

Satellite microwave detected SST anomalies and hurricane intensification

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Abstract Sea surface temperature (SST) from the remotely sensed infrared measurements, like the GOES, AVHRR, and MODIS, etc., show missing values of SST over the cloudy regions associated with hurricanes. While satellite microwave measurements, like the Tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI), can provide SST even under cloudy conditions. Both satellite microwave measurements and buoy observations show SST increase in advance of significant hurricane intensification. Moreover, hurricane intensification may also be related to the location of high SST. Our results indicate pre-existing high SST anomaly (SSTA) located at the right side of the storm track for Hurricane Katrina. Numerical simulations also confirm the important impacts of SSTA location on hurricane intensification. Similar situations are also found for Hurricanes Rita and Wilma. In contrast, if there is no high SSTA at the right location, hurricane may not undergo further intensification. This may explain why not all tropical cyclones associated with warm waters can attain peak intensity (categories 4 and 5) during their life cycle, and partially explains why hurricanes do not reach the maximum potential intensity as calculated only according to the magnitude of SST.

Keywords GOES · TMI · IR · Microwave · SST · SST anomaly (SSTA) · Hurricanes Katrina Rita and Wilma · Impacts of time and location of SSTA on hurricane intensification

1 Introduction

The year 2005 is a record-breaking year for Atlantic Hurricanes. There were 28 named storms and 15 hurricanes, including three Category 5 hurricanes, Katrina, Rita, and the strongest hurricane on record in the Atlantic basin: Wilma. Katrina

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became the costliest and one of the deadliest hurricanes in the US history. Better understanding and prediction of hurricanes will allow people being better prepared to minimize life and property damages.

The recent active period of intense hurricanes has triggered a hot debate in the scientific community whether the increase in the frequency and intensity of hurricanes is due to either the natural climate variability such as the El Niño/Southern Oscillation (ENSO), quasi-biennial oscillation (QBO), and Atlantic Multidecadal Oscillation (AMO) (Bove et al. 1998; Elsner et al. 1998; Gray 1984; Shapiro and Goldenberg 1998; Goldenberg et al. 2001; Virmani and Weisberg 2006), or the human-induced global warming (Knutson and Tuleya 2004; Emanuel 2005; Webster et al. 2005). Several studies suggest that global warming would likely result in SST increase, which may result in an increase in the intensity of tropical cyclones (Tsutsui 2002; Webster et al. 2005). The most recent study by Mann and Emanuel (2006) also claimed that the Atlantic hurricane trend is linked to anthropogenic forced warming or climate change. Nevertheless, they are all associated with the effects of warm SST. The dependence of tropical cyclone intensity on SST is well documented (Fisher 1958; Leipper 1967; Emanuel 1986, 1988; Holland 1997). SST plays a fundamental role in the inter-annual variability of tropical storm frequency and intensity (Vitart et al. 1999), and a direct role in providing moist enthalpy (i.e., latent and sensible heat flux) to intensify tropical cyclones (Goldenberg et al. 2001). Meanwhile, the intensification of individual hurricanes may not necessarily be spatially and temporally coincident with the distribution of high SST. SST was found to increase prior to the significant intensification of hurricane (Sun et al. 2006; Kafatos et al. 2006).

However, Scharroo et al. (2005) show that the SST in the entire Gulf of Mexico was uniformly $\sim 30^{\circ}\text{C}$ and therefore they concluded SST was not associated with the rapid intensification of Hurricane Katrina. Their SST image was constructed from the infrared sensors on the NOAA Polar Operational Environmental Satellites (POES), and the date was not given. SST from the remotely sensed infrared measurements show missing values over the cloudy regions associated with hurricanes, as shown in Fig. 1. While satellite microwave measurements, like Tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI), can provide cloud penetrating SST measurements. Microwaves penetrate clouds with little attenuation from non-raining clouds, giving a clear view of the ocean surface under all weather conditions except rain. The TMI SST can provide valuable measurements during severe storms, when the infrared SST retrievals are obstructed by clouds. Comparisons with ocean buoys show a root mean square difference of about 0.6°C , which is partly due to the satellite-buoy spatial-temporal sampling mismatch and the difference between the ocean skin temperature and bulk temperature. Retrieval errors in the TMI SST are primarily due to both wind speed and directions (Wentz et al. 2000).

The main goal of this study is to use the satellite microwave measurements and buoy observations, combine with numerical simulations to investigate the impacts of high SSTA and its relative position with respect to the storm track on hurricane intensification. The next section briefly describes the data and the control experiments design. Section 3 presents the results from the satellite and buoy observations and the control experiments. A summary and discussion are given in the final section.

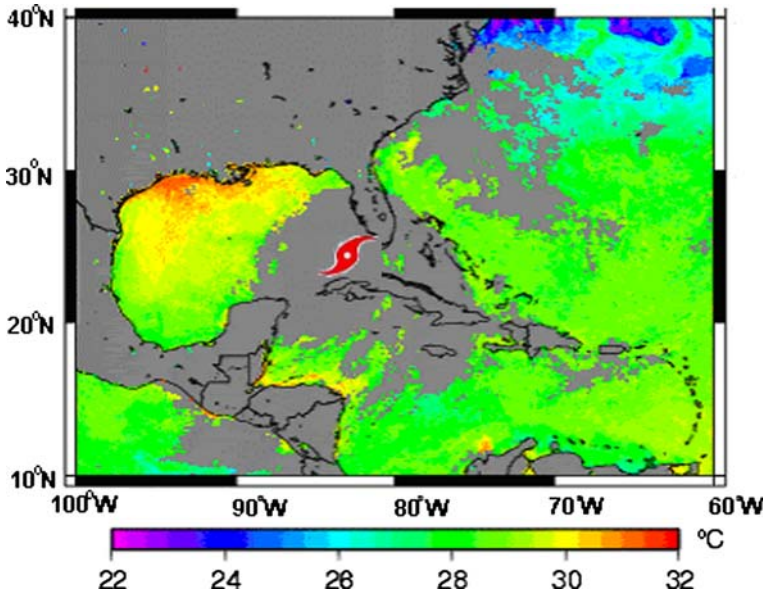


Fig. 1 SST image from the infrared sensors on the Geostationary Operational Environmental Satellite (GOES) on 27 August 2005. The Katrina position is indicated by a red hurricane symbol

2 Data and methodology

2.1 Data

- SST from the Geostationary Operational Environmental System (GOES) at 6 km resolution from the NASA JPL (<http://podaac.jpl.nasa.gov/>).
- SST from the tropical rainfall measuring mission (TRMM) microwave imager (TMI) at 0.25° resolution from the Remote Sensing Systems (<http://www.ssmi.com>). The advantage of using SST from microwave observations, like the TMI, is that it provides retrievals even under intense cloudy conditions associated with hurricanes. Since the microwave radiance can penetrate through cloud layers.
- Buoy observations of winds, SST, surface air temperature, and dew point from the National Data Buoy Center (NDBC) (<http://www.ndbc.noaa.gov/>).

2.2 Control experiments

In order to investigate the impact of warm SSTA position on hurricane intensification, using the latest PSU/UCAR mesoscale model MM5 (version 3.7), three control experiments were designed. In the first experiment, model initialized with weekly composite TMI SST ending on August 27th, 2005, which include the warm SSTA at the right side of the storm track, hereafter referred to as the WAR (Warm SST Anomaly at Right side). In the second experiment, model initialized with the eight-year averaged SST in August, which had no warm SSTA, hereafter referred to as NWA (No Warm SST Anomaly), while holding all the other parameters identical for the two control simulations. We performed 96-h simulations initialized at 00Z 26 August 2005 using a triply nested grid configuration with grid resolutions of 54, 18,

and 6 km, covering the stages of Katrina's rapid intensification across the Gulf and the subsequent landfall in the northern Gulf coast. The Medium Range Forecast (MRF) Planetary Boundary Layer (PBL) parameterization is used. The other model's initial and lateral boundary conditions were obtained from the NOAA NCEP GFS (Global Forecasting System) $1^\circ \times 1^\circ$ global analysis. A bogus vortex representing the inner circulation of Katrina was used in the model initial conditions (Goerss and Jeffries 1994; Zhu et al. 2004). In order to test the effect of pre-existing warm SST, SST was held unchanged during the simulations.

3 Results

Both the buoy observations and TMI measurements show SST increase in advance of about 2 day prior to the significant intensification of Hurricane Katrina, while surface

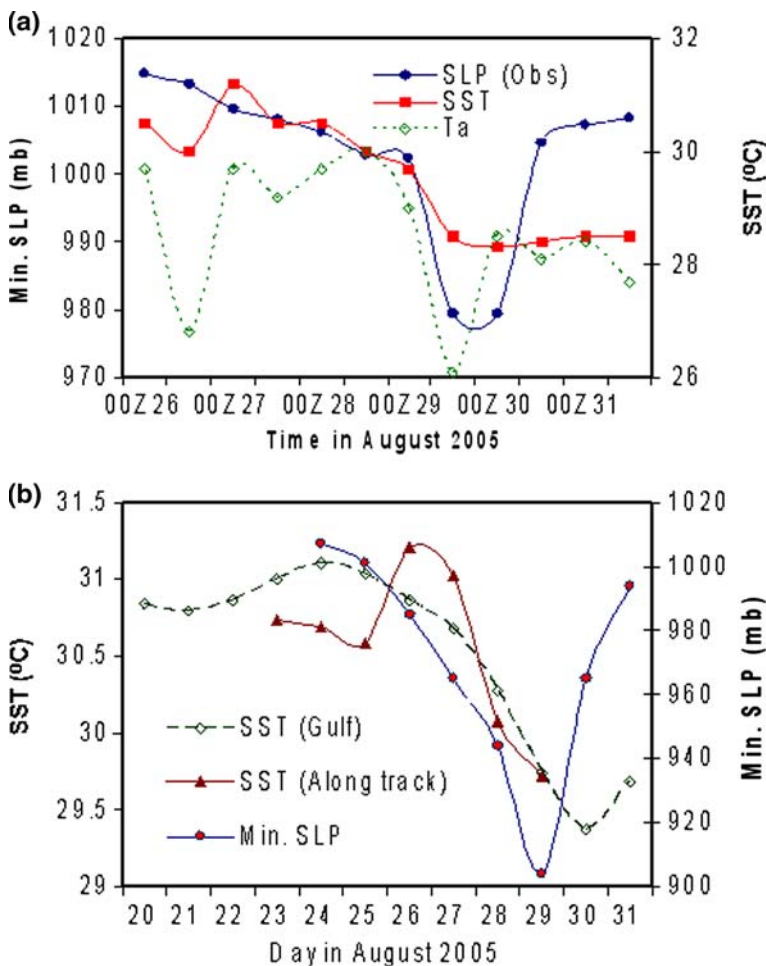


Fig. 2 Time series of (a) sea level pressure (SLP), SST, and surface air temperature (Ta) from buoy 42040 observations, (b) SST from the TMI as averaged along the storm track (500 km \times 500 km centered on the eye) and SLP from the observations

air temperature declined and reached the minimum at the time of the maximum hurricane intensity (Fig. 2). This may be because it may need a period of time for a tropical cyclone to accumulate energy for developing into a hurricane, similar like the evaporation of water vapor, which may need some time to heat the water and make it evaporate, while evaporative cooling makes surface air temperature decrease.

Figure 3 compares the pre-storm SST (27 August 2005) with the post-storm SST (30 August 2005). Figure 3a shows that SST right before the storm was above 31°C along the Gulf coast and storm track and much warmer than the long-term mean in August (Fig. 3c), while the SST right after the storm passage shows cooling at the right side of the storm track (Fig. 3b). As compared to the pre-storm SST (Fig. 3a), the strongest cooling in SST is over 6°C, and occurred in the right-front quadrant of the storm track and near the location of the strongest intensity (category 5 as represented by red circles), where higher, longer, and more developed waves usually produce higher sea drag (Moon et al. 2004).

As shown in Fig. 3, the SST prior to the storm, such as 26 and 27 August 2005, was very hot and higher than 31°C along the Gulf coast and northern Gulf of Mexico (Fig. 3a) and much warmer than the 8-year average (Fig. 3c), while the post-storm SST is cooler than the average SST. The difference between the SST prior to and after the storm is related to the storm intensity (Zhu and Zhang 2006). The stronger the tropical cyclone/hurricane, the larger the difference is found. For the Katrina, the pre-storm and post-storm SST difference was up to 6°C.

In order to show how SST warmer or cooler than the long-term (8 year from 1998 to 2005 for the TMI case) mean, we calculate the SST anomaly (SSTA) by subtracting the 8-year averaged monthly mean in August (Fig. 3c) from the SST values. Positive values of SSTA indicate the SST is warmer than the multi-year average. The SST map shows the entire Gulf of Mexico was almost uniformly ~30°C prior to Katrina's intensification (Fig. 3a), while the SSTA shows clearly there existed a hot patch along the right side of the storm track (Fig. 4a), where Hurricane Katrina underwent quick intensification and reached the strongest intensity when it moved over the Gulf of Mexico. It has been found that most clouds and precipitation develop at the right side of the storm track (Zhu et al. 2004). Figure 4b shows the storm developed the strongest radar reflectivity or rainfall asymmetry to the north/northeast quadrants or to the right side of the storm track, at least at its mature stage (categories 3–5). Desflots et al. (2004) indicate it is the vertical wind shear caused this wavenumber one rainfall asymmetry, while shear is due to change of direction of the upper-level wind. In our simulations, when upper-level wind was mainly northwesterly, the simulated upper-level divergence was mostly symmetric, while when wind direction became southwesterly, the upper-level divergence and anti-cyclonic circulation developed asymmetry in the right quadrant of the storm (Fig. 5). This preliminary analysis seems to indicate that the upper-level divergence played an important role for the wavenumber one radar reflectivity or rainfall asymmetry.

Although latent heat is a function of wind speed (Eq. 1) and hence reflects the intensities, SST plays a direct role in providing moist enthalpy (i.e., latent and sensible heat flux) to intensify tropical cyclones (Goldenberg et al. 2001).

$$\text{LHF} = \rho L_v C_e (U_z - U_0) (Q(\text{SST}) - Q_z) \quad ((1))$$

where U and Q represent the wind speed and specific humidity at surface and height z , L_v is the latent heat of vaporization. C_e is the exchange coefficient.

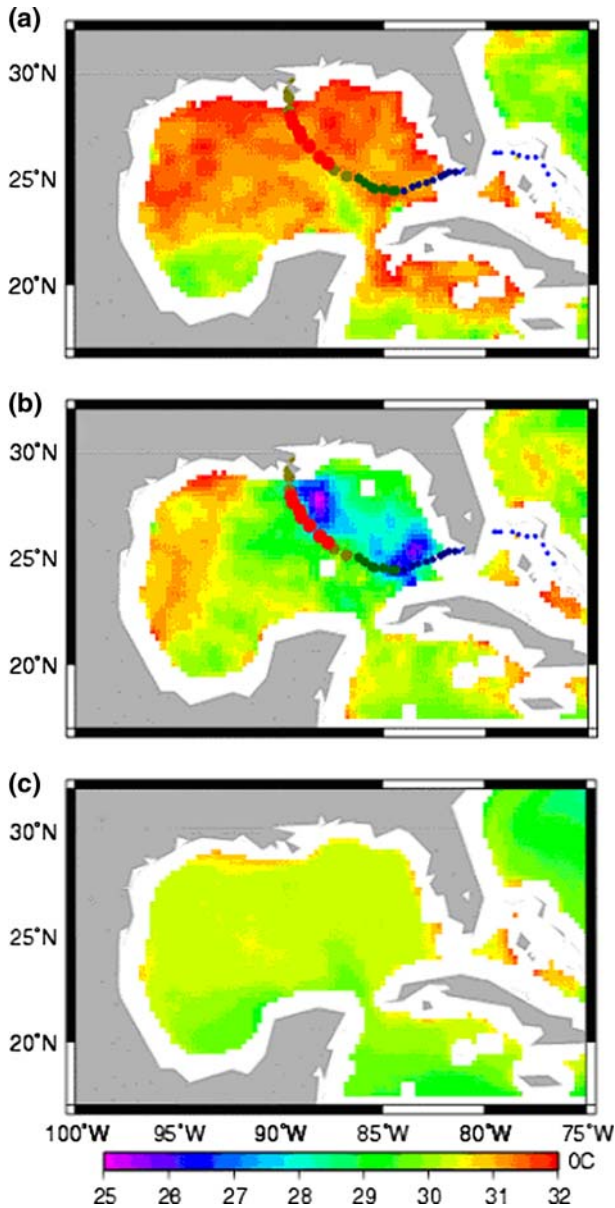


Fig. 3 TMI SST on: (a) 26 August 2005 for two days prior to the storm, and (b) 30 August 2005 for one day after the storm, and (c) 8-year (1998–2005) averaged monthly mean SST in August. The color bars in (a) and (b) is the same as in (c). The circles of different colors indicate the track and intensity of Hurricane Katrina

Braun and Tao (2000) showed the significant sensitivity of Hurricane Bob (1991) to several Planetary Boundary Layer (PBL) schemes in the MM5 and suggested the dependence of simulated intensity on surface fluxes. Figure 6a shows the maximum latent heat flux (LHF) occurs at the northeast quadrant or to the right side of storm track, at least at its mature stages. Although the wavenumber one asymmetry may

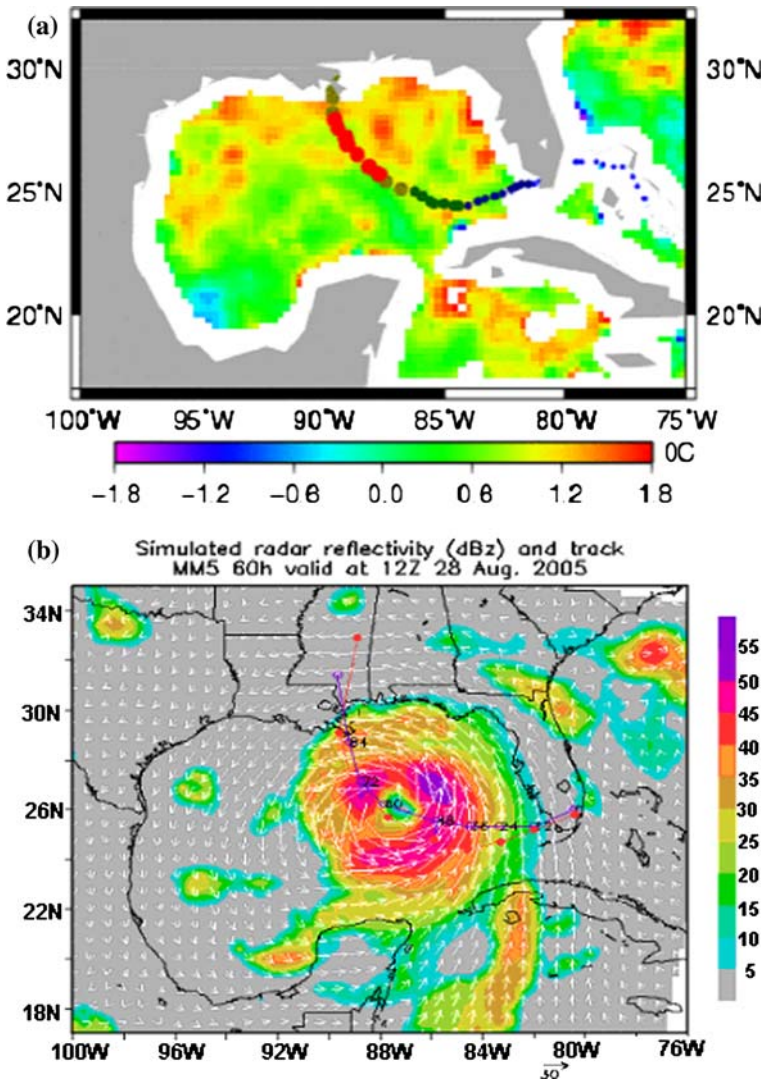


Fig. 4 (a) TMI SSTA in relative to the 8-year (1998–2005) average on 27 August 2005 overlapped with the storm track, the locations and intensities of Hurricane Katrina were indicated by circles of different colors for different stages with red one as category 5. (b) Simulated radar reflectivity (dBz) and simulated (purple empty circles) and observed (red solid circles) storm track

not be caused by warm SSTA, because warm SST exists at the location of the maximum LHF, and increases the LHF, enhances the effect of the LHF, and therefore may have played an important role in hurricane intensification.

In order to investigate the effect of the SSTA on hurricane intensification, we performed two control numerical experiments using the latest version of mesoscale model MM5. The difference in the simulated tracks is minor (Fig. 6a). Figure 6b shows the difference in the simulated minimum sea level pressure (SLP) from the two numerical experiments is not evident till 36–48 h simulations, which also confirm the observations about the time lag of about two days from SST increase to hurri-

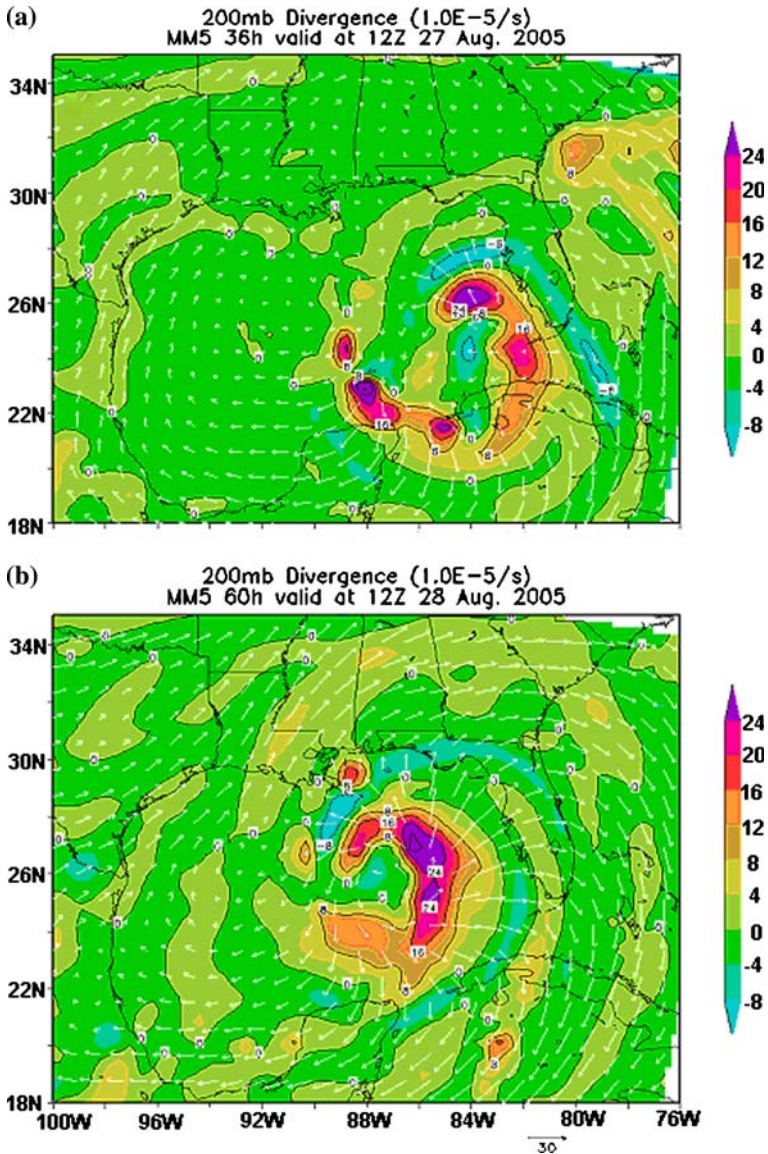


Fig. 5 MM5 simulated upper-level (200 mb) divergence over the outer domain (54 km) at simulation time: (a) 36 h, and (b) 60 h

cane intensification. As indicated by the pronounced difference in simulated minimum SLP, the simulated hurricane intensity shows remarkable sensitive to the high SSTA (Fig. 4a). During the 36–84 h simulations, the control experiment without the warm SSTA generates weaker intensity or higher minimum SLP than that with the warm SSTA. Although the SST reduction due to storm-induced upwelling and vertical mixing should result in a weaker-simulated hurricane intensity than that simulated when the SST was held unchanged during the simulations as in this study, the simulated LHF from the experiment with the warm SSTA at the right side of the

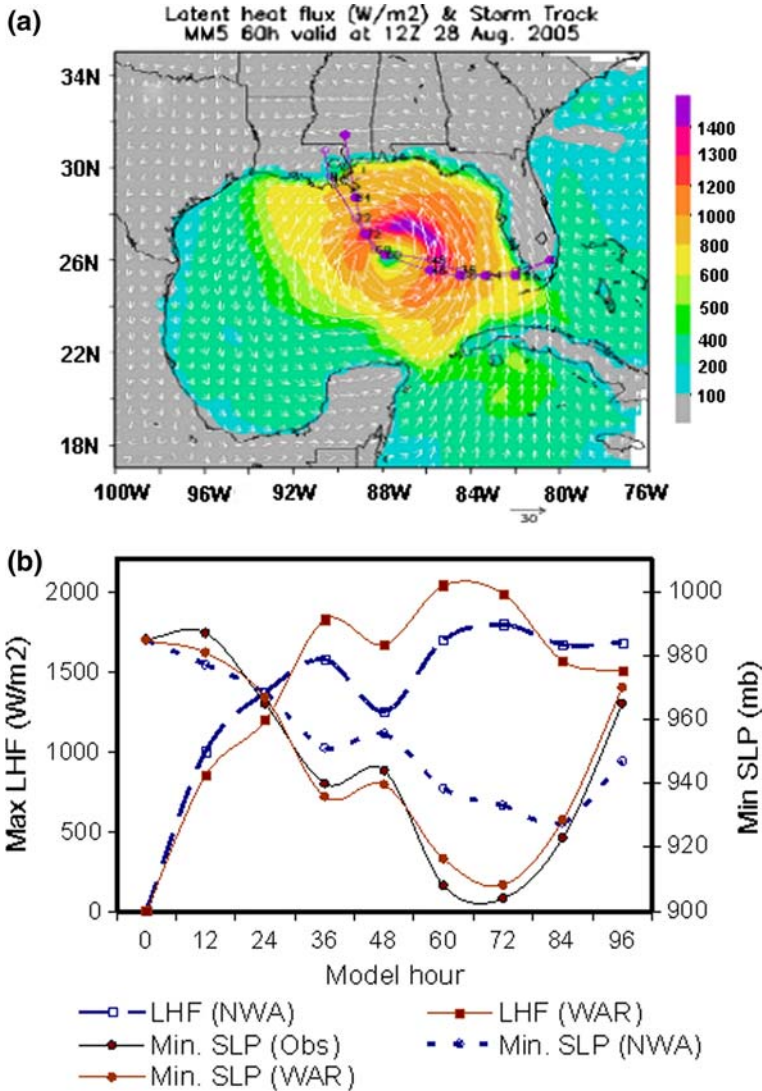


Fig. 6 (a) Spatial distribution of MM5 simulated LHF at 60 h valid at 12H 28 August 2005 from the simulation with warm SSTA, and simulated storm tracks with warm SSTA (solid circle) and without SSTA (empty circle), (b) The maximum LHF and the minimum SLP from the two control numerical experiments, and minimum SLP from the observations

storm track is higher than that from the control experiment without warm SSTA, leading to the stronger deepening in the minimum SLP. These experiments further confirm the TMI observations and show the important impacts of the warm SSTA on hurricane intensification.

Similar situation is also found for Hurricane Rita’s case (Fig. 7a). In September 2005, Rita underwent rapid intensification when it crossed over the Gulf of Mexico with pre-exist warm SSTA to the right side with respect to the storm track. Later in October 2005, Hurricane Wilma also intensified into Category 5 when it passed over

the Caribbean Ocean with more than 1°C warm SSTA pre-existed to the right of its track (Fig. 7b). We can see because of the southward migration of warm SST with the seasons, the positions of the strongest hurricane stages (Category 5, as marked with red circles in Figs. 3, 4, and 7) also moved southward. In contrast, the TMI

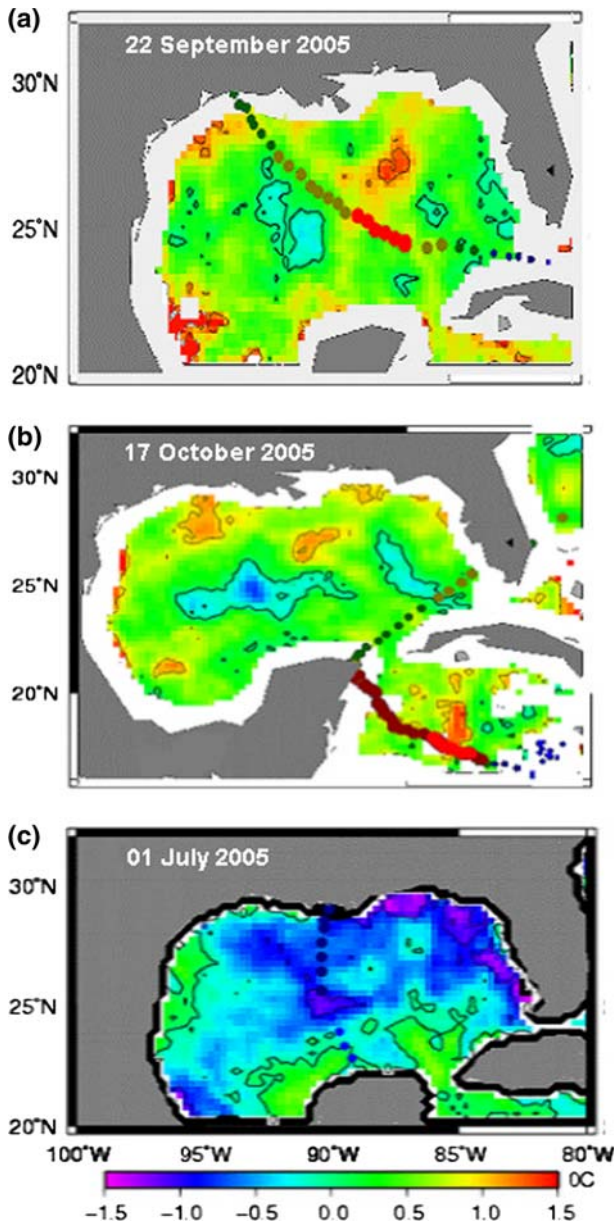


Fig. 7 TMI SSTA on: (a) September 22, (b) October 17, and (c) July 01, 2005. The locations and intensities of Hurricanes: (a) Rita, (b) Wilma, and (c) Cindy, were indicated by circles of different colors for different stages with red one as category 5

observations reveal that there was no warm SSTA at the time of Hurricane Cindy when it crossed over the Gulf (Fig. 7c), this may explain why Cindy didn't get further development into an intense hurricane. Our results show the spatial location of high SSTA over the open ocean with respect to the storm track may be a very important factor for hurricane intensification. Satellite microwave sensor may not provide measurements over the immediate coastal region, as shown in Figs. 3, 4, and 7. However, this may not affect its application to hurricane intensification analysis, because when hurricane approach the coast, increasing friction and decreasing heat fluxes or energy supply from the ocean makes it weaken quickly before making landfall, therefore warm SSTA located along the coast should not have significant effect on hurricane intensification.

Besides the magnitude and location of high SSTA, the time is also an important factor. As shown in Fig. 2, it may need about two or more days for a tropical storm to travel over the warm open ocean to accumulate energy for further intensification into hurricane strength.

4 Summary and discussions

In this study, the effects of high SST anomaly and its relative position with respect to the storm track on hurricane intensification are investigated by using SST from the TRMM microwave imager combined with the buoy observations and numerical sensitivity simulations. Three 96-h control experiments are performed by (1) initializing model with weekly composite TMI SST with warm SSTA to the right of the storm track, (2) removing the warm SSTA, while keep all other factors identical and SST fixed during simulations.

The analysis from the TMI measurements and buoy observations show SST increase in advance of two or more days before the significant hurricane intensification. The difference in the simulated minimum SLP from the two numerical experiments is not evident till 36–48 h simulations, which also confirm the observations about the time lag of about two days between the SST increase and significant hurricane intensification.

Although the wavenumber one radar reflectivity or rainfall asymmetry may be caused by upper-level divergence, the warm SST located at the right position may amplify the effect of surface heat fluxes and played a significant role in hurricane intensification. It is found that the simulated hurricane intensity is very sensitive to the warm SSTA. In the absence of warm SSTA, the model produced a weaker hurricane. The minimum SLP from the control experiment was more than 20 mb weaker than the observations. While the simulated storm with the warm SSTA at the right side of the storm track is stronger than the control experiment. The analysis here suggests the important impacts of high SST anomaly ($>1^{\circ}\text{C}$) over open-ocean at the right side in relative to the storm track on the rapid intensification of Hurricane Katrina. Similar situations are also found for Hurricanes Rita and Wilma. Our analysis further confirmed that with the southward migration of warm SST with seasons, the locations of the most intense hurricane stages (category 5) also moved southward.

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