P2G.2 THE EFFECTS OF SEA-SURFACE TEMPERATURE AND STATIC STABILITY ON WRF-SIMULATED INTENSITY AND TRACK OF SELECTED 2005 ATLANTIC HURRICANES

Stanley D. Gedzelman and Kwan-yin Kong
The City College of New York, New York, New York

1. Introduction

Sea-surface temperature (SST) has long been identified as an important controlling factor on hurricane formation and intensification. However, surprisingly few numerical studies of hurricanes have experimented with SST on hurricane intensity. This paper highlights some of the results we have obtained from numerical experiments of SST and atmospheric temperature, and how they affect the intensity and structure of four 2005 Atlantic hurricanes—Katrina, Ophelia, Rita, and Wilma—using the Weather Research Forecasting model (WRF).

For each of the four hurricanes, we ran the WRF version 2.1.2 on a single domain that encapsulated the hurricanes for a 72 hour span. The grid resolution of the domain was 15 km on 30 unevenly spaced sigma levels with 50 hPa to be the model top. The WRF 5-class, Grell-Devenyi, and Yonsei University (YSU) were chosen to be the microphysics, cumulus, and boundary layer schemes. This combination of parameterization schemes was chosen based on satisfactory results using similar schemes in a previous MM5 study on subtropical storm Allison (Kong and Gedzelman, 2004). We began running the model using the native NCEP 1°x1° observational grid file as the initial and boundary conditions. We then progressively lowered the SST everywhere and re-ran the model. Simulation results from these SST experiments were compared with those obtained from using the observed SST. As results from these SST experiments emerged, the scope of the study was expanded to include the effects of atmospheric static stability on hurricane intensity.

The following table shows the times of initialization and the general locations for each chosen storms.

Name	Time of initialization	General location
Katrina	00Z 24 Aug 2005	East of Florida
Ophelia	00Z 10 Sep 2005	Off the Carolinas
Rita	00Z 18 Sep 2005	SE of Florida
Wilma	00Z 17 Oct 2005	Caribbean

Corresponding author email: stan@sci.ccny.cuny.edu
Second author current affiliation: Hydrometeorological Prediction Center, Camp Springs, MD.
Email: kwan-yin.kong@noaa.gov

2. The SST experiments

Figure 1 shows the minimum central pressure attained by the four simulated hurricanes as a function of SST change during a 72-hour run. As expected, the maximum intensity of all of the simulated hurricanes decreases as the SST decreases. Hurricane Rita barely develops into a closed circulation as the SST is reduced by 4°C. Hurricane Wilma, on the other hand, manages to maintain a weak but closed circulation even after the SST has been reduced by 10°.

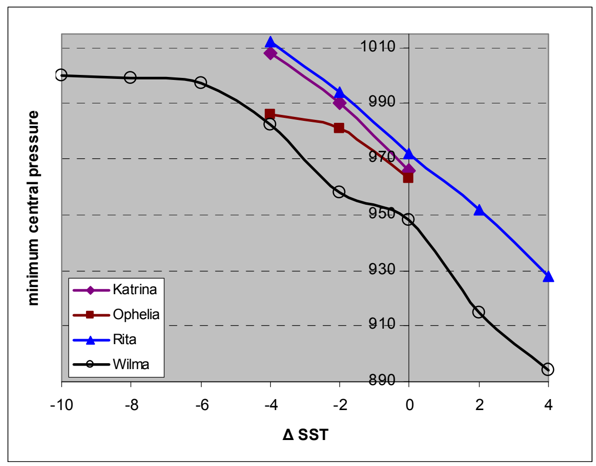

Fig. 1 Minimum central pressure attained by the four simulated hurricanes as a function of SST change in °C.

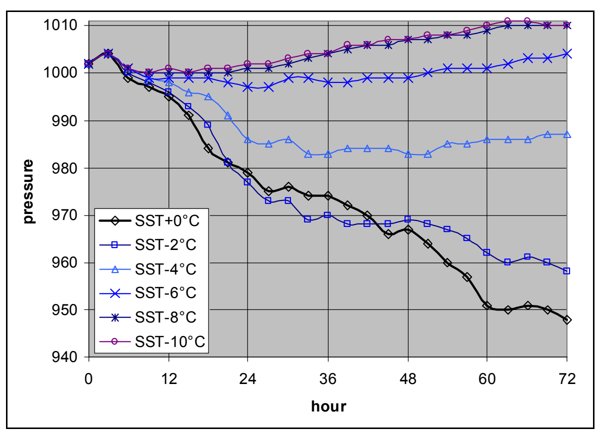

Fig. 2 Time series of WRF simulated central pressure of Wilma as SST was successively lowered by 2°C.

Figure 2 shows the time-series of central pressure of the simulated hurricane Wilma in a 72-hour run as SST is lowered every 2°C. For the most part, it shows that Wilma weakens as the

SST lowers. However, Wilma is stronger on the SST-2°C run between hour 21 and 43 compared with SST+0°C. A structural comparison between the two runs reveals that Wilma has a tighter core in the SST-2°C run. Scattered convection that develops further out from the core in the SST+0°C run might have consumed some of the energy that would otherwise be available for intensification.

As for the tracks of the simulated hurricanes, there is a tendency for the circulation to take a more western and southern track as the SST lowers and as the circulation gets weaker. The exception is Katrina which tracks more to the northwest into Florida as the SST decreases.

3. The atmospheric stability experiments

The SST experiments demonstrated that the simulated hurricane intensities were in direct proportion to the SST change. Note that this change was applied independently from the atmosphere above. Thus, the heat and moisture fluxes from the sea were abruptly changed, and would progressively alter the vertical thermodynamic stratification in the atmosphere. This motivated the second author to explore the effect of the atmospheric static stability on hurricane intensity.

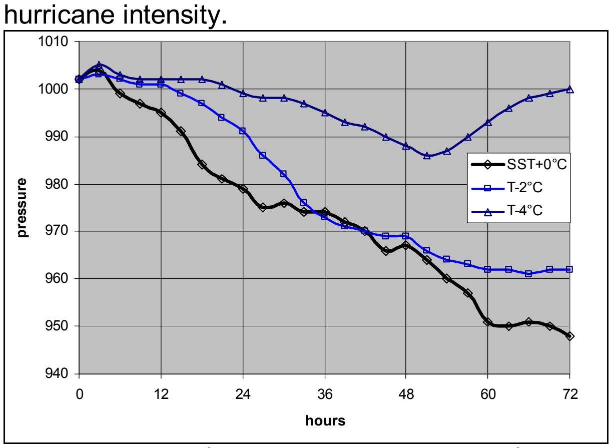

Fig. 3 Time series of WRF simulated central pressure of Wilma as SST and atmospheric temperature were lowered by 2°C and 4°C.

a. *Lowering both SST and the atmospheric temperature by a constant*

Hurricane Wilma was chosen for the atmospheric stability experiment. Both the SST and the atmospheric temperature everywhere in the domain was successively lowered by 2°C while preserving the humidity in and around the initial circulation of Hurricane Wilma as defined by the 1004 hPa isobar. Figure 3 shows the central pressure of Wilma in the T-2°C and the T-4°C cases as compared with the control case. As in the SST experiments, Wilma's intensity decreases with decreasing SST and T, but not as rapidly as lowering the SST alone.

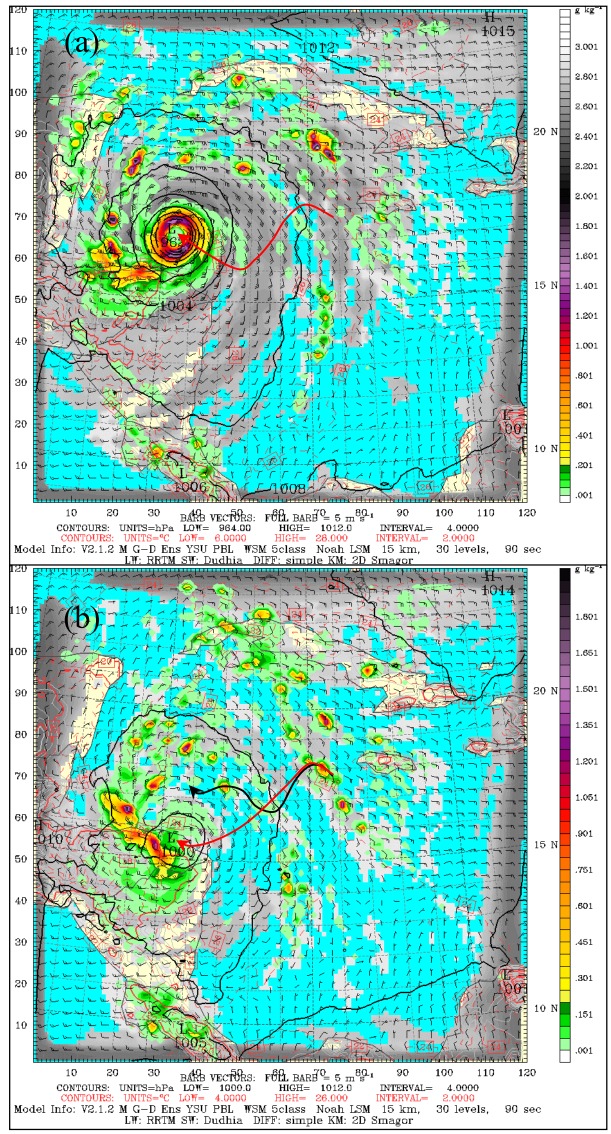

Fig. 4 WRF simulation at hour 72 showing surface features of Hurricane Wilma after the SST and atmospheric temperature have been reduced everywhere by (a) 2°C, and (b) 4°C. The simulated track is plotted in red along with the track in the control run in black.

Similar to the reduced SST experiments, the overall tracks of Wilma shift further and further to the south and west as the atmospheric temperature is lowered. In fact, Wilma makes landfall on the north coast of Nicaragua on the T-4°C run (fig. 4b). This is the reason for the increase in central pressure after 51 hour shown in figure 3.

b. *Lowering the atmospheric temperature profile moist adiabatically*

Our next experiments involved successively lowering the SST and the atmospheric temperature profile moist adiabatically. This would effectively preserve the convective available potential energy (CAPE) of the original troposphere. To accomplish this objective, we obtained an approximate formula that related the increase of temperature separation between two adjacent moist adiabats with height. The moist adiabat intersecting at 25°C and 1000 hPa was chosen for this approximation. This formula was then used to adjust the atmospheric temperature. Figure 5 shows the original sounding at 17.0°N, 82.0°W together with a modified sounding after a moist adiabatic reduction of 10°C has been applied. Note that a 10°C reduction would lower the SST to 20°C! Note also that the temperature at 200 hPa would have to be more than 20°C colder in order to preserve the original CAPE. In addition, a decision has to be made regarding the height of the tropopause and the stratospheric temperature. It was decided that a nearly isothermal layer is extrapolated down from the 100 hPa temperature to meet with the adjusted tropospheric temperature at a tropopause, which happened to be at around 200 hPa.

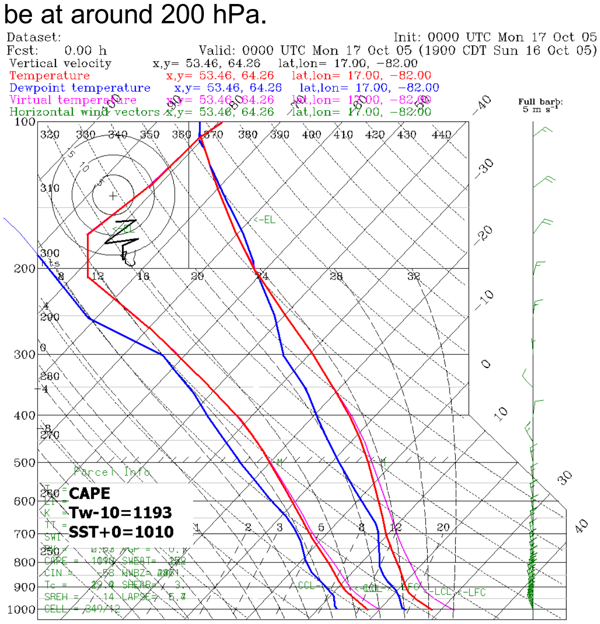

Fig. 5 Soundings from the original data, and after a moist adiabatic reduction of 10°C at the initialized time (00Z 17 Oct 2005) at 17°N, 82°W.

Figure 6 shows the simulated central pressure of Wilma after the SST and the moist adiabatic adjustments of -4°C and -10°C (TW-4°C and TW-10°C) have been applied. It can be seen that Wilma's intensity has not changed significantly after the -4°C adjustment. The TW-10°C is an interesting run. Wilma is able to deepen steadily but more slowly than the control run over 20°C water. The central pressure of 967 hPa at the end of the run is less deep than the control and TW-4°C runs but is much deeper than the SST-10°C run.

Figures 7 and 8 show a comparison of the simulated cloud and surface features of Wilma between the control run and the SST-10°C run. Wilma, after the -10°C adjustment, has a significantly broader circulation than the control run. The rain intensities are weaker and the coverage is broader than the control run. The overall structure of the low is reminiscence of a subtropical cyclone.

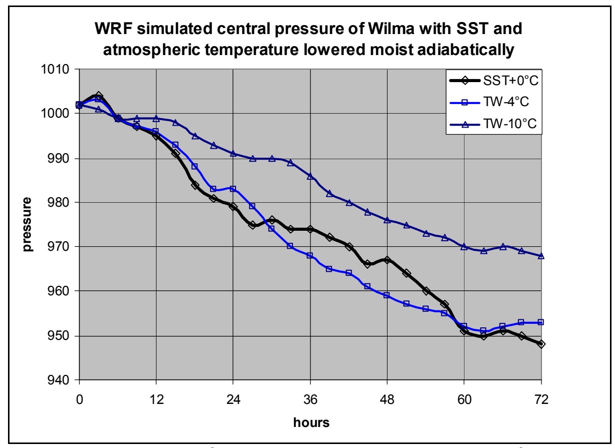

Fig. 6 Time series of WRF simulated central pressure of Wilma as the SST and atmospheric temperature were lowered moist adiabatically by 4°C and 10°C.

4. Discussion

The SST experiments have clearly shown a directly relation between SST and hurricane intensity. It is hypothesized that SST modulates the hurricane intensity by modifying the stability in the overlying atmosphere. Let us consider why this is the case. Kong (2006) showed the derivation of the following pressure tendency equation for a hydrostatic atmosphere (see also Godson, 1948).

$$\frac{\partial p_1}{\partial t} = -\rho_1 g \int_{z_1}^{z_2} \left[-v \cdot \nabla_p T_v + \frac{R}{g}\left(\Gamma + \frac{\partial T_v}{\partial z}\right)\frac{\omega}{p} + \frac{\dot{Q}}{c_p T} \right] dz$$

where $\frac{\partial p_1}{\partial t}$ is the pressure tendency at the bottom boundary of a layer of atmosphere at height z_1, ω is the vertical velocity in pressure coordinates, and Γ is the virtual temperature lapse rate of a moist adiabatic profile if the air is at saturation. The second term in this equation reveals how the static stability and vertical motion must work in tandem to produce a surface pressure change. For example, one way for the surface pressure to fall is to have air rising in an unstable lapse rate. In the SST experiments, we increased the SST without changing the air temperature. The PBL scheme in the model would transfer the heat from the ocean into the air and result in a more unstable lapse rate, which would lead to a larger pressure fall according to the pressure tendency equation.

The atmospheric temperature adjustment experiments were intended to test the above hypothesis from another vantage point. If changes in hurricane intensity were the result of modified atmospheric static stability due to SST adjustment, then direct adjustments on atmospheric static stability should result in similar changes in hurricane intensity. This was indeed shown to be the case. When the air temperature was lowered by a constant everywhere, more instability was introduced into the atmosphere, and we saw that the simulated Wilma became more intense than when the SST alone was lowered. Nevertheless, the intensity of Wilma still showed a significant downward trend. It was hypothesized that the instability introduced was insufficient to preserve the original CAPE since the instability of the hurricane environment should be in reference to the moist adiabatic lapse rate. This means that the amount of temperature reduction must increase with height in order to preserve the original CAPE. The 4°C moist adiabatic reduction indeed resulted in a Wilma with similar intensity comparing with the control run. The 10°C moist adiabatic reduction yielded a somewhat weaker Wilma. It is hypothesized that the lower prescribed tropopause and the generally weaker vertical motion at lower temperatures reduced the magnitudes of pressure tendency.

5. Conclusions

SST has long been identified as an important controlling factor on hurricane formation and intensification. This present study tested the effect of SST change on the intensities of four 2005 Atlantic hurricanes using the WRF model. The SST experiments showed a definite decrease in hurricane intensity as SST decreased. It was pointed out that the decrease in hurricane intensities was attributed to an increase in static stability in the atmosphere due to the colder sea surface. This had led to a series of atmospheric stability experiments in which the air temperatures in the boundary conditions were adjusted. In the last experiment, the SST and the air temperature were lowered moist adiabatically by 10°C. Its results showed that Wilma was able to deepen to a 967 hPa low despite over a cold 20°C SST.

The results of these experiments imply that the amount of CAPE that feeds into a hurricane circulation is crucial to its intensity. The development of Wilma over 20°C water would also challenge the notion of a threshold SST (i.e. 26°C) as a necessary condition for hurricane formation. In recent years, there have been hurricanes forming over cool waters previously unknown to hurricane formations (Kong, 2006). In addition, hurricane-like vortices such as the “Mediterranean hurricanes” (Emanuel, 2005), polar lows, and extratropical storms transforming into hurricanes (Davis and Bosart, 2004) all appear to have a close tie to a cold upper low. Research interests relating tropical cyclogenesis and hurricane intensity to SST should also consider the tropospheric static instability for a more complete assessment of the full thermodynamic potential.

6. References

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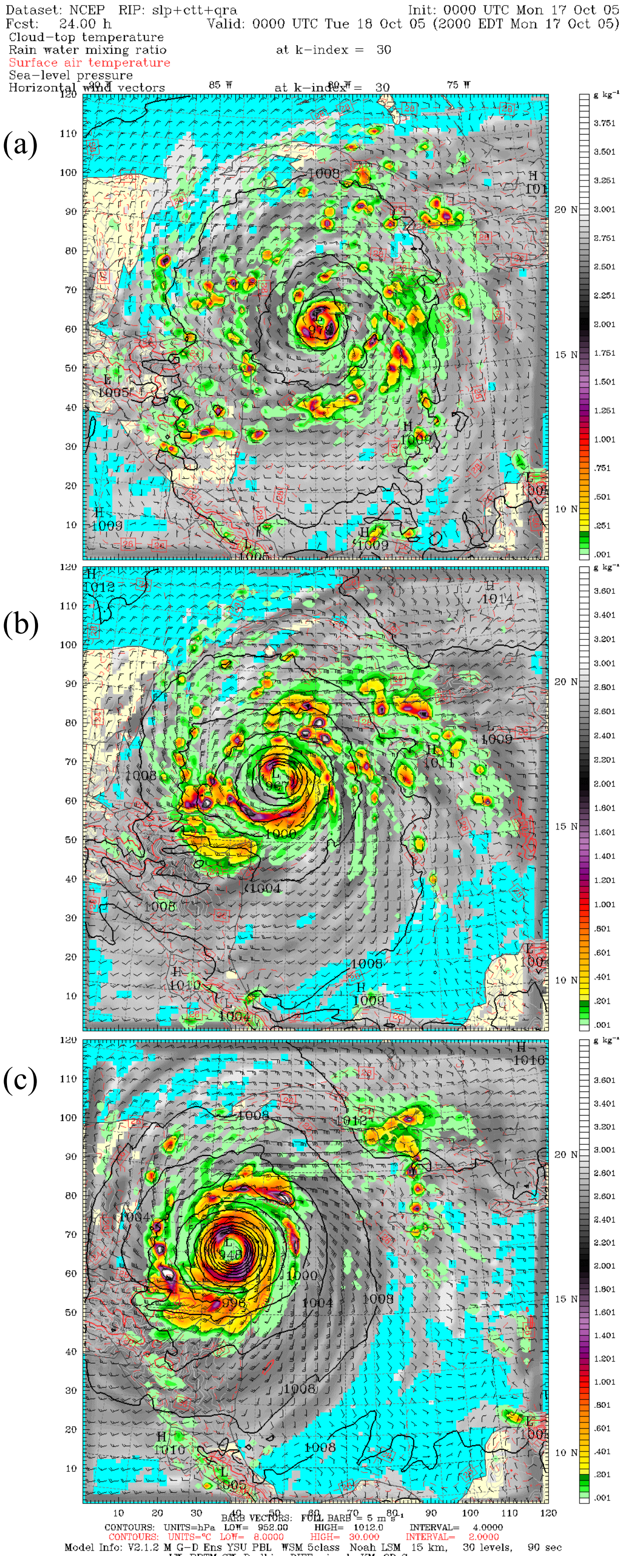

Fig. 7 (a) 24, (b) 48, and (c) 72-hour WRF simulations of the surface features (isobars, wind barbs, and rain water mixing ratio in colors) and cloud top temperature (gray shades) of Hurricane Wilma using the observed SST.

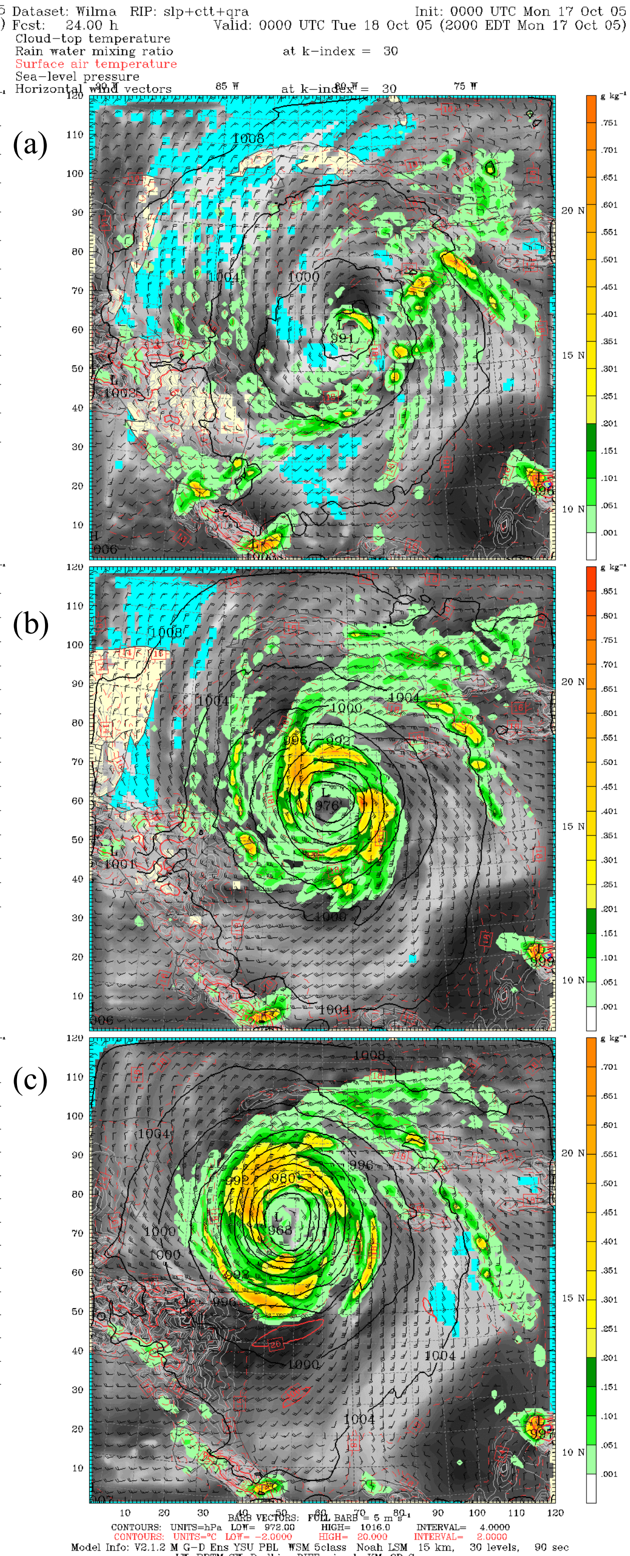

Fig. 8 As in figure 7 but after the SST and atmospheric temperature have been reduced moist adiabatically everywhere by 10°C.