2006

Role of Anomalous Warm Gulf Waters in the Intensification of Hurricane Katrina

Menas Kafatos
Chapman University, kafatos@chapman.edu

D. Sun
George Mason Univ

Ritesh Gautam
ICAR CIARI

Z. Boybeyi
George Mason University

Ruixin Yang
George Mason University

See next page for additional authors

Recommended Citation

Kafatos, M., Sun, D., Gautam, R., Boybeyi, Z., Yang, R., Cervone, G. (2006) Role of anomalous warm gulf waters in the intensification of Hurricane Katrina, *Geophysical Research Letters*, Vol. 33, L17802, 2006. doi:10.1029/2006GL026623

Role of Anomalous Warm Gulf Waters in the Intensification of Hurricane Katrina

Comments
This article was originally published in *Geophysical Research Letters*, volume 33, in 2006. DOI: 10.1029/2006GL026623

Authors
Menas Kafatos, D. Sun, Ritesh Gautam, Z. Boybeyi, Ruixin Yang, and G. Cervone

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L17802, doi:10.1029/2006GL026623, 2006

Role of anomalous warm gulf waters in the intensification of Hurricane Katrina

Menas Kafatos,[1] Donglian Sun,[1] Ritesh Gautam,[1] Zafer Boybeyi,[1] Ruixin Yang,[1] and Guido Cervone[1]

Received 18 April 2006; revised 7 June 2006; accepted 17 July 2006; published 1 September 2006.

[1] The year 2005 experienced several strong hurricanes intensifying in the Gulf of Mexico before making landfall that severely damaged the Gulf States, especially Hurricane Katrina. Remarkable similarities between sea surface temperature anomaly (SSTA) and major hurricane (categories 3 and higher) activity over the Gulf are identified. However, the intensification of individual hurricanes may not necessarily be temporally and spatially coincident with the distribution of warm waters or high sea surface temperature (SST). High SST values are found in advance of significant intensification of Hurricane Katrina. We emphasize that high SSTA which occurred at the right time and right place was conducive to the hurricane intensification. In particular, high SSTA in the northeastern quadrant of the storm track induced significant increases in surface latent heat fluxes (LHF) contributing to the rapid intensification of Katrina. We also compared and verified model simulations with buoy observations. **Citation:** Kafatos, M., D. Sun, R. Gautam, Z. Boybeyi, R. Yang, and G. Cervone (2006), Role of anomalous warm gulf waters in the intensification of Hurricane Katrina, *Geophys. Res. Lett.*, *33*, L17802, doi:10.1029/2006GL026623.

1. Introduction

[2] Despite large reductions in track forecast errors over the past three decades [*McAdie and Lawrence*, 2000], there has been little improvement in forecasts of storm intensity. Observational and modeling studies have shown the significant influence of vertical wind shear on hurricane intensity changes. Strong vertical wind shear ($|V_z|$) between the upper and lower troposphere prevents the intensification of tropical cyclones due to the so-called "ventilation" effect of the hurricane warm core [*Gray*, 1968; *Goldenberg and Shapiro*, 1996; *Bracken and Bosart*, 2000; *Wong and Chan*, 2004]. However, *Zhu et al.* [2004] found that Hurricane Bonnie intensified simultaneously with the increases of vertical shear; suggesting that in addition to the magnitude of wind shear, the direction of wind shear may as well be significant for the intensification of hurricanes. The overall dependence of tropical cyclone intensity on SST is well documented [*Fisher*, 1958; *Leipper*, 1967; *Emanuel*, 1986, 1988; *Holland*, 1997], with an increase of 1°K of SST leading to a 12–14 mb deepening in hurricane minimum central pressure [*Hong et al.*, 1995; *Zhu et al.*, 2004]. 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].

[3] 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]. Other studies indicate the effect of warm core ring associated with the loop current in the intensification of hurricanes is important [*Hong et al.*, 2000; *Scharroo et al.*, 2005]. Nevertheless, they are all associated with the effects of warm SST. At the same time, we note that not all tropical cyclones associated with warm waters attain peak intensity (categories 4 and 5) during their life cycle.

[4] Specifically, the current period after 1995 has signaled an active period, especially for major hurricanes (categories 3, 4, and 5) [*Goldenberg et al.*, 2001]. The last several years set records for the most intense hurricanes ever in any given year, except for the El Niño year 1997 when hurricane occurrences were low. The SSTA trends over the North Atlantic coincide well with the Atlantic Multidecadal (~50 years) Oscillation (AMO) [cf. *Virmani and Weisberg*, 2006]. However, as we will report later, there is evidence of increasing trends that may be associated with global warming.

[5] On August 23, 2005, Katrina formed into a tropical depression (TD) from a broad area of low pressure in the central Bahamas. Over the next few days, Katrina rapidly intensified into a category 5 after it crossed south Florida on August 26, 2005 and entered the warm Gulf of Mexico with SST values over 30°C. Katrina made second landfall as a powerful category 4 storm over the southeastern Louisiana and southern Mississippi on August 29, 2005, causing catastrophic flooding to the city of New Orleans and the surrounding areas, resulting in thousands of deaths.

[6] In this study, we focus our analysis on the variations of SST for the Hurricane Katrina case. We note the recent increase in Gulf hurricane activity, especially for intense hurricanes (categories 3, 4, and 5), while studies in the past predicted only minor differences in intense hurricane activity in the Gulf [*Goldenberg et al.*, 2001]. Furthermore, the significant role of SST and the resulting air-sea interactions

[1]Center for Earth Observing and Space Research, School of Computational Sciences, George Mason University, Fairfax, Virginia, USA.

0094-8276/06/2006GL026623

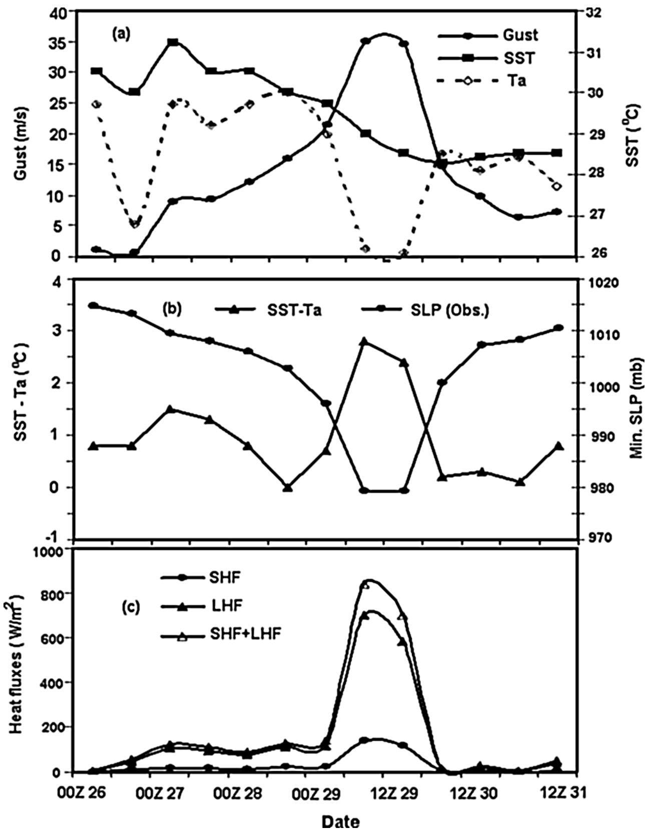

Figure 1. Time series of (a) wind speed, SST, and Ta, (b) sea level pressure (SLP) and sea-air temperature contrast (SST-Ta), and (c) surface sensible heat flux (SHF) and latent heat flux (LHF) from buoy 42040 observations.

associated with the intensification of Katrina are investigated, through the combination of satellite and buoy observations along with numerical model simulations.

2. Data and Methodology

[7] The following data and methodology apply in our study:

2.1. Data

[8] a. SST from the tropical rainfall measuring mission (TRMM) microwave imager (TMI) at 25 km 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.

[9] b. 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. Methodology

[10] In order to investigate the impact of warm SSTA on Katrina's intensity variations, using the latest PSU/UCAR mesoscale model MM5 (version 3.7), two control experiments were designed. In the first experiment, SST data from the TMI observations on August 26, 2005 were used as the model's initial conditions (hereafter referred to as fixed SST or FSST). In the second experiment, a uniform 1.5°C anomaly was added to FSST in order to capture the impact of high SST anomaly on the hurricane's characteristics (referred to hereafter as FSST + 1.5). We performed a 96-h simulation initialized at 00Z August 26, 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 other model's initial and lateral boundary conditions were obtained from the NOAA NCEP GFS (Global Forecasting System) 1° × 1° global analysis. A bogus vortex representing the inner circulation of Katrina was used in the model initial conditions [*Goerss and Jefferies*, 1994; *Zhu et al.*, 2004]. In order to test the effect of pre-existing warm SST, SST was held unchanged during the simulations.

3. Warm Gulf Waters and Hurricane Katrina

[11] As shown in Figure 1, the NDBC buoy 42040 observations at South of Dauphin Island, AL (29.18°N, 88.21°W), located northeast of Katrina's track (Figure 2a shows the location of the buoy with a red star), indicated SST over 30°C in advance of about two days before Katrina reached its strongest intensity or the maximum wind speed (gust). However, the increase of wind speed associated with Katrina's intensification resulted in the decrease of SST. As a result of evaporative cooling in the near-surface environment under warm SST (at least 27°C) conditions, the surface air temperature (Ta) decreased significantly (Figure 1a) [*Cione et al.*, 1999] and the sea-air temperature difference (SST-Ta) reached its largest value at the time of the peak hurricane intensity (Figure 1b) [*Shay et al.*, 2000]. The increase in air-sea temperature contrast induced the strengthening of atmosphere-ocean heat flux exchange. We have computed the surface heat fluxes from the buoy observations, including sensible heat flux (SHF) and latent heat flux (LHF) as follows:

$$\begin{aligned} SHF &= \rho_a C_p C_s U_{10}(SST - T_a) \\ LHF &= \rho_a L C_E U_{10}(q_s - q_a) \end{aligned} \quad (1)$$

where q_s is the specific humidity ($g \cdot kg^{-1}$) of the water surface, q_a is the specific humidity of the air near the surface, U_{10} is the surface wind speed (m/s) at 10m height, L is the latent heat of vaporization ($M\ J \cdot kg^{-1}$), and ρ_a is the surface air density ($kg \cdot m^{-3}$), Cp is the specific heat of air, Cs and C_E are the exchange coefficients. The calculated SHF and LHF, with the use of constant exchange coefficients (Cs = 0.9e − 3 and C_E = 1.35e − 3), are the strongest at the time of maximum hurricane intensity (Figure 1c) due to the atmosphere-ocean energy exchange, which causes storms to receive energy from warm oceans for further intensification.

[12] From the buoy observations, it is found that the storm intensity changes are well correlated with the sea-air temperature contrast (SST-Ta) and surface heat fluxes over the time. However, buoy stations are sparse and unevenly distributed. From the numerical model (MM5) simulations, the spatial distribution of the maximum LHF values at the intense stages (category 3 and up) was found to be located at the right side of the storm track (Figure 2a), where winds were also usually stronger (Figure 2a) and most clouds and precipitation develop [*Zhu et al.*, 2004]. LHF is believed to

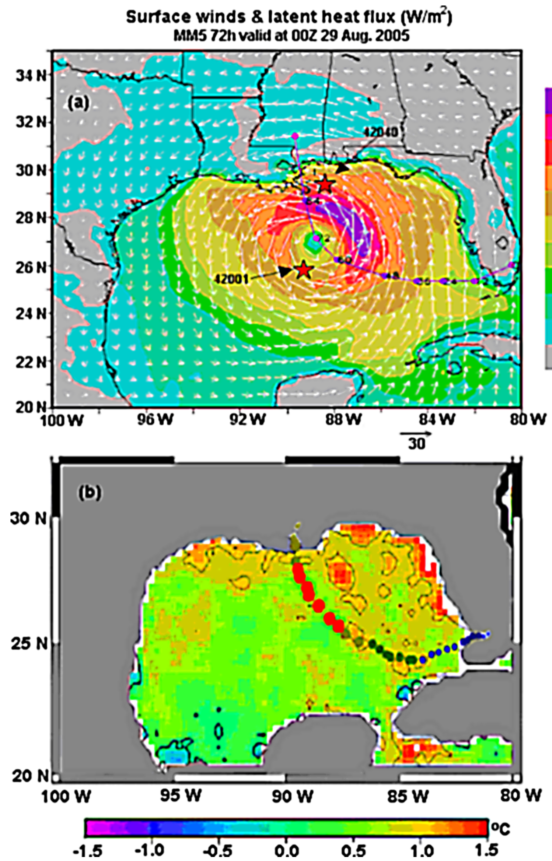

Figure 2. (a) MM5 simulated track, surface winds (vectors) and LHF (W/m^2) at 72 h simulation valid at 00Z 29, August 2005. The locations of buoys 42040 and 42001 are indicated with red stars. (b) Weekly mean (ending on August 27, 2005) SST anomaly in relative to 8-year (1998–2005) average and the circles of different colors indicate the observed track and intensity of Hurricane Katrina.

be one of the major drivers in the hurricane energy systems and plays a vital role in development and intensification of tropical cyclones (TC) [*Guinn and Schubert*, 1993; *Bender and Ginis*, 2000; *Hong et al.*, 2000; *Shay et al.*, 2000; *Gautam et al.*, 2005].

[13] Satellite observations show the SST was unusually warm and around 30°C over the entire Gulf before Katrina's perturbation [*Scharroo et al.*, 2005]. At the same time, the SSTA from the TMI observations was more than 1°C along the hurricane track and its right side (Figure 2b). Considering the large heat capacity of the ocean, this anomaly is very significant. It has been shown that relatively modest changes in SST of order 1°C can effectively alter the maximum total enthalpy (latent plus sensible heat flux) by 40% or more [*Cione and Uhlhorn*, 2003]. Katrina underwent rapid intensification into category 5 when it moved across the Gulf with high SSTA to the right side of its track (also at the location of the maximum LHF). This may imply high SSTA at the right side of the storm track may be a very important factor for hurricane intensification.

[14] The model simulations indicated that the maximum LHF was always located at the northeastern quadrant of the storm track, at least during the intense stages (category 3 and up), primarily due to the ambient flow relative to the storm motion and diabetic heating resulted from the spatial distribution of SSTA. Also, time series of LHF always shows the largest value at the time of the hurricane's maximum intensity.

[15] From equation (1), we can see that LHF depends on both wind speed and SST, as q_s is calculated from SST. Increase in wind speed also enhances the LHF. In order to distinguish the effect of SST on the LHF from wind speed, we performed two numerical experiments in which all other conditions, including winds, were identical, but only the SSTs were different. As consistent with the buoy observations (Figure 1c), numerical model simulations show that when the LHF increased and peaked during August 28 and 29, 2005, Katrina received and accumulated energy through the ocean-atmosphere energy exchange and the central sea level pressure (SLP) reached its lowest value and Katrina attained its strongest intensity (Figure 3). From these two experiments with the same wind speed but different SSTs, we can clearly identify the effects of warm SST inducing significant increases in LHF, especially at the stages when Katrina underwent rapid intensification (Figure 3). While the difference in the minimum SLP between the two experiments is not evident until the 48-h simulation, when the storm began to receive more energy supply through the air-sea interaction processes (Figure 3), this is consistent with the buoy observations (Figure 1).

[16] In order to validate the model simulations, we have also calculated surface LHF from buoy 42001 observations according to equation (1). The exchange coefficient C_E in equation (1) reflects the efficiency of the vertical exchange

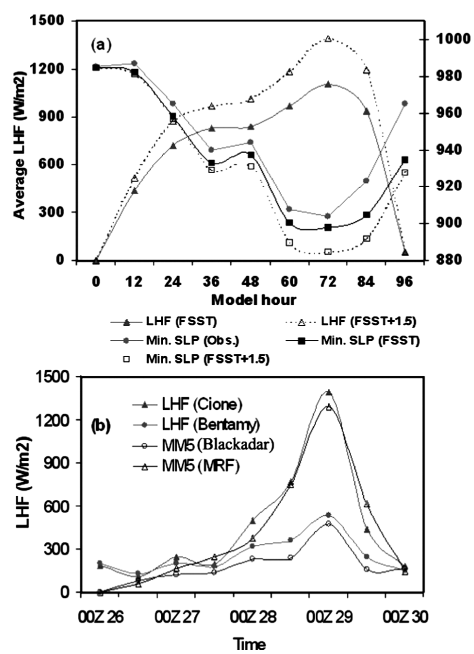

Figure 3. (a) Time series of MM5 simulated area-averaged (400 km × 400 km over the inner region centered on the eye) LHF with the MRF PBL scheme and minimum SLP from the two numerical experiments, and the observed minimum SLP. (b) Comparison of LHF values from buoy 42001 observations using exchange coefficients from *Cione et al.* [1999] and *Bentamy et al.* [2003] methods and MM5 simulations with Blackadar and MRF PBL schemes.

of water vapor and energy flux and is affected by the stability of the surface air. Several studies show that C_E depends on wind speed and different empirical relationships [*Liu et al.*, 1979; *Large and Pond*, 1982; *Cione et al.*, 1999; *Bentamy et al.*, 2003], while *Emanuel* [2005] suggests the dependence of C_E on temperature. Here, we performed two experiments: In one experiment, C_E was determined under relatively high wind conditions >20 m/s and increase linearly with wind speed [*Cione et al.*, 1999], referred as the Cione method here:

$$C_E = (0.75 + 0.067U_{10})*10^{-3} \tag{2}$$

[17] While in another method, C_E decreases with wind speed [*Bentamy et al.*, 2003], referred as the Bentamy method here.

$$C_E = \left(a\exp[b(U_{10}+c)] + \frac{d}{U_{10}} + 1\right)*10^{-3} \tag{2'}$$

Where a = −0.146, b = −0.292, c = −2.206648, and d = 1.6112292.

[18] The LHF values from the Bentamy method, during the maximum hurricane intensity (category 5), are almost half compared to that from the Cione method, while the differences during other times are small. The LHF values from numerical model MM5 simulations depend on the PBL schemes used. The Blackadar and Medium-Range Forecast (MRF) schemes are selected for tests here; since they have nearly identical representations of surface fluxes except for the exchange coefficients or the definition of the non-dimensional stability functions are different. The LHF values produced by the Blackadar PBL scheme [*Zhang and Anthes*, 1982] are almost twice as low as those from the MRF PBL scheme at the time of the maximum intensity, while the differences during other stages are not evident. As a result, the simulated intensity from the Blackadar PBL scheme is weaker than that from the MRF scheme (not shown). It is found that MM5 simulated LHF from the Blackadar PBL scheme is close to that calculated from the buoy observations using the C_E decreasing with the wind speed (the Bentamy method), while the MRF PBL scheme is close to the Cione method with the C_E increasing with the winds (Figure 3b). Previous study by *Braun and Tao* [2000] also showed the remarkable sensitivity of Hurricane Bob (1991) to several PBL schemes in the MM5 and suggested the dependence of simulated intensity on surface exchange coefficients for heat and momentum or the parameterization of surface fluxes. A special PBL model may be needed especially for hurricane case.

[19] Nevertheless, what we want to emphasize here is that no matter what method or PBL scheme is used, the spatial and temporal distributions of LHF are found to be similar. The maximum LHF is always located to the right side of the storm track at its intense stages, coincident with the location of high warm SSTA. Time series of LHF always shows the largest value at the time of hurricane's maximum intensity.

4. Summary and Discussions

[20] Remarkable resemblance is found between SSTA and the major hurricane activities over the Gulf. High SSTA played an important role in the recent increase of intense hurricane activity over the Gulf, especially after 1995. However, the intensification of individual hurricanes may not be spatially and temporally coincident with the distribution of warm waters or high SST. This may be due to the fact that in addition to warm SST, the spatial location of high SST anomaly over the open ocean with respect to the storm track is another significant factor.

[21] Observations show Katrina intensified when it entered the warm Gulf with SST over 30°C. SST is found to increase in advance of the intensification of Hurricane Katrina, also confirmed by numerical simulations. This is because it may need some time for a tropical cyclone to accumulate energy for further intensification. High SSTA at the northeastern quadrant of the storm track over the Gulf induced significant increases in surface heat fluxes and appears to have played a vital role in Katrina's intensification. Our present analysis combining numerical model simulations together with satellite and buoy observations shows the significant impact of anomalous warm Gulf waters on the rapid intensification of Hurricane Katrina and the role of high SSTA in governing the air-sea interactions associated with the intensification of Katrina into a category-5 hurricane.

[22] **Acknowledgments.** This work was supported by the VAccess/MAGIC project funded by the NASA's Science Applications Program, and the NSF from grant NSF0543330. We are grateful to the reviewers for their thorough review and helpful comments.

References

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

Bentamy, A., K. B. Katsaros, A. M. Mestas-Nuñez, W. M. Drenaan, E. B. Forde, and H. Roquest (2003), Satellite estimate of wind speed and latent heat flux over the global oceans, *J. Clim.*, *16*, 637–656.

Bove, M. V., J. J. O'Brien, J. B. Elsner, C. W. Landsea, and X. Niu (1998), Effect of El Niño on U.S. landfalling hurricanes, revisited, *Bull. Am. Meteorol. Soc.*, *79*(11), 2477–2482.

Bracken, W. E., and L. F. Bosart (2000), The role of synoptic-scale flow during tropical cyclongenesis over the North Atlantic Ocean, *Mon. Weather Rev.*, *128*, 353–376.

Braun, S. A., and W. K. Tao (2000), Sensitivity of high-resolution simulations of Hurricane Bob (1991) to planetary boundary layer parameterizations, *Mon. Weather Rev.*, *128*, 3941–3961.

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

Cione, J. J., P. G. Black, and S. H. Houston (1999), Surface observations in the hurricane environment, *Mon. Weather Rev.*, *128*, 1550–1561.

Elsner, J. B., A. B. Kara, and M. A. Owens (1998), Fluctuations in North Atlantic hurricane frequency, *J. Clim.*, *12*, 427–437.

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

Emanuel, K. A. (1988), The maximum intensity of hurricanes, *J. Atmos. Sci.*, *45*, 1143–1155.

Emanuel, K. A. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686–688.

Fisher, E. L. (1958), Hurricane and the sea surface temperature field, *J. Meteorol.*, *15*, 328–333.

Gautam, R., G. Cervone, R. P. Singh, and M. Kafatos (2005), Characteristics of meteorological parameters associated with Hurricane Isabel, *Geophys. Res. Lett.*, *32*, L04801, doi:10.1029/2004GL021559.

Goerss, J. S., and R. A. Jefferies (1994), Assimilation of synthetic tropical cyclone observations into the Navy Operational Global Atmospheric Prediction System, *Weather Forecasting*, *9*, 557–576.

Goldenberg, S. B., and L. J. Shapiro (1996), Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity, *J. Clim.*, *9*, 1169–1187.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity, causes and implications, *Science*, *293*, 474–479.

Gray, W. M. (1968), Global view of the origin of tropical disturbances and storms, *Mon. Weather Rev.*, *96*, 669–700.
Gray, W. M. (1984), Atlantic seasonal hurricane frequency: part I: El Niño and 30 mb quasi-biennial oscillation influences, *Mon. Weather Rev.*, *115*, 1649–1668.
Guinn, T. A., and W. H. Schubert (1993), Hurricane spiral bands, *J. Atmos. Sci.*, *50*, 3380–3403.
Holland, G. J. (1997), Maximum potential intensity of tropical cyclones, *J. Atmos. Sci.*, *54*, 2519–2541.
Hong, X., S. W. Chang, S. Raman, L. K. Shay, and R. Hodur (2000), The interaction between Hurricane Opal (1995) and a warm core ring in the Gulf of Mexico, *Mon. Weather Rev.*, *128*, 1347–1365.
Knutson, T. R., and R. E. Tuleya (2004), Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization, *J. Clim.*, *17*, 3477–3495.
Large, W. G., and S. Pond (1982), Sensible and latent heat flux measurements over the ocean, *J. Phys. Oceanogr.*, *12*(5), 464–482.
Leipper, D. (1967), Observed ocean conditions and hurricane Hilda, 1964, *J. Atmos. Sci.*, *24*, 182–196.
Liu, W. T., K. B. Katsaros, and J. A. Businger (1979), Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface, *J. Atmos. Sci.*, *36*, 1722–1735.
McAdie, C. J., and M. B. Lawrence (2000), Improvements in tropical cyclone track forecasting in the Atlantic basin, 1970–98, *Bull. Am. Meteorol. Soc.*, *81*, 989–998.
Scharroo, R., W. H. F. Smith, and J. L. Lillibridge (2005), Satellite altimetry and the intensification of Hurricane Katrina, *Eos Trans. AGU*, *86*(40), 366.
Shapiro, L. J., and S. Goldenberg (1998), Atlantic sea surface temperature and tropical cyclone formation, *J. Clim.*, *11*, 578–590.
Shay, L. K., G. J. Goni, and P. G. Black (2000), Effects of a warm oceanic feature on Hurricane Opal, *Mon. Weather Rev.*, *128*, 1366–1383.
Tsutsui, J. (2002), Implications of anthropogenic climate change for tropical cyclone activity: A case study with the NCAR CCM2, *J. Meterol. Soc. Jpn.*, *80*(1), 45–65.
Vitart, E., J. L. Anderson, and W. F. Stern (1999), Impact of large-scale circulation on tropical storm frequency, intensity, and location, simulated by an ensemble of GCM integrations, *J. Clim.*, *12*, 3237–3254.
Virmani, J. I., and R. H. Weisberg (2006), The 2005 hurricane season: An echo of the past or a harbinger of the future?, *Geophys. Res. Lett.*, *33*, L05707, doi:10.1029/2005GL025517.
Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang (2005), Changes in tropical cyclone number, duration and intensity in a warming environment, *Science*, *309*, 1844.
Wong, M. L. M., and J. C. L. Chan (2004), Tropical cyclone intensity in vertical wind shear, *J. Atmos. Sci.*, *61*, 1859–1876.
Zhang, D., and R. A. Anthes (1982), A high-resolution model of the planetary boundary layer: Sensitivity tests and comparisons with SESAME-79 data, *J. Appl. Meteorol.*, *21*(11), 1594–1609.
Zhu, T., D. L. Zhang, and F. H. Weng (2004), Numerical simulation of hurricane Bonnie (1998): part I: Eyewall evolution and intensity changes, *Mon. Weather Rev.*, *132*, 225–241.

Z. Boybeyi, G. Cervone, R. Gautam, M. Kafatos, D. Sun, and R. Yang, Center for Earth Observing and Space Research, School of Computational Sciences, George Mason University, Fairfax, VA 22030, USA. (dsun@gmu.edu)