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The impact of ocean coupling on hurricanes during landfall

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Abstract.
The impact of ocean coupling on landfalling hurricanes is studied using a coupled hurricane-ocean model with idealized atmospheric and oceanic conditions. We focus here on coastal sea surface temperature responses and their effects on hurricanes during landfall. We find that given the ocean thermal stratification, the hurricane-induced sea surface cooling is nearly independent of the ocean depth as long as the ocean is considerably deeper than the mixed layer. After the storm center moves inland, the near-surface processes around the storm core area are influenced by the sea surface cooling behind and on the right side of the storm track via reduction of near-surface entropy advection into this area. The impact of ocean coupling is generally limited to the early times after landfall and nearly disappears after the hurricane center reaches about 200 km inland.

Introduction

In this paper we investigate the effects of ocean coupling on landfalling hurricanes using a coupled hurricane-ocean model. Previous studies [*Tuleya and Kurihara* 1978; *Tuleya et al*, 1984] used the GFDL (Geophysical Fluid Dynamics Laboratory) hurricane model to study the hurricane intensity and structure changes during landfall. It was indicated that as the hurricane center moves inland, higher low-level air entropy exists on the right side of the hurricane due to the moist air advection from the ocean. These studies used an uncoupled hurricane model and therefore assumed fixed in time sea surface temperatures (SSTs). It is well established that hurricane intensity over the open ocean may be significantly reduced due to the sea surface cooling caused by air-sea interaction [*e.g., Khain and Ginis*, 1991; *Schade and Emanuel*, 1999; *Bender and Ginis*, 2000]. Therefore, it is important to know how ocean coupling affects the hurricane intensity and structure during landfall. This study focuses on two associated aspects of hurricane-ocean interaction during landfall: 1) the hurricane-induced coastal SST changes and 2) their influences on the near-surface thermodynamic processes and hurricane intensity after the hurricane center encounters the coast.

Methodology

The GFDL/URI coupled hurricane-ocean system described in Bender and Ginis (2000) is used for our investigation. The numerical experiments are designed in such a way that a westward moving hurricane interacts with an initially resting ocean underneath and encounters a shore elongated in the meridional direction 7^o west of the initial hurricane center. A hurricane Fran (1996)-like vortex is placed initially at 19.5N. An easterly wind of 5 m/s is specified in the environment of a GATE III sounding [*Shen et al*, 2000], but an easterly of 2.5 m/s is also applied in some additional experiments. For convenience, the initial longitudinal position of the vortex is set to be zero. In the primary set of experiments land surface wetness, a simple coefficient representing the surface evaporation effectiveness, and land surface temperature are assumed to be fixed in time. Land surface wetness is set to 0.3 and the land and initial ocean surface temperatures are set to 28.5^oC. Land surface roughness of 25cm is used in all cases. The initial vertical temperature profile in the ocean is shown in Fig. 3b and represents a typical structure of the coastal waters at the northern Gulf Mexico in September. In most of the experiments the ocean depth is set to 500 m, but ocean depths varying from 100 m to 1000 m are also applied to investigate the sensitivity of hurricane-induced SST anomalies to ocean depth. Note that according to observations, the water column in summer is usually well stratified over the continental shelf, even in very shallow water areas with depths less than 100 m.

Results and discussion

Fig. 1 shows the hurricane intensity evolutions in the coupled and uncoupled landfall experiments which are compared with control, open ocean runs. In general, the intensity difference between the coupled and uncoupled cases reaches its maximum shortly before landfall (*hereafter, "before" and "after" landfall are referred to as before and after the hurricane center encounters the shore, respectively*). After landfall, the storms rapidly decay. The intensity differences due to the ocean coupling almost disappear when the storm center is about 200 km inland (about half a day after landfall for a translation speed of about 6 m/s), implying that the influences of the ocean coupling and ocean coupling-related intensity difference before landfall become negligible when the storm center is about 200 km inland. In additional experiments (not shown) with a slower translation speed of about 3 m/s, the ocean coupling-induced central pressure reduction before landfall was almost doubled (~9hPa). But this intensity difference nearly vanished after the storm center reached about 200 km inland.

Figs. 2 (a) and 2 (b) show the hurricane-induced SST anomalies and the surface ocean currents at 37 h (about

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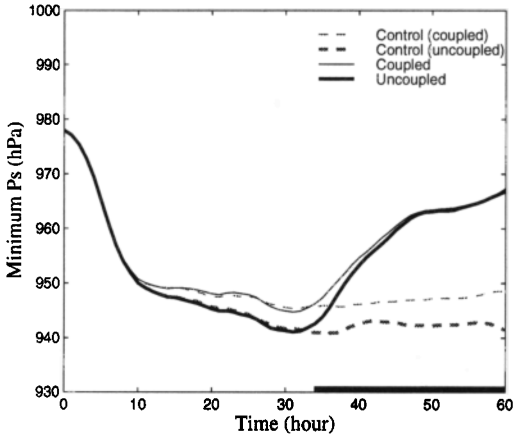

Figure 1. Intensity evolutions of landfalling hurricanes in the coupled and uncoupled experiments. The reference bar on the bottom symbolizes land. Control, no land (open ocean), runs are also shown for comparison.

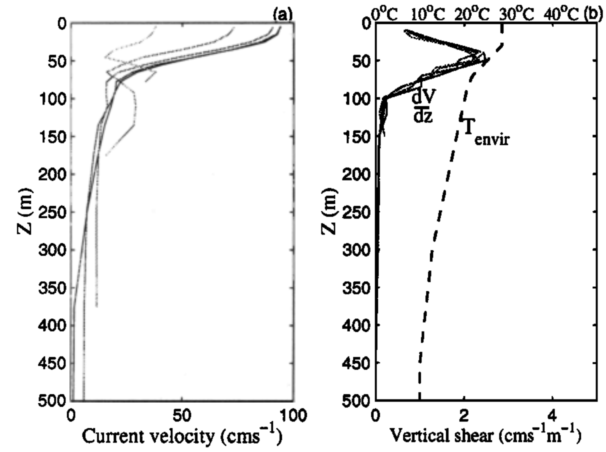

Figure 3. (a) Vertical distributions of the magnitude of the baroclinic velocity averaged over the area shown by the thin dashed line in Fig. 2 (a). (b) The area-averaged shears of the ocean currents, $|\frac{dV}{dz}|$, and the initial ocean temperature profile.

3 hours after landfall) and at 42 h. It is important to note that the SST anomalies and the ocean currents at 37 h are quite similar to those in the control coupled ocean case (not shown) including their positions, magnitudes, and patterns. The region in which the ocean response is appreciably influenced by the shore-related friction and deflection is mostly confined to the shore. When the hurricane moves further inland (Fig. 2(b)), the SST anomaly contours do not extend westward as much as would be in the control case.

A set of sensitivity experiments was also performed using the same conditions as in the experiment shown in Fig. 2 except for different ocean depths ranging from 100 m to 1000 m. It was found that the hurricane-induced SST anomalies are not sensitive to the ocean depths (not shown). Figs. 3 and 4 are served to illustrate the main reasons of this result. They indicate that while the vertical profiles of the ocean baroclinic

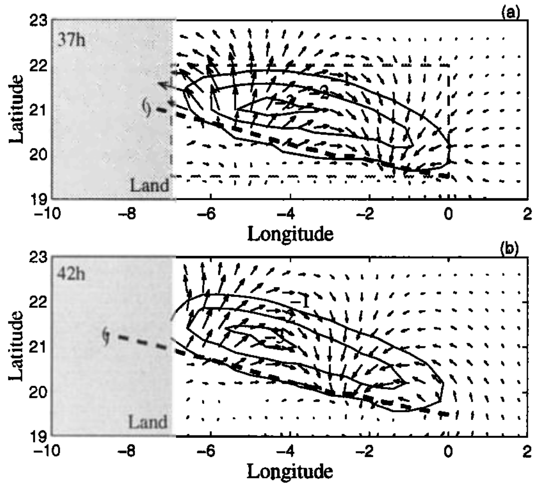

Figure 2. SST anomalies and surface ocean currents at 37 h (a) and 42 h (b) in the coupled case. The thick dashed lines denote the hurricane tracks.

(full velocity minus the depth-averaged) velocity vary significantly for different ocean depths (Fig. 3(a)), the vertical shear of the velocity, $|\frac{dV}{dz}|$ which is primarily responsible for turbulent mixing and thus sea surface cooling, remains almost the same (Fig. 3(b)). Fig. 4 shows the baroclinic velocity fields at the surface and at 60 m for the cases with the total ocean depths of 100 m and 1000 m. It is seen that the surface velocities have similar patterns but different magnitudes in both cases. However, at 60 m the velocity pattern is reversed in the shallow water case while it remains similar but with reduced magnitude in the deep water case. This implies that the velocity shears shown in Fig. 3(a) are largely due to the directional change of the currents in the shallow water case while the magnitude changes is the main source of the velocity shears in the deep water case.

We now consider hurricane intensity change due to air-sea interaction during landfall. In terms of hydrostatic balance, applied in the GFDL hurricane model, the surface pressure drop from the environment to the storm center and thus the hurricane intensity is determined by the atmospheric thermal state difference above. The hurricane-induced sea surface cooling is typically localized near and behind the hurricane core and has negligible influence on the overall sounding in the environment. However, the sea surface cooling under the hurricane core affects the air thermal state above by reducing the surface heat fluxes underneath the core. For this reason, high correlation exists between the magnitude of sea surface cooling under the hurricane core and the hurricane intensity reduction [*Emanuel*, 1999; *Shen et al*, 2000]. The cool wake behind the core also influences the thermal state in the core by reducing the low-level entropy advection inward. This is the way by which the cooled ocean surface behind the hurricane affects the hurricane intensity after landfall. Fig. 5(a) shows the differences in the surface thermodynamic disequilibrium between the coupled and uncoupled cases, corresponding to the SST changes shown in Fig. 2(a). It is seen that the ocean coupling affects the surface thermodynamic disequilibrium over both the ocean and the

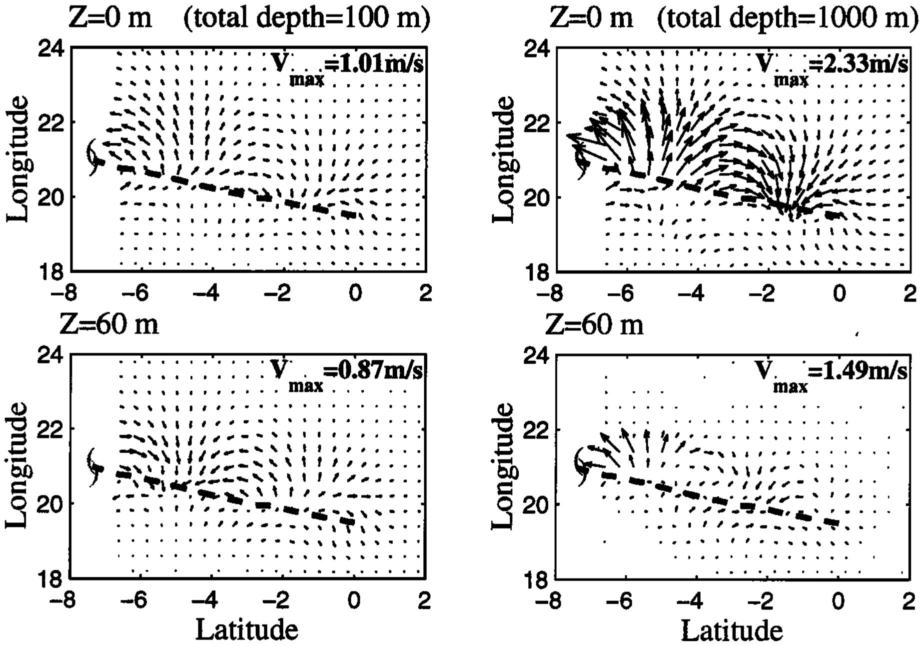

Figure 4. Baroclinic velocity fields at surface and at 60 m for the cases with ocean depths of 100 m (left) and 1000 m (right).

land. The cooled sea surface leads to a reduction of heat fluxes from the ocean surface and thus less air entropy advection inward. The latter causes an increase of the surface thermodynamic disequilibrium over the land to the right of the storm track (the positive anomalies area in Fig. 5(a)). Related to these surface disequilibrium differences are the surface heat flux differences in these regions (Fig. 5(b)). There is a heat flux increase on the right side due to the increased surface thermodynamic disequilibrium. This heat flux increase is found to be dominated by the surface evaporation. As the hurricane moves further inland, the impact of the cooled ocean on the near-surface processes and surface heat fluxes in the core area quickly diminishes.

It should be pointed out that the specific magnitudes of the heat flux changes shown in Fig. 5(b) are related to the given land surface wetness and other land surface conditions that are assumed to be fixed in time. In reality, land surface conditions, such as land surface temperature and wetness, change due to hurricane-land interaction. Additional experiments with the land temperature predicted by a slab land model with a typical soil layer of depth of 16 cm and heat capacity of 0.5 cal cm^{-3}K^{-1} [*Tuleya*, 1994] were also performed. The results (not shown) indicate that the ocean coupling-induced land surface heat flux changes are substantially reduced due to the hurricane-induced land surface cooling. However, the land surface flux changes shown in Fig. 5 may still be possible over swampy or flooded regions where surface wetness and heat capacity are significantly larger. In general, the quantitative changes in the land surface heat flux due to ocean coupling depend on the land surface conditions that vary largely in reality. Therefore, further investigation of these processes for real hurricanes with a more realistic land surface scheme is warranted.

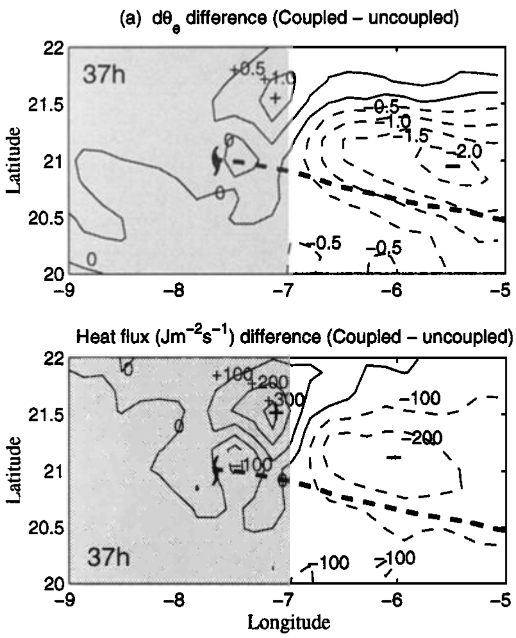

Figure 5. Surface thermodynamic disequilibrium, $d\theta_e$ and heat flux differences between the coupled and uncoupled cases with fixed land surface conditions corresponding to the SST changes shown in Fig. 2 (a). $d\theta_e = \theta_e(0) - \theta_e(z1)$ where $\theta_e(0)$ is the equivalent potential temperature of the surface air saturated at the sea surface pressure and temperature, and $\theta_e(z1)$ is the same but at the lowest model layer (~40m high). The +/- signs denote increase/decrease of thermodynamic disequilibrium or heat fluxes, respectively, due to the ocean coupling.

Conclusions

Idealized numerical experiments have been performed with a coupled hurricane-ocean model to demonstrate the responses of coastal SSTs to landfalling hurricanes and their influences on hurricanes during landfall. The results indicate that the sea surface cooling behind the hurricane center is nearly unaffected by the shore before and shortly after landfall. The surface cooling is also insensitive to the ocean depth as long as it is much deeper than the mixed layer. Shortly after landfall, the ocean surface cooling behind acts to reduce the near-surface entropy advection into the hurricane core, thus reducing the major energy source during that time. The reduced entropy advection leads to larger heat flux from the land surface to the right side of the hurricane track. This flux increase, with its magnitude depending on the land surface conditions, however, is generally much smaller than the reduction of entropy advection from the ocean. The impacts of the ocean coupling and ocean coupling-related intensity difference before landfall are mostly confined to the early times after landfall and quickly diminishes off as the hurricane moves further inland.

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