FORUM

COMMENT & REPLY

Comment on "Satellite Altimetry and the Intensification of Hurricane Katrina"

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In a recent *Eos* article, *Scharroo et al.* [2005] reported that the dynamic sea topography anomalies along the track of Hurricane Katrina were the most prominent factors causing the intensification of Katrina as it passed over these anomalous regions in the Gulf of Mexico. They show that the sea surface temperature (SST) in the entire Gulf of Mexico was uniformly ~30°C and was not associated with the rapid intensification of Katrina.

We partly agree with their findings based on the results of dynamic topography associated with Katrina's intensification; however, we do not concur with their idea that SST was not linked with the rapid intensification of Katrina. Here, we show the significant impact of high SST anomaly in the Gulf on Katrina's rapid intensification and the role of anomalous SST in governing the air-sea interactions during its intensification.

The SST distribution over the Gulf of Mexico during Katrina's intensification shows a discernible warm patch of ~32°C associated with the upper shelf in the northern Gulf [see also *Sharroo et al.*, 2005, Figure 2a]. According to *Sharroo et al.*, 2005, the warm SST along the Gulf coast may be shallow. However, a more than 1°C SST anomaly (SSTA) is found at the northeastern quadrant or to the right of the storm track (Figure 1a, outlined in red), where winds are usually stronger and most clouds and intense precipitation develop [*Zhu et al.*, 2004].

The SST over the Gulf and along the track of Katrina shows a significant increase prior to the drop of sea level pressure (SLP) to its minimum value of 902 mbar (Figure 1b). To investigate the impact of SST on Katrina's intensity variations, we used the latest Pennsylvania State University/University Corporation for Atmospheric Research (PSU/UCAR) mesoscale model MM5 (version 3.7) to perform 96-hour simulations covering the period of rapid development across the Gulf and landfall at the northern Gulf coast, initialized at 0000 UT on 26 August 2005. This model simulation helps to measure SST as a function of the heat flux or energy exchange through the air-sea interactions. The maximum latent heat flux (LHF), which is associated with intensity variations of hurricanes [*Gautam et al.*, 2005], shows significant increases (when additional SST was fed into the model's initial conditions) during rapid intensification of Katrina (Figure 1c). SST was found to increase prior to the significant deepening of the hurricane central minimum SLP, which occurred after the 48 hours when the simulated storm began to receive more energy supply through the air-sea interac-

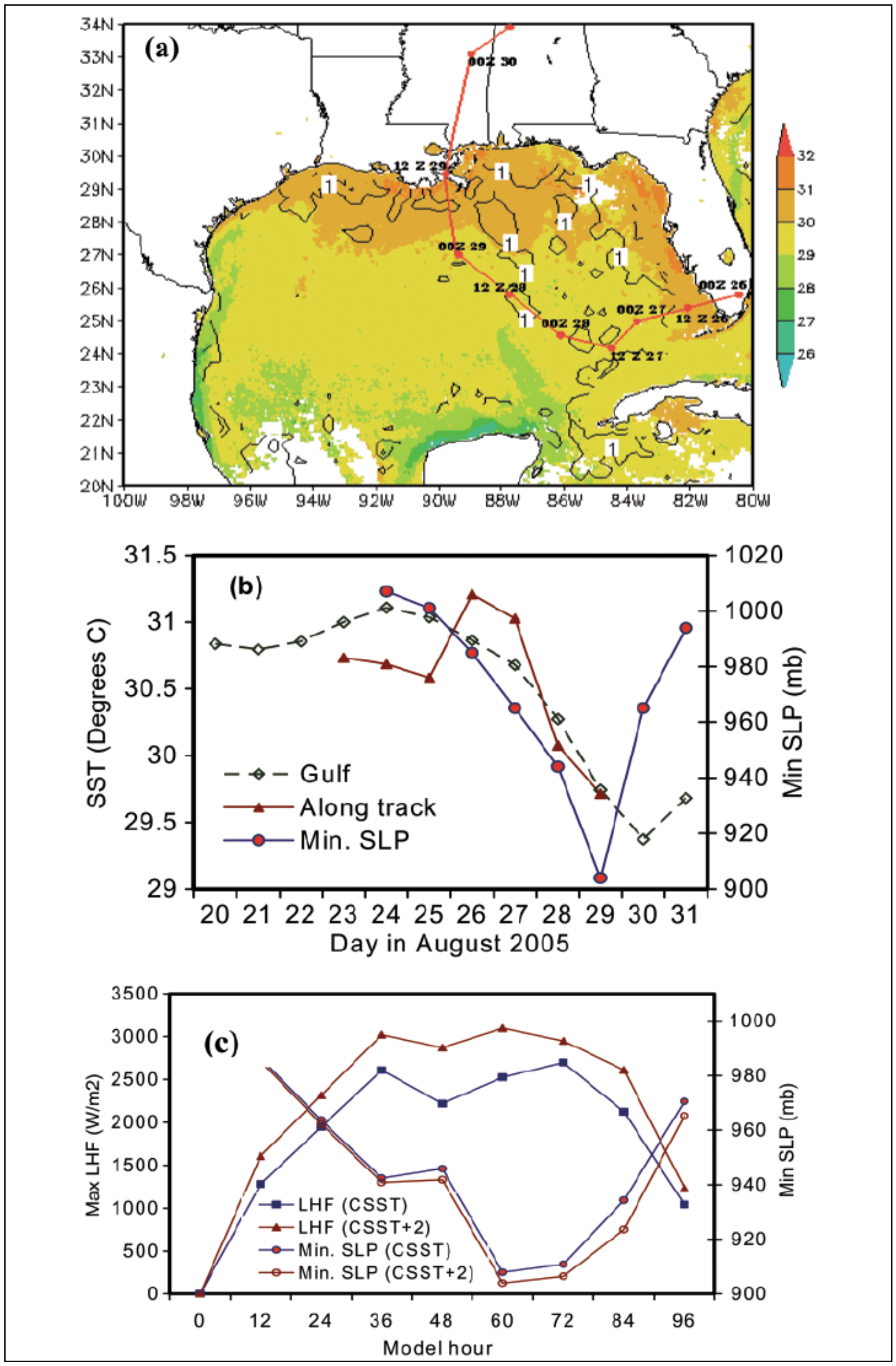

Fig. 1. (a) Sea surface temperature (SST) (shaded) and SST anomaly (contours overlaid) during 21–27 August 2005 (the '1's indicate areas where SST anomaly is above 1 °C) (b) SST averaged over the Gulf of Mexico (22~30°N, -98 ~ -81°W) and along the track of Katrina (1000 km×1000 km area-average centered on the eye) with the observed minimum sea level pressure (c) Minimum sea level pressure and maximum latent heat flux from two numerical simulations: (1) CSST, where monthly mean SST during August 2005 was input as the model's initial conditions, and (2) CSST + 2, where an addition of 2°C was inputted in order to capture the impact of the observed SST anomaly in relation to 8-year average from 1998 to 2005 on the hurricane's characteristics.

tion processes (Figure 1c). We found a phase lag of about two days between SST increase and the significant drop of the minimum SLP, which is consistent with the observations (Figure 1b).

These model simulations, complemented by remote sensing observations, show that high SST anomaly affected Katrina's rapid intensification by inducing significant increases in latent heat releases associated with the hurricane through dominant sea-air interactions. However, the intensification may not be spatially and temporally consistent with the distribution of warm SST.

Since sea topography reflects the integrated influence of SST and salinity through the water column, and a canonical correlation analysis shows that sea topography and SST anomalies vary coherently at large spatial scales [*Cummins et al.*, 2005], our present results therefore confirm the impact of SST on the rapid intensification of Katrina and the role of anomalous SST in governing the air-sea interactions associated with the intensification of Katrina into a Category 5 hurricane.

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Reply to Comment on "Satellite Altimetry and the Intensification of Hurricane Katrina"

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In their comment on our *Eos* article [*Scharroo et al.*, 2005], *Sun et al.* [this issue] conclude that sea surface temperature (SST) had a significant impact on the rapid intensification of Hurricane Katrina. Although SST may have played some role, we want to stress that dynamic topography is a more reliable proxy than SST for upper ocean heat content, which is ultimately responsible for the cyclone's intensification.

As evidence of the impact of SST on sea level pressure (SLP), *Sun et al.* [this issue, Figure 1c] present the outcome of model simulations in which the SST over the Gulf of Mexico was raised by as much as 2ºC. After a two-day lag, this comparatively large increase in SST caused SLP to decrease by a mere 10 millibar. However, since the SST along Katrina's track across the Gulf of Mexico varied by no more than 1ºC, whereas the SLP dropped by about 90 millibar (Figure 1), their results actually indicate that the impact of SST on the hurricane intensification was neither rapid nor significant. Moreover, the perceived correlation between SST and SLP was very weak.

Although the shelf water in the northern part of the Gulf of Mexico is about 1ºC warmer than the central Gulf, the hurricane in fact lost strength as soon as it entered this region (see Figure 1). Katrina reached maximum intensity somewhat earlier as it crossed a warm core ring (WCR) and experienced the most rapid drop in sea level pressure when crossing the Loop Current. Both oceanographic features are prominently displayed as maxima in the dynamic topography but are obscured in SST due to a thin, warm surface layer. As Figure 1 shows, the minimum sea level pressure near the eye of the storm coincides with the maximum in dynamic topography while crossing the WCR, not with the maximum SST near the shore.

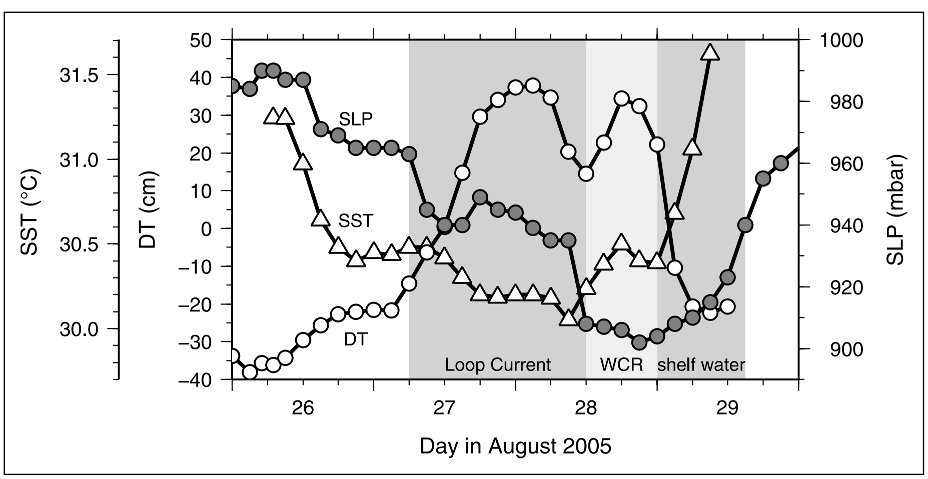

Fig. 1. Sea surface temperature (SST, triangles), dynamic topography (DT, open circles), and sea level pressure (SLP, solid circles) along the track of Hurricane Katrina during the period 26–29 August 2005. Shaded bars indicate the crossing of the Gulf Loop Current, a warm core ring (WCR), and the northern Gulf shelf water. Intensification of Katrina, indicated by decreasing SLP, correlates well with higher dynamic topography.

Shay et al. [2000] have reported a similar case for the intensification of Hurricane Opal (September and October 1995) while crossing a WCR in the Gulf of Mexico. They, too, came to the conclusion that high SST is a necessary, but insufficient, condition for hurricane intensification.

However, more relevant is the upper ocean heat content, as determined by the upper ocean temperature and the depth of the thermocline, which is reflected in the dynamic topography. In the case of Typhoon Imbudo (July 2003), *Goni and Trinanes* [2003] showed that the depth of the 26ºC isotherm decreased as a result of the release of thermal energy to the atmosphere.

These cases emphasize the important contribution of the sea surface height to the estimation of the tropical cyclone heat potential, which more efficiently predicts hurricane intensification than sea surface temperature alone.

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