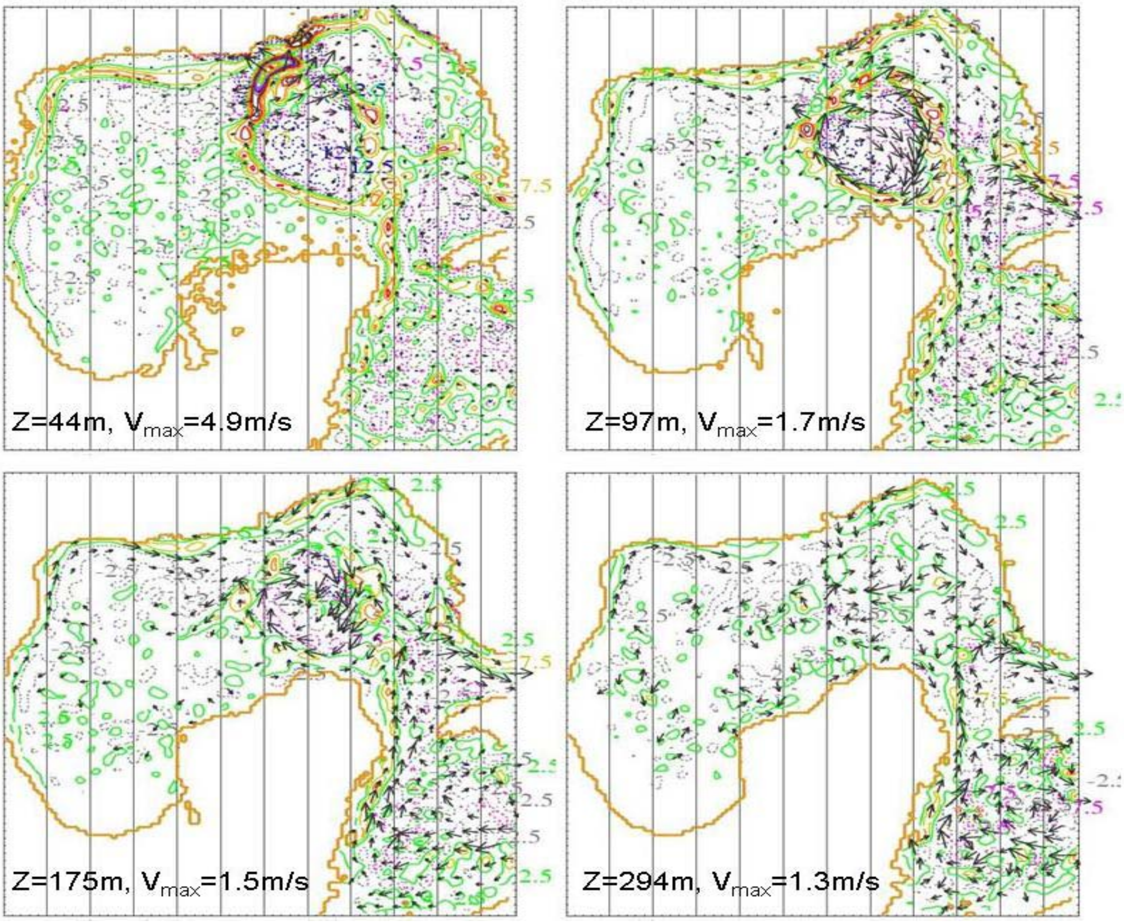

Figure 2: the sub-surface layer vorticity and velocity vectors at hour 56.