6C.4 USING AXBTS TO IMPROVE THE PERFORMANCE OF COUPLED HURRICANE-OCEAN MODELS

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1. INTRODUCTION

Hurricanes develop and are maintained by heat energy they receive from the sea surface. The warmer the sea surface temperature (SST) is below the hurricane, the more energy is available to the hurricane (e.g. Emanuel 1986; 1999). Wind-induced mixing of the upper ocean by a hurricane can cool the sea surface via entrainment of cooler water into the oceanic mixed layer (OML) from below (e.g. Shay et al. 1992; Ginis 2002). Therefore, the future intensity (and perhaps track) of a given hurricane depends not only on the initial temperature of the sea surface below the hurricane, but also on the magnitude of the wind-induced sea surface cooling in the region providing heat energy to the hurricane (Bender and Ginis 2000; Shay et al. 2000; Cione and Uhlhorn 2003). The magnitude of the wind-induced cooling depends on the magnitude of the surface wind stress, the depth of the OML, and the temperature gradient at the base of the OML.

Scientists at the Hurricane Research Division (HRD) measure ocean temperature profiles in the pre-hurricane environment and in the wind-induced cold wake via airborne expendable bathythermograph (AXBT) instruments dropped from aircraft (Cione and Uhlhorn 2003). Such ocean temperature profiles can also be derived from the Geophysical Fluid Dynamics Laboratory/University of Rhode Island coupled hurricane-ocean model (hereafter GFDL model), which has been run operationally at the National Centers for Environmental Prediction (NCEP) to forecast hurricane track and intensity since 2001 (Falkovich et al. 2005). If initial and predicted temperature profiles in the GFDL model are inconsistent with AXBT observations, then steps should be taken to improve the GFDL model's representation of the 3D ocean temperature field.

2. GFDL MODEL: 2005 OPERATIONAL VERSION

2.1 *Background Information*

Since 2001, yearly upgrades have been made to the operational version of the GFDL model. The ocean component of the 2005 version of the GFDL model is the Princeton Ocean Model (POM) (Mellor 2004), which has 1/6° grid spacing and 23 vertical sigma levels. Before the GFDL model is run to produce a hurricane forecast, POM is run twice to "spin-up" the ocean. During the first preliminary POM run (hereafter phase 1), which operationally forecasts out 48 hours, the General Digital Environmental Model (GDEM) monthly ocean temperature and salinity climatology with 1/2° grid spacing (hereafter GDEM 0.50°) is assimilated with NCEP real-time SST, and ocean fronts are imposed as necessary. The inclusion of ocean fronts is based on a feature-based modeling approach called "sharpening" that has been used since the 2003 version of the GFDL model (Falkovich et al. 2005). During the second preliminary POM run (hereafter phase 2), which operationally forecasts out 72 hours, the cold wake is created by assimilating the surface wind speed information from the hurricane message file (hereafter MSG) provided by the Tropical Prediction Center (TPC). Henceforth, the 2005 version of the GFDL model is referred to as OP05.

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2.2 *Comparison with 15 September 2005 AXBTs*

On 15 September 2005, 19 AXBTs were dropped in the Gulf of Mexico between 25°N and 28°N latitude, 93°W and 85°W longitude. These AXBTs are used to test the ocean initialization of OP05 one week in advance of Hurricane Rita (2005). According to the NCEP real-time SST, horizontal SST variation throughout the Gulf of Mexico (GoM) was less than 2°C on 15 September (Fig. 1a). Examining September GDEM 0.50° temperature at 75-m depth, however, reveals a warm tongue of water intruding into the relatively cold GoM (20-23°C) from the relatively warm Caribbean (> 27°C) (Fig. 1b). Since a hurricane is not present, assimilation of the NCEP SST with sharpened September GDEM 0.50° yields the ocean initial condition (i.e. phase 1) (Fig. 1c). The warm tongue present in Fig. 1c is the OP05 representation of the Loop Current (LC). This representation is unrealistic because the LC shape, size, and position are known to vary with time on an irregular cycle that cannot be captured accurately by a monthly ocean climatology (Falkovich et al. 2005; Gyory et al. 2006).

The temperature profiles for two of the 19 AXBTs are compared with profiles from the initialization of OP05 that have been interpolated in time and space to coincide with the AXBTs (Fig. 1d). AXBT "A1", which was dropped in the northern GoM at 27.895°N, 88.623°W (Figs. 1a-1c), yields a temperature profile that is consistent with the analogous OP05 profiles (Fig. 1d).

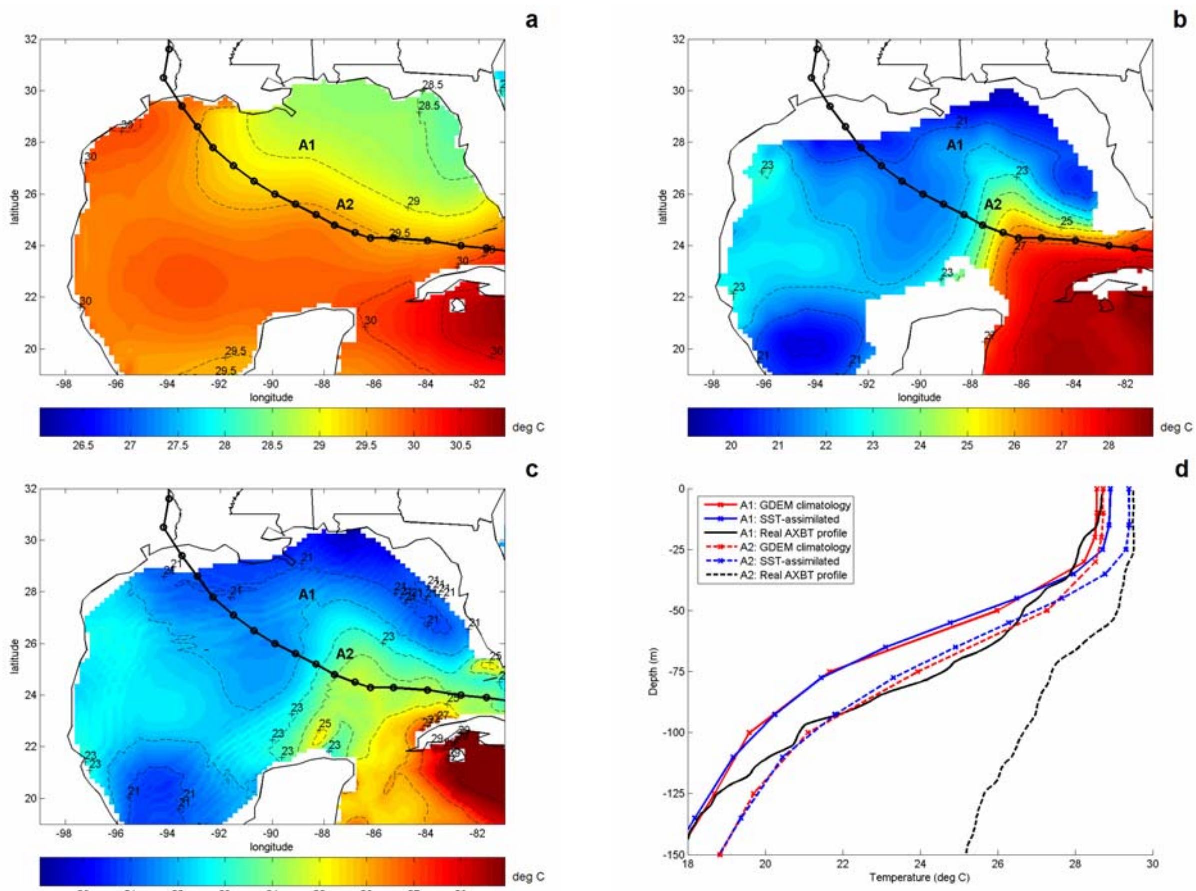

FIG. 1. *(a) NCEP SST in the GoM on 15 Sept. 2005 with future track of Rita overlaid; (b) September GDEM 0.50° temperature at 75-m depth; (c) same as (b) but sharpened and with SST assimilated (i.e. end of OP05 phase 1); (d) temperature profiles for AXBTs "A1" (black solid) and "A2" (black dashed) and the analogous climatological (red) and OP05 phase 1 (blue) profiles.*

AXBT "A2", however, which was dropped to the south-southeast of A1 at 25.579°N, 87.174°W (Figs. 1a-1c), yields a temperature profile that is significantly warmer than the analogous OP05 profiles (Fig. 1d). After SST assimilation, the A2 OP05 profile is similar to AXBT A2 from the surface to 30-m depth, but below 30-m, the AXBT reveals that the actual mixed layer depth is deeper and the upper thermocline is significantly warmer than the OP05 profile suggests. Since the AXBT A2 profile is more representative of Caribbean water than GoM water, this location is hypothesized to be within or on the Caribbean-facing side of the LC, which is inaccurately represented by OP05.

3. GFDL MODEL: NEW LC INITIALIZATION

3.1 *Background Information*

In research mode (and perhaps future operations), a new type of feature-based modeling is being developed that represents the LC more accurately. This approach is discussed in detail by Falkovich et al. (2005). With the new LC initialization, GDEM 0.50° is not only assimilated with NCEP real-time SST and sharpened during phase 1, but also may be assimilated with available real-time sea surface height (SSH) data by, for example, adjusting the northern extent of the LC. Since the writing of Falkovich et al. (2005), the LC initialization has undergone a series of improvements based on satellite altimetry and AXBT profiles. For example, LC water has been made more similar to Caribbean water, and the horizontal temperature gradient on the periphery of the LC has been made sharper. The latest version under development will incorporate warm and cold core rings (WCRs and CCRs, respectively) and changes in the orientation of the LC axis, but this latest version was not yet available as of the writing of this paper. Therefore, the two main advantages of the LC initialization version used here (versus OP05) are the ability to manually adjust the northern extent of the LC and the improved temperature gradient at the LC periphery. Henceforth, the use of the new LC initialization in conjunction with the initial climatology is distinguished from OP05 by referring to the former as "SSH/SST-assimilated" and the latter as "SST-assimilated". The ability of satellite altimetry to aid forecasters in identifying regions of hurricane intensification is discussed in further detail by both Goni and Trinanes (2003) and Goni et al. (2003).

3.2 *Comparison with 15 September 2005 AXBTs*

Satellite altimetry reveals that in the pre-Rita GoM, the LC reaches northward to at least 27°N and has a complex structure that bulges westward on the northern end towards a recently-separated WCR (Fig. 2a). Based on this information, the northern extent of the LC is set to 27.6°N using SSH/SST-assimilated initialization to obtain phase 1 temperature profiles that are more synonymous with the available AXBTs. Figure 2b shows the resulting SSH at the end of phase 1, which is similar to the satellite altimetry (Fig. 2a) except for the lack of both WCR and westward LC bulge. The SSH/SST-assimilated GDEM 0.50° temperature (i.e. phase 1) at 75-m depth (Fig. 2c) closely resembles the phase 1 SSH (Fig. 2b).

Temperature profiles for two of the 19 AXBTs are compared with profiles from the SSH/SST-assimilated initialization that have been interpolated in both time and space to coincide with the AXBTs (Fig. 2d). AXBT A2 is the same AXBT discussed in section 2.2. AXBT A2's temperature profile is still warmer than the analogous SSH/SST-assimilated profile, but the SSH/SST-assimilated profile is much more reasonable than the SST-assimilated profile (Fig. 1d). The difference between the AXBT A2 profile and the analogous SSH/SST-assimilated profile, especially at depths > 30 m, can be attributed to the slight difference between the orientation of the LC axis according to satellite altimetry (Fig. 2a), in which A2 is near the center of the LC axis, and according to the SSH/SST-assimilated initialization (Fig. 2b), in which A2 is west of the LC axis.

To achieve more synergy, it is constructive to compare AXBT A2's temperature profile to an SSH/SST-assimilated profile located near the center of the SSH/SST-assimilated LC axis. Since AXBT "A3" was dropped near the SSH/SST-assimilated LC axis (25.792°N, 86.565°W), its coordinates are used for this

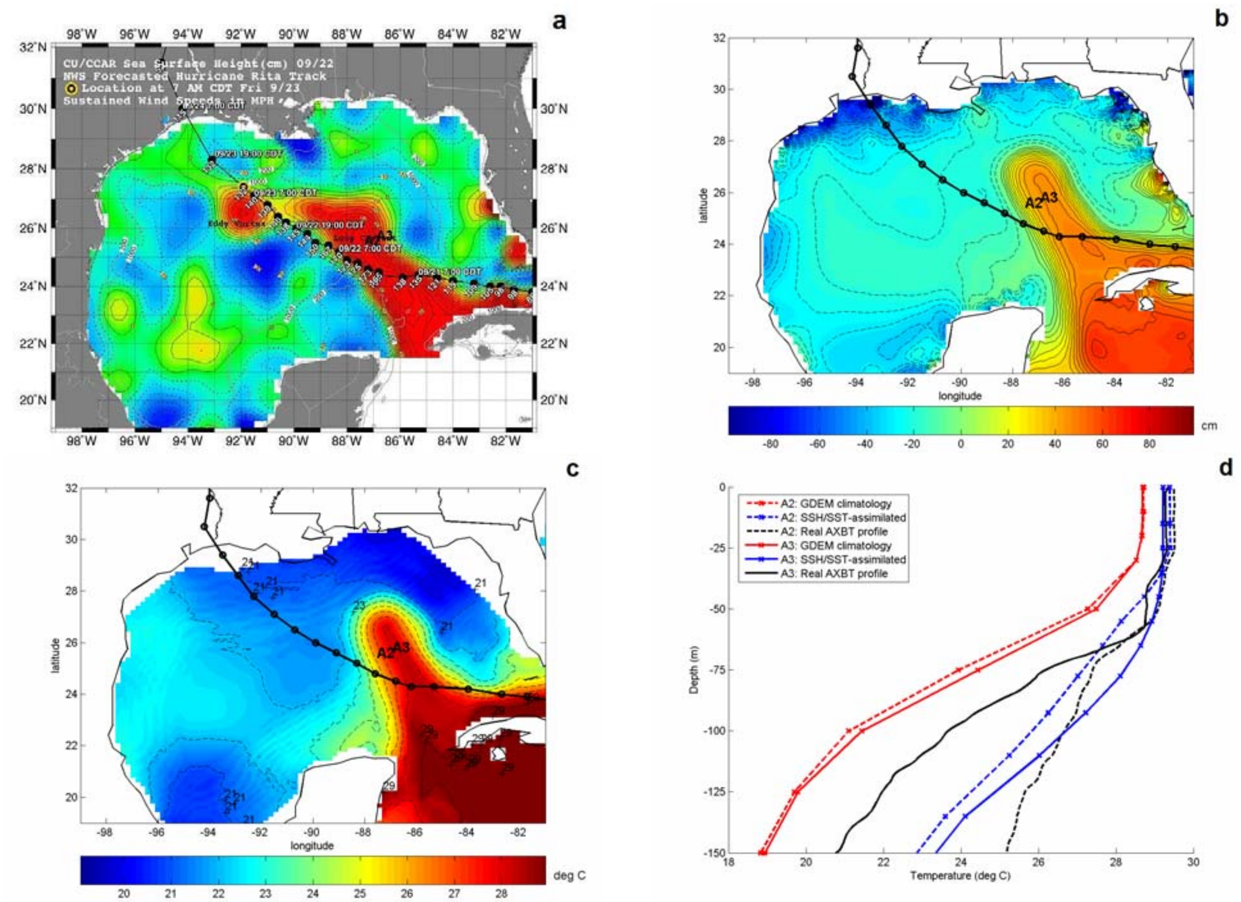

FIG. 2. (a) Satellite altimetry in the pre-Rita GoM with track of Rita overlaid (courtesy of NASA/JPL/University of Colorado); (b) SSH at the end of phase 1 with both SSH and SST assimilated; (c) September GDEM 0.50° temperature at 75-m depth sharpened and SSH/SST-assimilated; (d) temperature profiles for AXBTs "A2" (black dashed) and "A3" (black solid) and the analogous climatological (red) and SSH/SST-assimilated phase 1 (blue) profiles.

purpose. The SSH/SST-assimilated A3 temperature profile (blue solid) is colder than the AXBT A2 temperature profile (black dashed) below 100 m, and the former is warmer than the latter between 60 m and 100 m, but these two profiles are nearly identical in the OML above 60 m. Once the new LC version is ready, the LC axis tilt will be adjusted so the AXBT temperature profiles and SSH/SST-assimilated temperature profiles are comparable at the *same* locations.

4. GFDL MODEL: OTHER OCEAN CLIMATOLOGIES

4.1 *Background Information*

Rather than using GDEM 0.50° as the initial ocean climatology in phase 1 (Fig. 3a), it is possible to use alternative monthly ocean climatologies. Here we consider two other options. The first option is GDEM but with 1/4° grid spacing (hereafter GDEM 0.25°) (Fig. 3b). The second option is to use the Levitus climatology (Boyer and Levitus 1997), which also has 1/4° grid spacing (hereafter Levitus 0.25°) (Fig. 3c). Initially, it was hypothesized that GDEM 0.25° and/or Levitus 0.25° might be superior to GDEM 0.50° because of the increased horizontal resolution, especially when using SSH/SST-assimilation for LC initialization.

4.2 *Comparison with 15 September 2005 AXBTs*

Comparisons with AXBTs reveal that the September GDEM 0.50° is at least as accurate as the other two climatologies after SSH/SST assimilation (e.g. Fig. 3d). Therefore, no plans are currently being made to change the initial climatology in future operational versions of the GFDL model. Another possible option is to use the United States Navy's Modular Ocean Data Assimilation System (MODAS) as an initial ocean climatology, which incorporates MCSST instead of NCEP SST (Fox et al. 2002). This option is being considered for future research but has not yet been tested in phase 1 or compared with the available pre-Rita AXBTs.

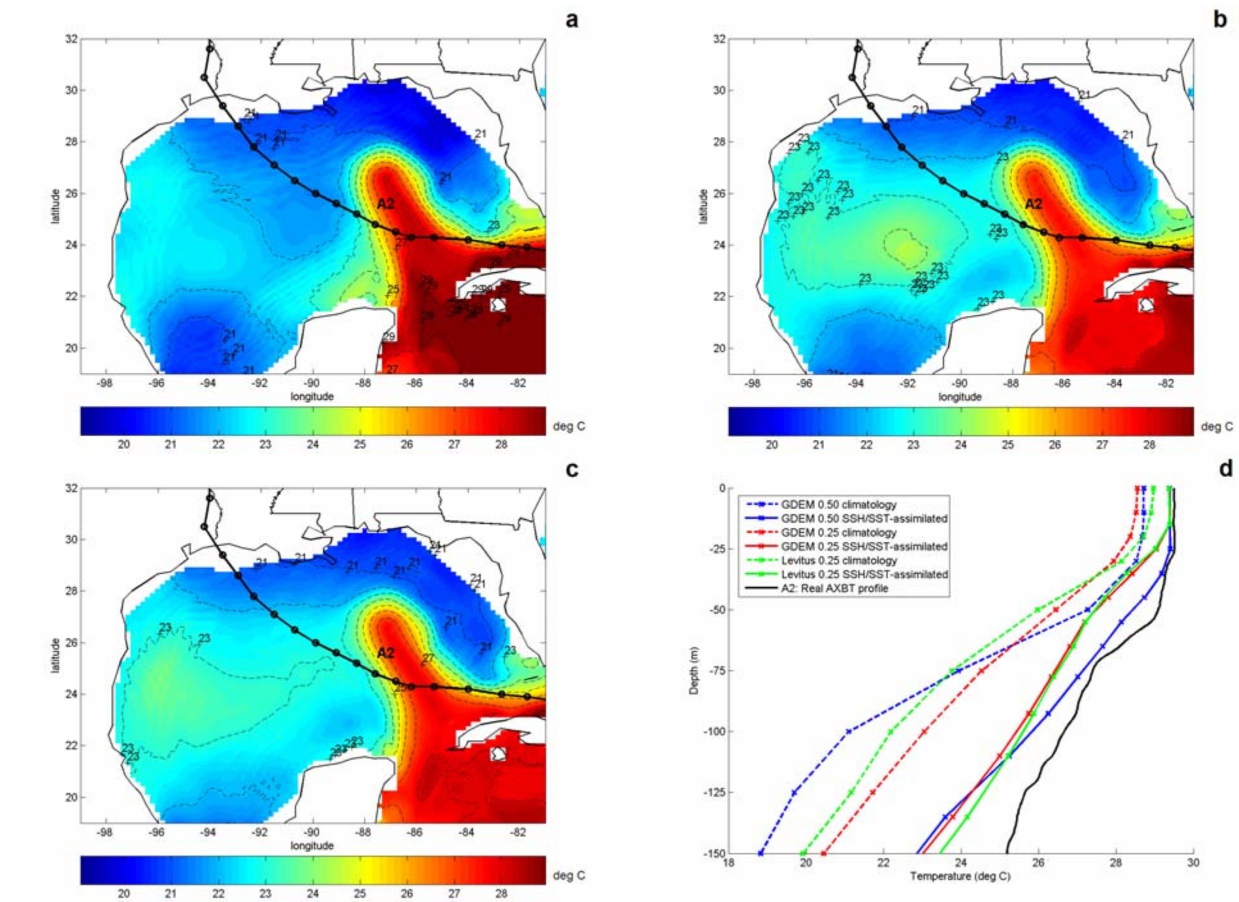

FIG. 3. *(a) September GDEM 0.50° temperature at 75-m depth sharpened and SSH/SST-assimilated; (b) same as (a) but with GDEM 0.25°; (c) same as (a) but with Levitus 0.25°; (d) temperature profile for AXBT "A2" (black solid) and the analogous climatological (dashed) and SSH/SST-assimilated phase 1 (solid) profiles for GDEM 0.50° (blue), GDEM 0.25° (red), and Levitus 0.25° (green).*

5. GFDL MODEL: ALTERNATIVE WIND STRESS

5.1 *Background Information*

In OP05, the wind stress used in phase 2 is derived from MSG wind (see section 2.1). After interpolating the MSG wind onto the POM grid, the wind stress is calculated as follows (hereafter "OLD c_D"):

$$\tau_{x,y} = \begin{cases} \left[\rho_a c_D W\right](u,v) & W \le 35ms^{-1} \\ \left[\dfrac{3.3368 + \left(W - 34.0449\right)^{0.3}}{W}\right](u,v) & W > 35ms^{-1} \end{cases} \quad (1)$$

$$c_D = \begin{cases} 1.14\times10^{-3} & W < 10ms^{-1} \\ \left(0.49 + 0.065W\right)\times10^{-3} & W \ge 10ms^{-1} \end{cases} \quad (2)$$

In (1) and (2), "W" is the 10-m horizontal wind speed in m s^{-1}, which has "u" and "v" components.

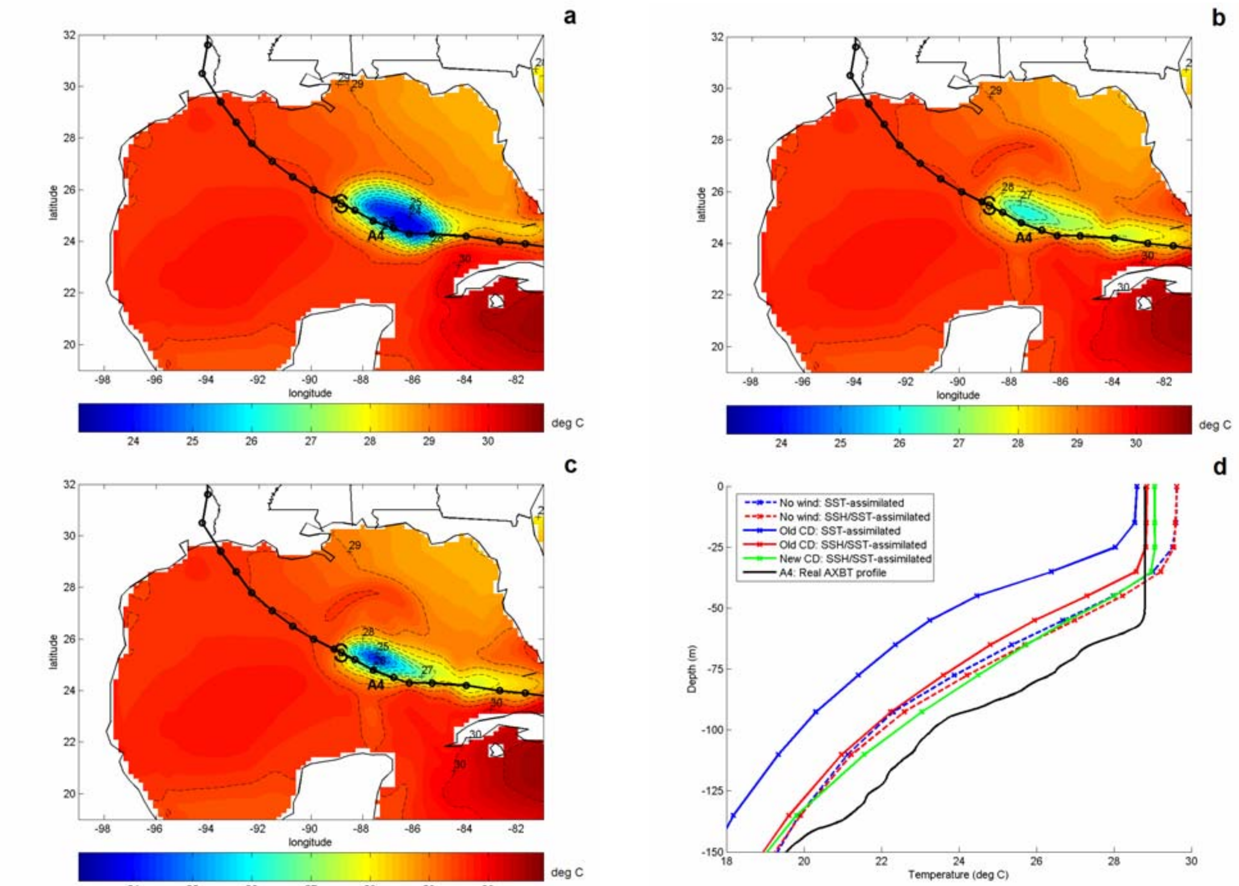

FIG. 4. *(a) SST-assimilated/OLD c_D-initialized phase 2 SST in the GoM at ~1600 UTC 22 Sept. 2005 with Rita storm center position indicated by "S"; (b) same as (a) but SSH/SST-assimilated; (c) same as (b) but NEW c_D-initialized; (d) temperature profile for AXBT "A4" (black solid) and the analogous profiles for no wind (blue and red dashed) (i.e. end of phase 1), OLD c_D (blue and red solid), and NEW c_D (green solid).*

Recently, a new method of calculating wind stress from the MSG wind was developed based on hurricane simulations using a coupled wave-wind model (Moon et al. 2006). In this new method, wind stress is calculated as follows (hereafter "NEW c_D"):

$$\tau_{x,y} = \left[\rho_a c_D W\right](u,v) \quad (3)$$

$$c_D = \left(\frac{0.4}{\ln\left(10/z_0\right)}\right)^2 \quad (4)$$

$$z_0 = \begin{cases} \left(0.0281e^{0.190669W}\right)\times10^{-3} & W < 12.5ms^{-1} \\ \left(0.0739793W - 0.61841\right)\times10^{-3} & W \ge 12.5ms^{-1} \end{cases} \quad (5)$$

5.2 *Comparison with 22-23 September 2005 AXBTs*

During 22-23 September 2005, 24 AXBTs were dropped in the GoM between 24°N and 28°N latitude, 94°W and 87°W longitude. Some of these AXBTs were dropped in advance of Rita, while others were dropped in Rita's wake. Unfortunately, none of the AXBTs in Rita's wake were dropped on the right hand side of the storm track where the maximum cooling occurs (Price 1981). Here, one of the AXBTs dropped in Rita's wake to the left of the storm track (AXBT "A4") is used to test the accuracy of the ocean cooling generated via two different phase 2 wind stress parameterizations: "OLD c_D" and "NEW c_D".

At ~1600 UTC 22 September, the center of Rita was located at ~25.46°N, 88.82°W. During this time, the wake generated in phase 2 by OLD c_D using SST-assimilated GDEM 0.50° climatology is quite cold, with SSTs cooling to < 24°C in a large area to the right of the storm track (Fig. 4a). In contrast, the wake generated in phase 2 by OLD c_D using SSH/SST-assimilated GDEM 0.50° climatology is not as cold, with SSTs cooling to ~26-27°C in the same region (Fig. 4b). It is hypothesized that without SSH assimilation, the inability of the model to initialize the LC accurately leads to the anomalous cooling in Fig. 4a.

Next, the wake generated in phase 2 by NEW c_D using SSH/SST-assimilated GDEM 0.50° climatology is investigated (Fig. 4c). The cooling pattern with the NEW c_D is similar to the OLD c_D cooling pattern (Fig. 4b), but the maximum cooling is greater with the NEW c_D than with the OLD c_D. This strong cooling maximum occurs because unlike the OLD c_D parameterization, the wind stress with the NEW c_D parameterization is not truncated at very high wind speeds, and Rita was Category 5 during this time.

AXBT A4 was dropped in Rita's wake to the left of the storm track in the GoM (24.217°N, 87.459°W) at 1553 UTC 22 September. Considering only the SSH/SST-assimilated simulations, the OLD c_D and NEW c_D temperature profiles at A4 (red solid and green solid, respectively) are similar to each other. In both simulations, the OML depth is ~40 m, but according to the AXBT A4 profile (black solid), the actual OML depth is ~65 m. Some differences do exist between the two model profiles. The OML temperature with OLD c_D is nearly identical to AXBT A4, but the NEW c_D OML temperature is ~0.2°C too warm. In the upper thermocline, the NEW c_D temperature profile is nearly unchanged from the initial state (red dashed), but the OLD c_D temperature profile indicates upwelling.

6. CONCLUSIONS AND FUTURE WORK

Based on the results obtained in this study, AXBTs can provide vital information about the ocean temperature structure that can be used to improve the initialization of coupled hurricane-ocean models. When AXBTs are dropped in advance of a hurricane, the temperature profiles can be used in conjunction with satellite altimetry to adjust the position of mesoscale oceanic features such as the LC and WCRs. When AXBTs are dropped in the wake of a hurricane, the temperature profiles can be used to validate the wind stress parameterization and resulting SST cooling and OML deepening in the ocean model.

Soon, the simulations presented in this study will be rerun with the latest LC initialization version currently under development (see section 3.1) in the hopes of obtaining even better agreement between AXBTs and model temperature profiles. Then, other hurricanes for which AXBT profiles are available will be studied (e.g. Dennis (2005)). Eventually, AXBTs may be assimilated into future operational versions of the GFDL model and/or newer generation hurricane forecast models (e.g. Hurricane WRF) to obtain a more accurate initial ocean condition in real-time. By improving the initial ocean condition, coupled hurricane-ocean model forecasts may improve as well.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Bender, M. A., and I. Ginis 2000: Real case simulation of hurricane-ocean interaction using a high-resolution coupled model: Effects on hurricane intensity. *Mon. Wea. Rev.,* **128,** 917-946.

Boyer, T. P., and S. Levitus, 1997: *Objective Analysis of Temperature and Salinity for the World Ocean on a ¼ Grid.* NOAA Atlas NESDIS 11, 62 pp.

Cione, J. J., and E. W. Uhlhorn, 2003: Sea surface temperature variability in hurricanes: Implications with respect to intensity change. *Mon. Wea. Rev.,* **131,** 1783-1796.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.,* **43,** 585-604.

Emanuel, K. A., 1999: Thermodynamic control of hurricane intensity. *Nature,* **401,** 665-669.

Falkovich, A., I. Ginis, and S. Lord, 2005: Ocean data assimilation and initialization procedure for the Coupled GFDL/URI Hurricane Prediction System. *J. Atmos. Oceanic Technol.,* **22,** 1918-1932.

Fox, D. N., W. J. Teague, C. N. Barron, M. R. Carnes, and C. M. Lee, 2002: The Modular Ocean Data Assimilation System (MODAS). *J. Atmos. Oceanic Technol.,* **19,** 240-252.

Ginis, I., 2002: Tropical cyclone-ocean interactions. *Atmosphere-Ocean Interactions, Advances in Fluid Mechanics Series,* No. 33, WIT Press, 83-114.

Goni, G., and J. Trinanes 2003: Ocean thermal structure monitoring could aid in the intensity forecast of tropical cyclones. *EOS, Trans. Amer. Geophys. Union,* **84,** 573-580.

Goni, G., P. Black, and J. Trinanes, 2003: Using satellite altimetry to identify regions of hurricane intensification. *AVISO Newsletter,* **9,** 19-20.

Gyory, J., A. J. Mariano, and E. H. Ryan, cited 2006: The Loop Current. [Available online from http://oceancurrents.rsmas.miami.edu/atlantic/loop-current.html.]

Johns, E., W. D. Wilson, and R. L. Molinari, 1999: Direct observations of velocity and transport in the passages between the Intra-Americas Sea and the Atlantic Ocean, 1984-1996. *J. Geophys. Res.,* **100,** 817-838.

Mellor, G. L., cited 2006: Users guide for a three-dimensional, primitive equation, numerical ocean model (June 2004 version). [Available online from http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/FTPbackup/usersguide0604.pdf.]

Moon, I. J., I. Ginis, T. Hara, and B. Thomas, 2006: Physics-based parameterization of air-sea momentum flux at high wind speeds and its impact on hurricane intensity predictions. *Mon. Wea. Rev.,* submitted.

Price, J., 1981: Upper ocean response to a hurricane. *J. Phys. Oceanogr.,* **11,** 153-175.

Shay, L. K., P. G. Black, A. J. Mariano, J. D. Hawkins, and R. L. Elsberry, 1992: Upper-ocean response to Hurricane Gilbert. *J. Geophys. Res.,* **97,** 20 227-20 248.

Shay, L. K., G. J. Goni, and P. G. Black, 2000: Role of a warm ocean feature on Hurricane Opal. *Mon. Wea. Rev.,* **128,** 1366-1383.