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Effects of surface heat flux-induced sea surface temperature changes on tropical cyclone intensity

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[1] It is known that in deep and open oceans, the effect of sea surface sensible and evaporative heat fluxes on the tropical cyclone-induced sea surface cooling is small compared to that caused by turbulent mixing and cold water entrainment into the upper ocean mixed-layer. This study shows that tropical cyclone-induced surface heat fluxes dominate the surface cooling in near-coastal shallow ocean regions with limited or no underlying cold water. The thermal response of the ocean to the surface heat fluxes is nearly one dimensional through very quick vertical mixing in the ocean mixed layer. The flux-induced sea surface cooling may lead to appreciable reduction of storm intensity if the storm moves slowly. It is therefore important to account this negative feedback of ocean coupling in near-coastal regions for more skillful forecasting of landfalling tropical cyclones. *INDEX TERMS:* 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 9974 Corrections: Editorials. **Citation:** Shen, W., and I. Ginis, Effects of surface heat flux-induced sea surface temperature changes on tropical cyclone intensity, *Geophys. Res. Lett.*, *30*(18), 1933, doi:10.1029/2003GL017878, 2003.

1. Introduction

[2] Tropical cyclones represent an extreme case of air-sea interaction. The effect of this interaction as a negative feedback on tropical cyclone development and intensity has been well established. It is known that the strong surface winds in a tropical cyclone induce strong turbulent mixing in the upper ocean and entrainment of underlying cold water into the ocean mixed layer, which cools and deepens [e.g., *Bender et al.*, 1993; *Ginis*, 2002]. Both observational and real case numerical studies [e.g., *Black*, 1983; *Bender and Ginis*, 2000] showed that the SST anomalies induced by tropical cyclones can reach up to 5–6°C. Numerical simulation with coupled hurricane-ocean models indicate that ocean cooling may cause as much as 30 hPa change in central pressure for a medium intensity hurricane [*Bender and Ginis*, 2000]. Studies [e.g., *Emanuel*, 1999; *Shen et al.*, 2000] also showed that tropical cyclone intensity is more sensitive to the local SST changes under the hurricane core than to those beyond the core area.

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[3] Our knowledge of the tropical cyclone-ocean interaction is mostly limited to deep open oceans. A recent numerical modeling study using different ocean depth conditions by *Shen and Ginis* [2001] found that the hurricane-induced sea surface cooling is not sensitive to the ocean depth as long as it is much deeper than the mixed layer. The tropical cyclone-ocean interaction in shallow water regions with depths comparable to or less than the mixed layer, which is typical for coastal oceans, is the focus of this study. Better understanding of this interaction has important implication for improving forecasts of landfalling tropical cyclones. Shallow water regions may extend to large distances from the coastline. For example, in the northern Gulf of Mexico waters shallower than 35 m extend about 150 km or more from the coastline.

[4] In deep oceans, the role of surface heat fluxes in sea surface cooling is insignificant because surface cooling is mainly induced by turbulent mixing and entrainment of underlying cold water [*Price*, 1981]. It may, however, dominate the tropical cyclone-induced surface cooling over shallow waters with limited or no underlying cold water and lead to appreciable reduction of landfalling tropical cyclone intensity. This study aims to understand how tropical cyclone-induced surface heat fluxes affect the SST cooling and the significance of its feedback on tropical cyclone intensity over shallow waters.

2. Experiment Description

[5] The NOAA Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model coupled with the Princeton ocean model [*Bender and Ginis*, 2000] is used in this study with idealized oceanic and atmospheric conditions. For all the experiments in this study, the coupled model is integrated for 60 hours starting with a normal size initial vortex embedded in specified initial environmental conditions which are horizontally uniform. A GATE (Global Atlantic Tropical Experiment) III condition in tropics is used for the atmospheric environmental thermal profile, which has air temperature of 27°C and relative humidity of 84% at the lowest model level (about 40 m above surface). An easterly environmental wind of −5 m/s is used for most of the experiments. For some additional experiments, a resting environment is also assumed. The ocean is initially motionless with the sea surface temperature of 28.5°C. The initial vertical temperature profile with a mixed layer depth of 25 m and an underlying 0.1°C/m gradient in the upper thermocline layer is used. This is typical for the northern Gulf of

Table 1. Summary of Experiments

Environmental Wind	Uncoupled (Control)	Coupled
U = −5 m/s	Fixed SST (28.5C)	d = 500 m[a] d = 35 m[a] d = 25 m
U = 0 m/s	Fixed SST (28.5C)	d = 25 m d = 15 m

[a]Experiments without effects of heat fluxes on ocean are also performed.

Mexico in September. For simplicity, in this study the same vertical temperature distribution is used within ocean depths of 500 m (representing a deep ocean), 35 m, 25 m and 15 m (see Table 1 for experiment summary). For the depths of 25 m and less the ocean is vertically homogeneous and the surface heat flux is the only mechanism of SST changes.

3. Results

3.1. Deep Ocean Case

[6] In the deep ocean experiments we consider the ocean response when the ocean depth is much deeper than the upper layer perturbed by tropical cyclones, typically of about 150 m or less. Here, we use an ocean depth of d = 500 m. Evolution of hurricane central pressure in the numerical experiments with different surface flux conditions is shown in Figure 1. In the control experiment in which no ocean coupling (constant SST) is assumed, the hurricane is noticeably more intense than in the coupled experiments. In the coupled experiment without the effect of surface heat fluxes, the SST change is determined exclusively by turbulent mixing and underlying cold water entrainment. Since the surface heat fluxes, dominated by the surface evaporative heat flux, are generally upward in the hurricane core region, the sea surface cooling should be reduced with exclusion of these fluxes. Figure 1 does show some impact of the surface heat fluxes on the hurricane intensity but the impact is minor compared to the sea surface cooling due to entrainment. In this case, the significant mixed-layer deepening (about 70 m) is the main reason for the relatively minor effect of the surface heat flux on SST. Table 2 summarizes the reduction of central pressure (hPa) and SST anomalies (SSTAs) under the storm core region, defined as a circular area around the storm center with r = 100 km. In the deep ocean case, the heat fluxes contribute to 0.14°C or about 20% of the total SSTA and 0.7 hPa or 11% of the total central pressure reduction.

[7] In general, the surface heat fluxes contribute to ocean cooling in two ways: via evaporation-induced cooling, direct heat transfer to the atmosphere, and via vertical mixing induced by changing convective instability in the mixed-layer. Further examination of the experiments (not shown) indicates that the latter contribution is negligible. Because of the significant ocean cooling caused by entrainment, the latent and sensible heat fluxes are greatly reduced and their impact on the SSTA is rather small in this case.

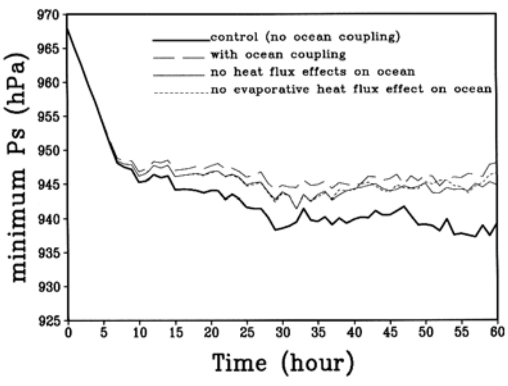

Figure 1. Changes of minimum surface pressure during 60-hour integrations with different surface heat flux conditions for the case with ocean depth of 500 m.

3.2. Shallow Water Cases

[8] In the shallow water experiments, the same initial vertical distribution of the ocean temperature as in the deep ocean case is used with the mixed layer depth of 25 m. In the experiments with an ocean depth of d = 35 m, the underlying thermocline layer has a depth of only 10 m thus limiting cold water available for entrainment. From Table 2 it is immediately evident that the surface heat flux effect on the SSTA in the d = 35 m case (0.17°C) is appreciably larger than that in the deep ocean (0.14°C). Corresponding to this is a larger intensity reduction due to the surface heat flux effect in this case (1.0 hPa) than in the deep ocean case (0.7 hPa). This is a direct result of a reduced effect of cold water entrainment. In this case the surface heat fluxes induce almost the same SST reduction under the storm core as does entrainment (0.17°C or 50% of the total SSTA) and contribute to 26% of the total storm intensity reduction. Without the thermocline layer underneath (d = 25 m), the hurricane intensity is reduced by 2.0 hPa due to the surface heat flux-induced ocean cooling. This is nearly 1/3 of the total intensity reduction (6.4 hPa) due to ocean coupling in the deep ocean case. We should note that these results show only relative importance of the heat flux effect on the hurricane-induced SSTA and subsequent storm intensity reduction. The specific magnitudes of SST and storm intensity changes depend on many factors in reality.

[9] Since the storm intensity reduction is also dependent on the SSTA beyond the storm core area [*Bender et al.*, 1993], Figure 2 shows the SSTA over the entire hurricane-induced cold wake in the d = 35 m case. In the run without surface heat fluxes (middle panel), the SSTAs are almost horizontally uniform over a large area behind the storm center and along the storm track. In this case the cooling is induced by entrainment only and due to the shallow ocean depth the mixed layer quickly reaches the bottom and creates a vertically uniform temperature profile. Figure 3 shows that the ocean is well mixed in the vertical near and

Table 2. Storm Intensity[a] Reduction and Underlying SSTA

Experiments	d = 500 m	d = 500 m (no FLX)	d = 35 m	d = 35 m (no FLX)	d = 25 m
Minimum Ps reduction (hPa)	6.4	5.7	3.8	2.8	2.0
SSTA (°C) within r = 100 km	−0.53	−0.39	−0.34	−0.17	−0.22

[a]24 hr (36 h–60 h) averaged minimum surface pressure is used.

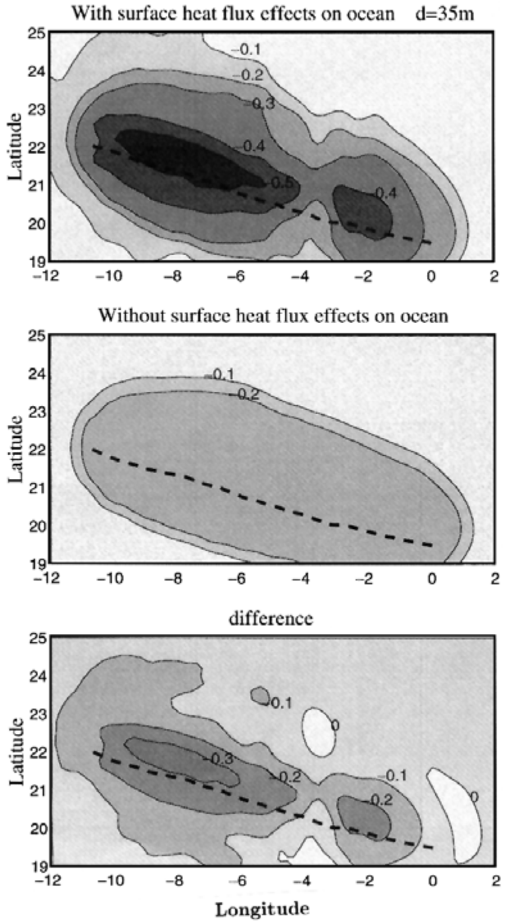

Figure 2. Sea surface temperature anomalies (SSTAs) at 54 h in the cases of ocean depth of 35 m with and without surface heat fluxes (upper and middle) and the SSTA differences (lower). The thick dashed lines denote the storm tracks.

behind the storm center. The hurricane-induced currents are vertically mixed as well and form a quasi-steady, cyclonic circulation (not shown), which is a characteristic feature of the shallow water ocean response to a hurricane [*Ginis and Sutyrin*, 1995]. We can, therefore, conclude that the main reason for the largest SSTA seen behind the storm center (upper panel in Figure 2) in this case is the surface heat flux effect. It is interesting that the largest cooling lies to the right side of the storm track (lower panel in Figure 2) as typically observed in the deep ocean response. While the SSTA asymmetries in the open ocean are due to enhanced entrainment to the right of the hurricane track caused by the stronger currents [*Ginis*, 2002], there are two primary reasons for such rightward bias in the shallow water case. Firstly, there are larger sensible and latent heat fluxes to the right of the track due to stronger surface winds. Secondly, the cyclonic circulation of the near-surface winds advects dryer air parcels originated over the cold wake behind the storm center to the right side of the track. As a result, the evaporation rate is increased, which leads to further cooling of the sea surface.

[10] Experiments with resting environmental atmosphere for the ocean depths of 25 m and less were also performed. So, the ocean cooling is induced exclusively by the surface heat fluxes and the storm movement is uniquely due to the β-effect. The use of resting environmental atmosphere obviously leads to an increase of sea surface cooling and its impact on the storm intensity due to a reduced storm translation speed. The storm intensity changes are shown in Figure 4. We see that the hurricane intensity reduction reaches up to about 8 hPa and 13 hPa in the d = 25 m and d = 15 m cases respectively. Thus, a potentially significant reduction of the hurricane intensity may be induced by ocean coupling in very shallow waters, especially when the storm moves slowly.

[11] The dashed line (d = 25 m*) comes from an experiment which treats the ocean as a single layer of a depth of 25 m without horizontal advection and diffusion. The d = 25 m* experiment is performed to help better understanding of the importance of the vertical mixing in the SST changes. As seen in Figure 4, the intensity reduction in the d = 25 m case is nearly the same as in the d = 25 m* case. It is also found that the overall SSTA patterns and magnitudes in the d = 25 m and d = 25 m* cases are quite similar (not shown). This implies that the extremely rapid and efficient vertical mixing is the dominant mechanism for the heat flux-induced SST changes in the d = 25 m case.

4. Summary

[12] A coupled hurricane-ocean model with idealized conditions is used to investigate the influences of sea surface heat fluxes on the SST changes and their feedback on tropical cyclone intensity focusing on shallow water such as occurring in near-coastal regions. The study indicates that the SST changes due to surface heat fluxes can be closely approximated as one-dimensional vertical mixing of infinitesimal time scale in the mixed layer. In shallow water regions with limited underlying cold water, the significance

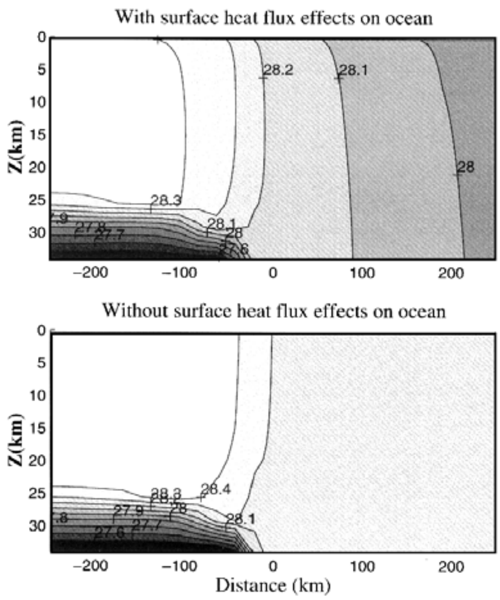

Figure 3. Vertical cross sections of ocean temperature along the storm path corresponding to the upper and middle panels in Figure 2.

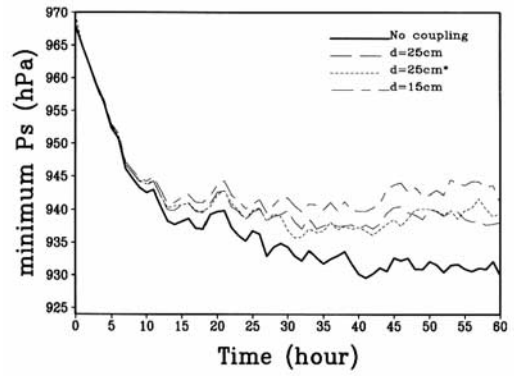

Figure 4. Similar to Figure 1, but for shallow oceans of vertically uniform initial temperature and resting atmospheric environment. In the d = 25 m* case, the horizontal advection and diffusion are ignored and the ocean is assumed to be well mixed in the vertical at any time.

of surface heat flux effect in reducing SST and tropical cyclone intensity increases due to the limitation of surface cooling and mixed layer deepening caused by cold water entrainment. Without underlying cold water, SST changes result from the surface heat fluxes only. In our idealized experiments such SST changes under the storm core reach 40% of the SST changes due to tropical cyclone-ocean interactions over a deep ocean. The storm intensity reduction due to the surface heat fluxes in this case reached 1/3 of the tropical cyclone intensity reduction in the deep ocean case. The relatively large SST and storm intensity reduction in shallow waters found in this study implies that potentially significant effect of air-sea interaction may occur for slow moving tropical cyclones near landfall. Since idealized settings are used in this study, we will in our future investigation focus on the effects of the surface heat flux-induced SST changes on tropical cyclones in real atmospheric and oceanic conditions.

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