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Unusually warm sea surface temperatures in the tropical North Atlantic during 2005

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[1] The 2005 Atlantic hurricane season was the most active and destructive on record. One of the factors that likely contributed to this record-breaking season was the presence of exceptionally warm sea surface temperatures (SST) in the tropical North Atlantic. Two long term moored buoys were well positioned to record the anomalous atmospheric and oceanic conditions associated with this warm event. Here we present results from a mixed layer heat budget analysis based on measurements from these buoys. We find that the primary cause of the anomalous warming was a weakening of the northeasterly trade winds and an associated decrease in latent heat loss from the ocean. Important secondary factors include changes in shortwave radiation and horizontal oceanic heat advection.

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1. Introduction

[2] Most of the deadliest and costliest hurricanes in the Atlantic basin form over the "Main Development Region" (MDR) located between 10°N–20°N, 20°W–80°W in the tropical North Atlantic Ocean and Caribbean Sea [*Goldenberg and Shapiro*, 1996]. Empirical studies have identified a correlation between elevated SST in the tropical North Atlantic and an increase in hurricane frequency and intensity [e.g. *Goldenberg et al.*, 2001], and theoretical studies suggest that SST in the MDR should affect incipient cyclones by altering the rate at which latent and sensible heat is transferred to the atmosphere [e.g., *Emanuel*, 1986]. Documenting a direct causal link between SST and hurricane activity is complicated though, because anomalously warm SST in the MDR is also associated with a decrease in vertical wind shear, which aids tropical storm and hurricane development [e.g., *Wang et al.*, 2006]. Nonetheless, both observations and theory suggest that SST is an important environmental parameter that needs to be better understood for hurricane research and forecasting.

[3] During 2005 tropical North Atlantic SST reached its warmest levels in at least 150 years (Figure 1). The peak SST anomalies occurred during March–July in conjunction with anomalously low vertical wind shear. These factors contributed to the formation of an unprecedented seven tropical storms before the end of July, a record two of which reached category 4 intensity (max. sustained winds >59 m s^{-1}) [*Shein*, 2006]. Part of the 2005 anomalous warmth has been linked to a combination of natural multidecadal variability and climate change [*Goldenberg et al.*, 2001; *Mann and Emanuel*, 2006]. SST in 2005 was exceptionally warm even with respect to the past decade's climatology, however, suggesting that shorter time scale variability also played an important role (Figure 2). Results from an atmospheric reanalysis suggest that most of the anomalous warming during 2004 and 2005 was due to a weakening of the subtropical high pressure system and an associated decrease in wind-induced latent heat loss [*Virmani and Weisberg*, 2006]. In this study we use atmospheric and oceanographic measurements from two moored buoys in the northwestern tropical Atlantic, together with satellite-derived surface fields and a mixed layer depth climatology, to investigate the causes of the abnormally warm SST in 2005.

2. Data and Methodology

[4] We use data from the northernmost moored buoy site of the Pilot Research Array in the Tropical Atlantic (PIRATA) [*Servain et al.*, 1998] located at 15°N, 38°W (Figure 2). Measurements at this location, begun in 1998 and continued through the present, include subsurface temperature and salinity, air temperature, relative humidity, wind velocity, shortwave radiation, and precipitation. From 1998 to June 2005, ocean temperature was measured at 11 depths between 1 m (i.e. bulk SST) and 500 m, with 20-m spacing in the upper 140 m, while salinity was measured at 1 m, 20 m, 40 m, and 120 m. Beginning in July 2005, additional temperature measurements have been made at 10 m and 13 m and additional salinity measurements at 10 m and 60 m. Air temperature and relative humidity are measured at a height of 3 m above sea level, shortwave radiation and rainfall are measured at 3.5 m, and wind velocity at 4 m. Daily averages are transmitted to shore in real-time, while high temporal resolution data (1 to 10 minute averages) are internally recorded. Here we use the daily averaged data for the time period 1998–2005.

[5] We also use surface measurements from a moored buoy of the Northwest Tropical Atlantic Station for air-sea flux measurement (NTAS), located at 15°N, 51°W (Figure 2). Available measurements include bulk SST (measured at a depth of 1.7 m), air temperature, relative humidity, wind velocity, shortwave radiation, incoming longwave radiation, barometric pressure, and precipitation (all measured at heights between 2.5 and 3.5 m). Hourly data are available from the Upper Ocean Processes group at Woods Hole Oceanographic Institute for the period March

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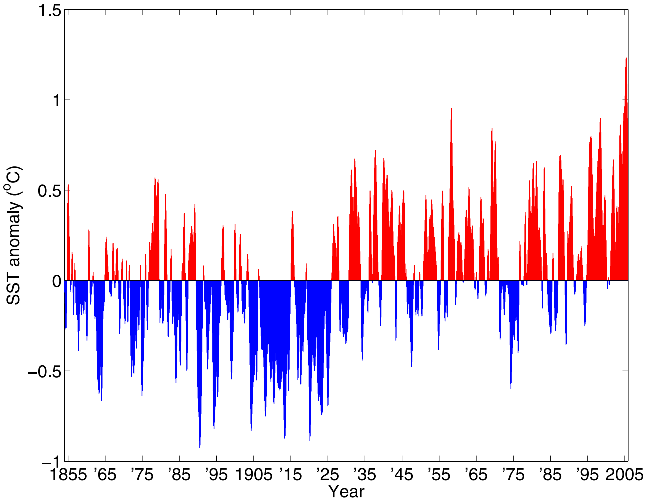


Figure 1. Interannual anomalies (with respect to 1854–2005 mean seasonal cycle) of *Smith and Reynolds* [2004] SST averaged in the tropical North Atlantic (10°N–20°N, 30°W–60°W; see Figure 2 for location). Here and in subsequent figures, anomalies have been smoothed with two passes of a 3-month running mean filter.

2001 – February 2006 and have been averaged to daily means.

[6] We use a variety of satellite and reanalysis data sets in order to examine the large-scale surface structure of the 2005 warm event and to aid in the heat budget analyses at the buoy locations. We have obtained satellite-based estimates of SST, wind velocity, and sea level. SST is available from the Tropical Rainfall Measuring Mission (TRMM) Microwave/Imager (TMI) on a 0.5° × 0.5° × daily grid beginning December 1997. Surface wind velocity is obtained from the SeaWinds scatterometer onboard the QuikSCAT satellite, available on a 0.25° × 0.25° × daily grid beginning July 1999. We also use NCEP/DOE reanalysis-2 (hereafter NCEP2) [*Kanamitsu et al.*, 2002] surface atmospheric pressure and air temperature on a 2° × 2° × daily grid and *Smith and Reynolds* [2004] SST on a 2° × 2° × monthly grid for 1854–2005. Each of the aforementioned data sets, with the exception of the *Smith and Reynolds* [2004] SST, has been regridded to a 1° × 1° × daily grid.

[7] In order to estimate geostrophic currents, we use altimeter sea level anomaly data from the ERS-1/2, TOPEX/Poseidon, and Jason missions, which is available for 1992–2005 from the CLS Space Oceanography Division. The anomalies are referenced to the 1993–1999 mean and are mapped according to the methodology of *Ducet et al.* [2000]. The data are available every 7 days on a $\frac{1}{3}^\circ \times \frac{1}{3}^\circ$ grid. We have added the 1993–1999 mean dynamic topography [*Rio and Hernandez*, 2004] to the sea level anomaly data in order to recover the total dynamic topography for estimation of the geostrophic surface currents. We have obtained monthly mean climatological mixed layer depths from *Montégut et al.* [2004], available on a 2° × 2° grid and based on the criterion of a 0.03 kg m^{-3} density increase from a depth of 10 m.

[8] To address the causes of the anomalously warm SST in 2005, we consider the oceanic mixed layer heat balance

$$\rho c_p h \frac{\partial T}{\partial t} = q_0 - \rho c_p h \mathbf{v} \cdot \nabla T + \epsilon \tag{1}$$

[9] The terms represent, from left to right, mixed layer heat storage, surface heat flux, horizontal mixed layer heat advection, and the collection of terms that we cannot easily estimate. Here h is the depth of the mixed layer and T and $\mathbf{v}$ are temperature and velocity, respectively, vertically averaged from the surface to a depth of $-h$.

[10] At the NTAS site we estimate mixed layer heat storage with climatological *Montégut et al.* [2004] mixed layer depth (MLD), and we use buoy SST as a proxy for T. At the PIRATA location, where subsurface temperature and salinity data are available from the buoy, we first estimate the isothermal layer depth (ILD) and MLD using criteria of a 0.1°C decrease and a 0.03 kg m^{-3} increase from a depth

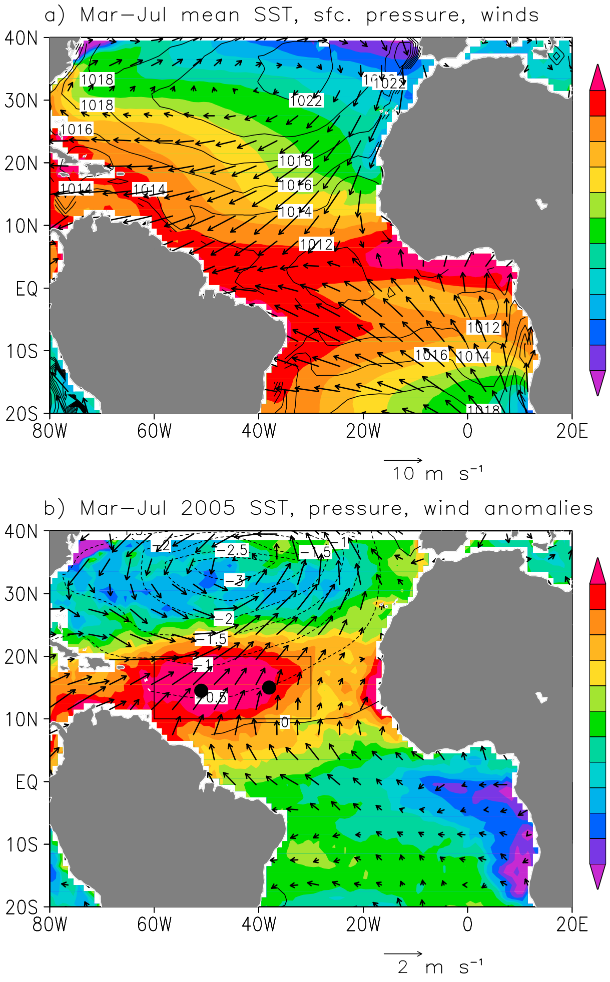


Figure 2. (a) Mean (1999–2005) March–July TMI SST (shaded), NCEP2 surface pressure (contours, hPa), and QuikSCAT wind velocity (vectors, m s^{-1}). (b) March–July 2005 anomalies (with respect to 1999–2005 mean seasonal cycle) of SST, surface pressure, and wind velocity. Closed circles in Figure 2b represent the positions of the moored buoys used in this study. Box encloses the region used to form the index shown in Figure 1.

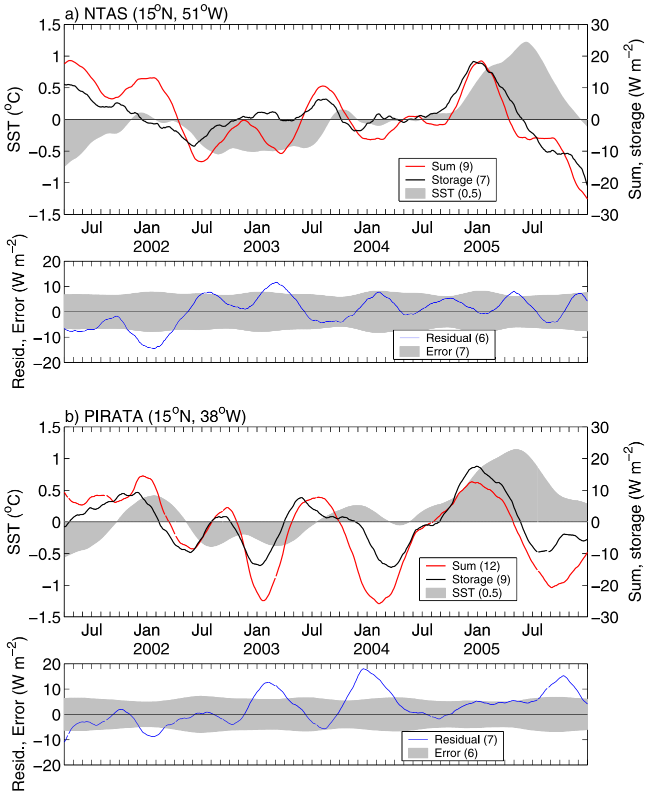


Figure 3. Top plots show anomalous SST (grey), mixed layer heat storage (black), and sum of net surface heat flux and horizontal advection (red) at the (a) NTAS and (b) PIRATA buoy locations. Here and in Figure 4 anomalies are with respect to the 2001–2005 and 1999–2005 mean seasonal cycles for NTAS and PIRATA, respectively. Bottom plots show error estimates for the storage-minus-sum residual (grey) and the actual residual (blue). The standard deviation for each term (in W m^{-2} for sum, storage, residual, and error; and °C for SST) is shown in parentheses.

of 10 m, respectively. For temperatures and salinities typically found at the PIRATA site (~26°C and ~36.5 psu, respectively) these criteria are identical when salinity does not vary with depth. Gaps in the SST record at the PIRATA site (mainly during the first half of 2005) are replaced with 20 m temperature after application a seasonal mean bias correction. Missing subsurface temperature data (mainly at 80 and 100 m during late 2003 and early 2004) are filled with vertical linear interpolation.

[11] Due to gaps in the salinity record, buoy MLD is available only during 2000–2001 and the second half of 2005. We therefore use the difference between the ILD and the daily mean seasonal cycle of barrier layer thickness (BLT; defined as ILD − MLD), repeated for each year, as a proxy for MLD at the PIRATA site. The BLT at this location ranges from 20–30 m in boreal winter to <5 m during the remainder of the year.

[12] The surface heat flux consists of latent and sensible heat loss, net longwave radiation emission, and shortwave radiation absorption. Latent and sensible heat loss are estimated from the Coupled Ocean-Atmosphere Response Experiment (COARE) bulk flux algorithm [*Fairall et al.*, 2003] with daily buoy estimates of SST, air temperature, relative humidity, and wind speed. Due to possible low-frequency drifts in air temperature during some deployments at the PIRATA site, we have replaced the buoy air temperature with NCEP2 air temperature before computation of the turbulent heat fluxes. The results of *Jiang et al.* [2005] indicate that errors in latent heat flux associated with the substitution of NCEP2 air temperature for Tropical Atmosphere-Ocean buoy air temperature are negligible (~1 W m^{-2}).

[13] At the NTAS site incoming longwave radiation is measured directly at the buoy. We therefore estimate net longwave radiation emission at this location as $Q_{lw} = \epsilon\sigma T_s^4 - Q_0$, where Q_0 is the incoming longwave radiation, $\epsilon = 0.97$ is the emissivity, and T_s is SST. At the PIRATA site we estimate net longwave radiation emission from the *Clark et al.* [1974] bulk formula following the methodology of *Foltz and McPhaden* [2005].

[14] The net surface shortwave radiation is available directly from the moorings, assuming an albedo of 6%. Following *Wang and McPhaden* [1999], we model the amount of shortwave radiation penetrating the mixed layer as $Q_{pen} = 0.47 Q_{surf} e^{-0.04h}$, where Q_{surf} is the surface shortwave radiation and h is the depth of the mixed layer. At both moorings we anticipate that the buildup of Saharan dust on the shortwave radiation sensors may affect the measurements [*Medovaya et al.*, 2002]. Indeed, the shortwave radiation record from the PIRATA buoy shows discontinuous jumps of up to 50 W m^{-2} immediately following periods when the buoy was serviced and the radiometer was cleaned. We eliminate all jumps using the methodology described by *Foltz and McPhaden* [2005]. Due to uncertainty associated with this method that may exceed the actual amplitude of the low-frequency shortwave radiation anomalies, we filter the corrected shortwave radiation time series to remove variability with periods >2 years.

[15] We anticipate that dust buildup may have a similar effect on the SWR and LWR measurements at the NTAS site but were unable to identify any obvious jumps in the records at this location. However, the full SWR and LWR records exhibit unrealistically large low-frequency fluctuations that vary in phase and significantly degrade the results presented in the next section. We have therefore removed all low-frequency variability (periods >2 years) from the SWR and LWR records at the NTAS site.

[16] To estimate horizontal mixed layer heat advection we use buoy measurements of surface wind velocity along with satellite SST and sea level to estimate mixed layer currents following the methodology of *Bonjean and Lagerloef* [2002]. These velocity estimates, which include both Ekman and geostrophic components, are then multiplied by the previously described MLD estimates and satellite SST gradients calculated as a centered difference over a distance of 2°.

[17] We have neglected vertical entrainment and diffusion since we cannot reliably estimate them. The results of *Carton et al.* [1996] and *Foltz and McPhaden* [2006] indicate that, on interannual time scales, these terms are unlikely to be important in the tropical North Atlantic in comparison to the other terms in (1). The relative unim-

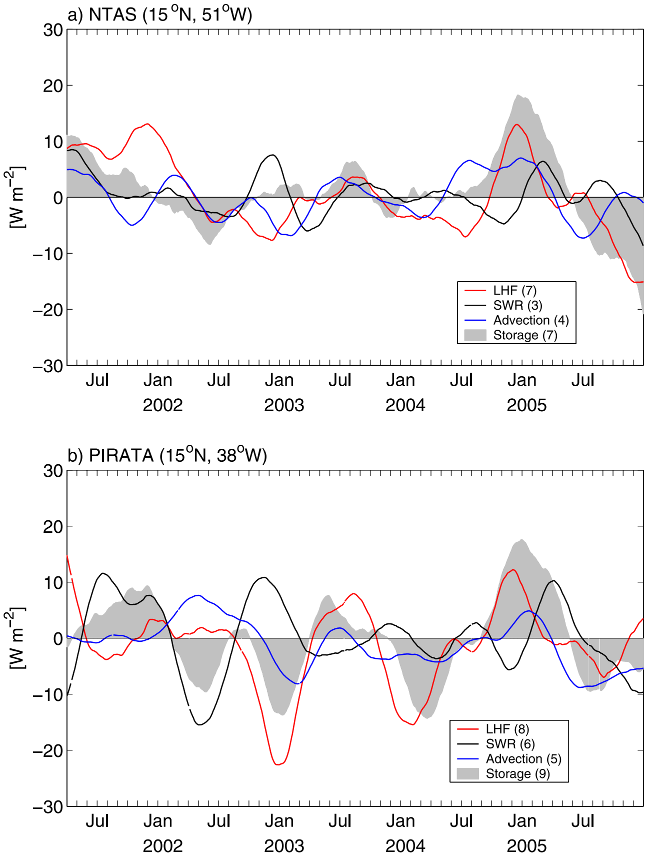


Figure 4. Anomalous latent heat flux (red), absorbed shortwave radiation (black), horizontal advection (blue), and mixed layer heat storage (grey) at the (a) NTAS and (b) PIRATA locations. The standard deviation for each term (in W m^{-2}) is shown in parentheses.

portance of these terms is most likely due to the combination of a thick mixed layer (>40 m), the presence at times of significant barrier layers, and annual mean downwelling at the base of the mixed layer at these locations.

[18] Uncertainties for all terms in equation (1) that we estimate directly (surface fluxes, horizontal advection) are calculated using instrumental errors for the PIRATA and NTAS sensors, available from http://www.pmel.noaa.gov/tao/proj_over/sensors.shtml and http://uop.whoi.edu/techdocs/techdoc.htm, respectively, and analysis errors for mixed layer currents, available from http://www.esr.org/%7Ebonjean/oscar/global_validation/index_files/Atlantic.htm. We also use error estimates for TMI SST that are based on comparisons to in situ measurements [*Gentemann et al.*, 2004].

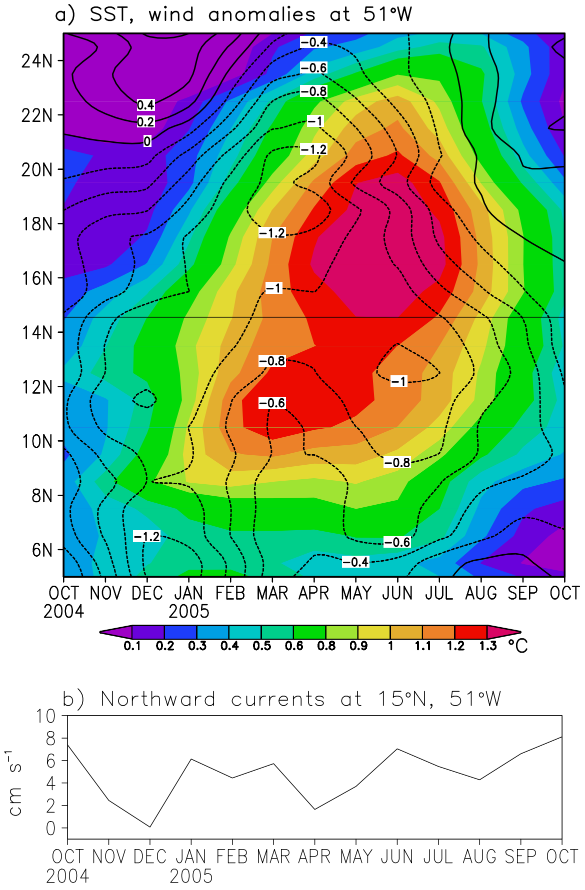
3. Results

[19] The climate of the tropical North Atlantic is influenced by a region of high atmospheric pressure to the north and a trough of low pressure overlying a band of warm SST to the south. Surface winds accelerate southwestward from the subtropical high, acquiring their greatest speed in the northwestern tropical Atlantic (Figure 2a). Previous studies suggest that SST variability in this region is driven primarily by wind-induced latent heat loss, with shortwave radiation and oceanic heat advection playing secondary roles [*Carton et al.*, 1996; *Tanimoto and Xie*, 2002; *Foltz and McPhaden*, 2006].

[20] A substantial decrease in the strength of the trade winds occurred in 2004 and early 2005. The abnormally low wind speed was associated with considerable weakening of the subtropical high pressure system centered in the North Atlantic (Figure 2). Coincident with these atmospheric circulation changes was intense anomalous heating of the underlying ocean. By boreal spring and summer 2005, SST anomalies of ∼1°C covered most of the northwestern tropical Atlantic (Figure 2b). Both the NTAS and PIRATA buoys were positioned near the center of the warm anomaly.

[21] At the PIRATA and NTAS sites, anomalous mixed layer warming was most intense between the end of 2004 and the middle of 2005, resulting in maximum SST anomalies of more than 1°C in May 2005 (Figure 3). At both locations most of the anomalous heating during early 2005 can be attributed to the combination of surface heat fluxes and horizontal mixed layer heat advection (Figure 3). Anomalous changes in mixed layer heat content prior to the 2005 warm event can also be explained reasonably well by the sum of net surface heat flux and advection. The storage-sum correlations for the full NTAS (2001–2005) and PIRATA (1998–2005) records are 0.8 (significant at the 1% level at both sites). The standard deviations of the sum and storage anomalies are of similar magnitude, though at both sites the standard deviation of the sum exceeds that of the storage by about 30%. Discrepancies are likely due mainly to uncertainties in mixed layer depth and heat storage, which are difficult to quantify and are not included in the error estimates shown in Figure 3. These uncertainties are associated with our use of a mixed layer depth climatology at the NTAS site, where moored temperature and salinity are not available; and a barrier layer thickness climatology at the PIRATA site, where there are large gaps in the salinity record. Additional uncertainties result from our neglect of vertical entrainment and turbulent diffusion.

[22] At both locations changes in mixed layer heat content are driven primarily by latent heat flux (LHF), with shortwave radiation (SWR) and horizontal heat advection playing important secondary roles (Figure 4). Indeed, LHF, SWR, and horizontal advection all contribute significantly to the development of the warm event in late 2004 and early 2005. In boreal summer 2004 anomalous cooling from LHF nearly balances anomalous warming due to meridional advection, resulting in very limited mixed layer warming at the NTAS site (Figure 4a). A rapid anomalous decrease in wind speed during late 2004 leads to a corresponding decrease in latent heat loss. At the same time, meridional advection continues to warm the mixed layer due to mean northward currents acting on an anomalous SST gradient, with higher temperature to the south (Figure 5). As a result, the rate of increase in mixed layer heat content reaches a maximum in December 2004. In early 2005, increased evaporative cooling associated with the rapidly warming SST counteracts the warming due to enhanced SWR and reduced wind-induced latent heat loss, leading to a reduction in the rate of mixed layer heat content increase. Meridional advection continues to warm the mixed layer


a) SST, wind anomalies at 51°W

b) Northward currents at 15°N, 51°W

Figure 5. (a) Latitude-time plot of anomalies (with respect to 1999–2005 mean seasonal cycle) of TMI SST (shaded) and QuikSCAT wind speed (contours, m s^{-1}) along 51°W. Solid horizontal line indicates the position of the NTAS buoy. (b) Estimated meridional mixed layer velocity at the NTAS buoy location.

until April, when the warmest SST anomalies shift to the north of the NTAS buoy (Figure 5). The mean northward currents induce anomalous mixed layer cooling during April–September, halting the growth of anomalously warm SST. The evolution of the warm event at the PIRATA site is qualitatively similar, with differences mainly in the magnitudes of the LHF, SWR, and advection anomalies.

[23] The unusual strength of the 2005 warm event and its potential impact on the early hurricane season resulted from a combination of factors. The strong positive anomaly in heat storage rate and the associated rapid anomalous warming during late 2004 was caused by positive anomalies of LHF and horizontal advection. The persistence of anomalously warm SST into boreal summer 2005 was due in large part to positive SWR anomalies during early 2005, which may have resulted from a positive feedback between low-level cloudiness and the exceptionally warm SST [*Tanimoto and Xie*, 2002]. Finally, the positioning of the warmest SST anomalies in the northwestern tropical Atlantic, where climatological SST is warmest (Figure 2), combined with the strong spatial coherence of the warm SST anomalies, likely aided the record generation and intensification of tropical cyclones during June and July 2005.

4. Summary

[24] The record-breaking Atlantic hurricane season of 2005 occurred in conjunction with significantly above-normal SST and a weakening of the northeasterly trade winds throughout most of the tropical North Atlantic. Through an analysis of the mixed layer heat budget at two moored buoys in the northwestern tropical Atlantic, we have shown that anomalous mixed layer warming prior to the peak of this event was caused by a combination of anomalies in wind-induced latent heat loss, shortwave radiation, and horizontal oceanic heat advection. Of the three, latent heat loss was the most important, providing anomalous warming throughout the event. Shortwave radiation acted as a weak negative feedback during the early stages of warming and a stronger positive feedback once the warm SST anomaly was well developed, thus tending to prolong the anomalous warming. Horizontal heat advection, due mainly to mean northward currents acting on anomalous SST gradients, reinforced the initial anomalous warming due to wind-induced LHF. Later however, cooling through meridional heat advection played an important role in the rapid termination of the event.

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