The Relative Roles of the Ocean and Atmosphere as Revealed by Buoy Air–Sea Observations in Hurricanes

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ABSTRACT

Results from this multihurricane study suggest that the criticality of the oft-cited 26°C hurricane threshold linked to hurricane maintenance may be more closely associated with atmospheric thermodynamic conditions within the inner core than previously believed. In all cases, a positive sea–air contrast was observed within the storm inner core (i.e., surface ocean temperature greater than surface air temperature), despite the fact that 6% of the hurricanes exhibited sea surface temperatures (SSTs) less than the 26°C. For the storms sampled in this study, inner-core surface dewpoint temperatures never exceeded 26.5°C. This finding may provide an alternate explanation as to the criticality of the 26°C threshold since SSTs *above* 26°C would, in almost all instances, be associated with a positive enthalpy flux condition. Analyses from this study also illustrate that high wind SSTs fluctuate as a function of storm latitude, while inner-core near-surface dewpoint temperatures are much less sensitive to this parameter. As a result, and assuming all other factors to be equal, low-latitude hurricanes would, on average, be expected to experience surface moisture fluxes ~1/3 greater than storms located farther to the north. For systems sampled within the deep tropics, inner-core SST was found to fluctuate much less than surface dewpoint temperature, suggesting that the atmosphere, not the ocean, is more likely to influence the key thermodynamic parameter controlling surface moisture flux for this subset of hurricanes.

1. Introduction

Palmen (1948) first noted that hurricane formation was correlated with SST in excess of 26°C. Since then, many other studies have found similar relationships between ocean surface temperatures and tropical cyclone (TC) formation and/or intensification (e.g., Miller 1958; Byers 1959; Ramage 1959; Perlboth 1967; Gray 1968; Dengler 1997; Rodgers et al. 2000; Dare and McBride 2011). In Leipper and Volgenau's (1972) study they expanded use of the 26°C threshold and devised an upper ocean thermal energy storage diagnostic known as upper ocean heat content (OHC), which is defined as:

$$\mathrm{OHC}(x, y, t) = \rho c_p \int_{z(T=26)}^{0} \Delta T(x, y, z, t)\, dz, \qquad (1)$$

where c_p is the specific heat of water at constant pressure ($4178\,\mathrm{J\,kg^{-1}\,K^{-1}}$), ρ is the average density of the upper ocean ($1026\,\mathrm{kg\,m^{-3}}$), and ΔT is the difference between $T(z)$ and 26°C over the depth interval dz. The units of OHC are typically expressed in $\mathrm{kJ\,cm^{-2}}$ ($10^7\,\mathrm{J\,m^{-2}}$). From (1) above it becomes evident that OHC is only positive when SST exceeds 26°C. Presumably, this stipulation was included in the formulation given earlier findings that hurricanes were rarely observed when the underlying SST was less than 26°C. At temperatures above 26°C, OHC provides a vertically integrated estimate of energy stored within the upper ocean. Over the past decade, researchers have attempted to correlate OHC magnitudes with subsequent changes in TC intensity (e.g., Shay et al. 2000; Hong et al. 2000; Mainelli et al. 2008; Price 2009). While some of these studies have illustrated statistically significant results linking OHC with intensity change, Cione and Uhlhorn (2003) have shown that OHC values are often orders of magnitude greater than maximum surface enthalpy flux values typically observed or estimated within hurricane inner-core environment (Cione et al. 2000; Black et al. 2007; Liu et al. 2011). Cione and Uhlhorn (2003) argued that for the large majority of propagating systems, the magnitude of OHC should not be a limiting factor affecting

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hurricane maintenance or intensification (Fig. 1). In cases where high or low OHC values correlate with observed changes in storm intensity, significant correlations may also exist between OHC and inner-core SST change. In effect, high (low) OHC cases are likely to be a proxy for storm events that exhibit minimal (significant) in-storm ocean cooling.

Instead of using an ocean-only heat storage diagnostic tool to crudely approximate in-storm SST cooling, a more direct method would be to measure and analyze the "qSST − qa_{10m}" term illustrated in (2) below, which represents the primary air–sea thermodynamic control associated with surface moisture flux (L_H):

$$L_H = -\rho U_{10m}[L_v C_e(\mathrm{qSST} - \mathrm{qa}_{10m})]. \tag{2}$$

Here, ρ is the density of air, U_{10m} represents the 1-min wind speed at 10 m, L_v is the latent heat of vaporization at a given temperature, C_e is the dimensionless coefficient of moisture exchange at 10 m, and qSST and qa_{10m} are the saturation specific humidity at the SST and the actual specific humidity of the air at 10 m, respectively. (The units for L_H are W m^{-2}.) By using qSST − qa_{10m} (or "Δq") instead of OHC, the individual contributions that atmospheric (qa_{10m}) and oceanic (qSST) variability each have on hurricane inner-core Δq (and therefore L_H) can be assessed and quantified.

This study will utilize in situ observations obtained from 62 hurricanes spanning 33 seasons to analyze how near-surface atmospheric and oceanic variability potentially impact the "26°C minimum threshold" often linked to hurricane maintenance. In addition, the relative roles the ocean and atmosphere each have in determining inner-core Δq, as well as possible meridional linkages associated with Δq variability will be investigated.

2. 26°C: An important threshold for hurricane maintenance

As previously mentioned, correlations between SST at or exceeding 26°C and hurricane formation and maintenance have been noted since the 1940s (e.g., Palmen 1948). For the large majority of cases, this relationship still holds true today. The widely held presumption associated with this finding, as evidenced by numerous recent TC OHC and/or ocean warm core ring studies (Jacob et al. 2000; Mao et al. 2000; Chan et al. 2001; Goni and Trinanes 2003; Jacob and Shay 2003; Lin et al. 2005, 2008, 2011; Mainelli et al. 2008; Yablonsky and Ginis 2013) is that below 26°C, the amount of stored available energy in the upper ocean is insufficient to maintain a storm at hurricane intensity. As will be shown, results from this study do not support that conclusion and instead suggest that the criticality of 26°C is much more closely tied to near-surface atmospheric conditions typically found within the inner core of most hurricanes.

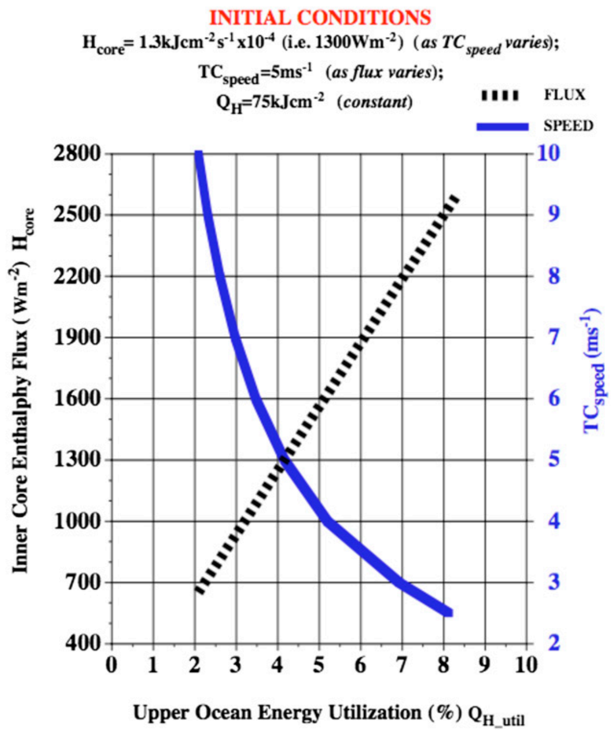

FIG. 1. The percentage of available upper-ocean energy extracted by a tropical cyclone (Q_{H_util}) as a function of inner-core surface enthalpy flux (H_{core}) and storm speed (TC_{speed}). In this illustration, H_{core} was initially held constant at 1300 W m^{-2}, while TC_{speed} varied between 2.5 and 10 m s^{-1}. Then, TC_{speed} was held constant at 5 m s^{-1}, while H_{core} varied between 650 and 2600 W m^{-2}. In all cases hurricane heat potential (aka "heat content") was 75 kJ cm^{-1}. [Note: Illustration initially published in Cione and Uhlhorn (2003).]

It should be noted that observations used in this study were obtained from the Tropical Cyclone Buoy Database (TCBD). The TCBD uses buoy measurements and other storm-specific information associated with Atlantic, Caribbean, and Gulf of Mexico TCs that occurred between 1975 and 2007. In all, the TCBD includes tens of thousands of near-surface observations in a storm-relative framework for over 62 Atlantic, Gulf of Mexico, and Caribbean hurricanes. Many of the observations included in the TCBD were originally obtained from the National Data Buoy Center's (NDBC) quality-controlled online archive buoy database (Gilhousen 1988, 1998). (Details related to platform locations, configurations, sensor descriptions, data accuracy, averaging techniques, and quality control can be found at http://www.ndbc.noaa.gov/.) In addition to information directly obtained from NDBC, the TCBD also incorporates non-air–sea specific data such as storm location, intensity, speed, large-scale shear magnitude, and shear direction for each buoy observation in the database (Cione et al. 2013).

Figure 2a depicts inner-core TCBD air–sea measurements for 22 hurricanes observed between 1975 and 2007, south of 32.5°N. To provide additional context, the location of the buoy platforms associated with these 245 individual observations is shown in Fig. 2b. A representative SST analysis for September (1971–2000) is included in this illustration. Observations from Fig. 2a show that SSTs within the hurricane core (<111 km) exceeded 26°C 94% of the time. This figure also depicts no instances whereby SST was observed to be lower than the 10-m air temperature despite the fact that 15 hurricane cases (~6%) exhibited inner-core SSTs at or below 26°C.

In Table 1, the 245 individual inner-core hurricane observations shown in Fig. 2a are stratified into latitudinal bands. It should be noted that latitude was chosen as the primary stratifying parameter (instead of SST) because of subsequent analyses designed to investigate the relative contributions of atmospheric and oceanic forcing on a key thermodynamic parameter controlling surface moisture flux as tropical systems move from the deep tropics northward. If results were instead sorted by inner-core SST, the variability of the oceanic component would have been explicitly and artificially constrained.

In addition to SST and 10-m air temperature shown in Table 1, information on inner-core surface dewpoint (10-m Td), specific humidity (qSST, 10-m qa), relative humidity (10-m RH), air–sea contrast (SST − 10-m Ta), specific humidity gradient (qSST − 10-m qa), and buoy latitude are provided. Table 1 also includes information on these same parameters over the same latitudinal bands within the ambient hurricane environment (defined to be 4°–5° latitude from the storm center, or 444–555 km). Using these additional data, estimates for inner-core SST cooling ($\mathrm{SST_{IC}} - \mathrm{SST_{amb}}$) were included when available. Here, ''IC'' represents inner-core SSTs (inside 111 km) while ''amb'' refers to ambient SST values 444–555 km from the storm center. Values notated in rows 1, 4, 7, 10, etc. in Table 1 are associated with buoy observations between 15° and 25.84°N. Similarly, rows 2, 5, 8, 11, etc. represent statistics associated with observations between 26° and 28.95°N while rows 3, 6, 9, 12, etc. depict buoy statistics for hurricanes sampled between 29.18° and 32.5°N. Boldface values in Table 1 denote statistically significant mean differences at the 95% level or higher between inner-core and ambient samples. The ''b'' footnotes represent statistically significant mean differences at the 95% level or higher between the lowest latitude [i.e., deep tropic (DT)] and midlatitude [i.e., subtropic (ST)] samples, while the use of ''a'' depicts statistically significant mean differences at or above the 95% level between the DT and the highest latitude [i.e., lower midlatitude (LML)] hurricane sample. The use of ''c'' highlights statistically significant mean differences at the 95% level or higher between the ST and LML samples.

Using information from Table 1, Fig. 3a illustrates ambient (444–555 km) and inner-core (<111 km) SST (blue), 10-m air temperature ($\mathrm{Ta_{10m}}$, red), and 10-m dewpoint temperature ($\mathrm{Td_{10m}}$, green) conditions for each latitudinal band depicted in Table 1. Figure 3a converts radial distance into dimensionless R/Rmax, which is defined as the radius of the observation to the storm center divided by the storm radius of maximum wind. Information on Rmax is included in the TCBD. For this illustration, average inner-core R/Rmax is ~2 while ambient values range between 12 and 14.

From Fig. 3a, we see that inner-core dewpoint ($\mathrm{Td_{10m}}$) is largely insensitive to changes in latitude. The difference in mean $\mathrm{Td_{10m}}$ between DT and LML systems is 0.32°C (i.e., 25.22° vs 24.55°C). This result is important since inner-core SSTs that were observed to be less than the inner-core surface dewpoint temperature would, by definition, ''shut down'' the storm's required source of surface moisture flux since $\mathrm{qSST} - \mathrm{qa_{10m}}$ (Δq) illustrated in (2) would be <0. In addition, surface sensible heat flux (SH) would be negative since the $\mathrm{SST} - \mathrm{Ta_{10m}}$ (ΔT) term in (3) would also be negative under these conditions. *[It should be noted that a separate analysis was conducted (not shown) whereby observations were sorted by inner-core SST (instead of latitude). Similar to the findings noted above, statistically significant differences in mean Td_{10m} were not found between high and low SST samples.]*

$$S_H = -U_{10\mathrm{m}}[C_p C_h(\mathrm{SST} - \mathrm{Ta_{10m}})]. \qquad (3)$$

Here $U_{10\mathrm{m}}$ represents the 1-min wind speed at 10 m, C_p is the specific heat of water vapor at a given temperature, C_h is the dimensionless coefficient of heat exchange at 10 m, and SST and $\mathrm{Ta_{10m}}$ are the sea surface temperature and the atmospheric air at 10 m, respectively. The units for S_H are in W m^{-2}. Assuming all other factors to be favorable for storm maintenance, maintaining this condition over time would lead to a weakening system. Given that the maximum inner-core surface dewpoint temperature (observed at any latitude for any storm) was 26.5°C, the approximate SST threshold of 26°C is indeed significant. When SSTs exceed 26°C, in almost all cases, both Δq and ΔT would be greater than zero, which would *ensure* positive surface enthalpy flux conditions within the hurricane inner-core environment. It should be noted that this observationally driven conclusion regarding the criticality of 26°C is notably different than

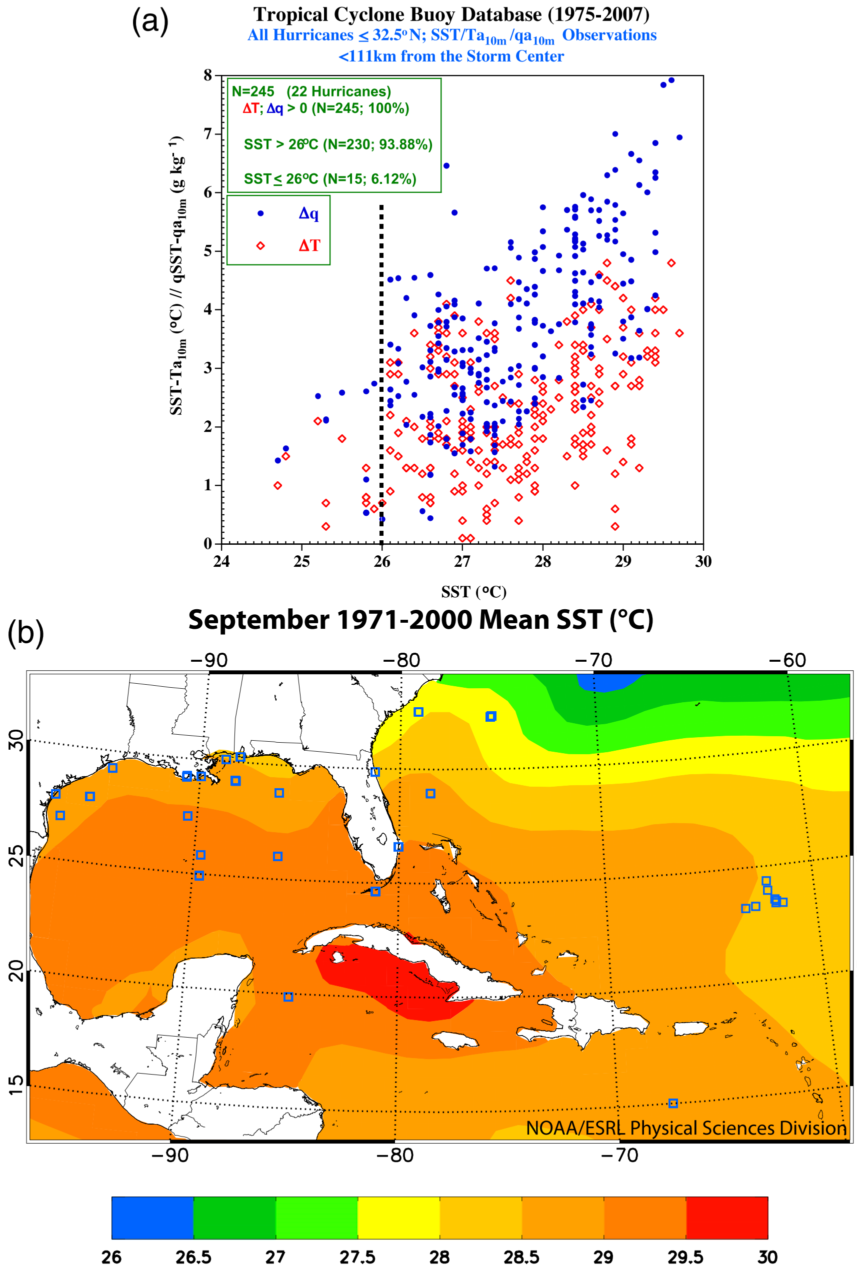

FIG. 2. (a) SST vs SST $-$ Ta_{10m} (red) and qSST $-$ qa_{10m} (blue) for Tropical Cyclone Buoy Database (TCBD) hurricanes observed between 1975 and 2007, south of 32.5°N. Only observations inside 1° radius (<111 km) of the analyzed storm center were utilized. SST, Ta_{10m}, and qa_{10m} had to be simultaneously available in order to be included in this comparative analysis. The black dashed vertical line represents the 26°C inner-core SST threshold. Statistical information as it relates to specific SST, SST $-$ Ta_{10m} (ΔT), and qSST $-$ qa_{10m} (Δq) thresholds is also provided. SST and SST $-$ Ta_{10m} are measured in °C, while qSST $-$ qa_{10m} is given in g kg^{-1}. (b) Average SST analysis in °C representative for the 30-yr period including 1971–2000. Buoy platform locations for individual observations included in (a) are also shown (blue boxes). This figure is provided courtesy of the NOAA/Environmental Science Research Laboratory/Physical Sciences Division.

TABLE 1. Latitude-stratified storm sample statistics. Inner core (<111 km from the storm center; no "eye" observations) vs ambient environment (444–555 km from the storm center). Rows 1, 4, 7, etc., represent buoy observations sampled between 15° and 25.84°N. Rows 2, 5, 8, etc., represent buoy observations sampled between 26° and 28.95°N. Rows 3, 6, 9, etc., represent buoy observations sampled between 29.18° and 32.5°N. Boldface font denotes statistically significant mean differences at the 95% level or higher between inner-core and ambient samples.

Buoy parameter	Min/max (<111 km)	Mean	Std dev	*N*	Min/max (444–555 km)	Mean	Std dev	*N*
SST (°C)	26.9/29.4	**28.30**[a,b]	0.62	58	26.3/30.3	**28.83**	1.02	115
SST (°C)	26.6/28.9	**27.73**[c,b]	0.74	60	26.9/31.0	**28.80**	1.24	75
SST (°C)	24.7/29.7	**27.22**[a,c]	1.13	127	23.9/31.3	**28.58**	1.93	112
10-m Ta (°C)	24.0/27.9	**25.83**[a]	0.88	58	23.0/30.5	**28.72**[a]	1.22	115
10-m Ta (°C)	22.9/28.6	**25.45**	1.43	60	25.4/30.9	**28.26**[c]	1.23	75
10-m Ta (°C)	22.7/27.4	**25.19**[a]	0.99	127	22.6/30.5	**27.30**[a,c]	1.94	112
10-m Td (°C)	22.9/26.4	24.54	0.85	58	18.8/27.3	24.91[a]	1.55	115
10-m Td (°C)	22.9/26.4	24.47	0.98	60	20.7/26.5	24.84[c]	1.32	75
10-m Td (°C)	20.4/26.5	**24.22**	1.10	127	17.8/26.3	**23.49**[a,c]	1.75	112
qSST (g kg^{-1})	22.3/25.3	**24.08**[a,b]	0.77	58	21.3/26.8	**24.70**	1.47	115
qSST (g kg^{-1})	21.8/25.0	**23.34**[c,b]	0.92	60	21.9/28.1	**24.51**	1.87	75
qSST (g kg^{-1})	19.8/26.2	**22.65**[a,c]	1.53	127	18.2/28.4	**24.25**	2.72	112
10-m qa (g kg^{-1})	17.7/21.9	19.77	1.121	58	13.6/23.0	19.91[a]	1.79	115
10-m qa (g kg^{-1})	17.6/22.1	19.72	1.19	60	15.2/21.8	19.80[c]	1.53	75
10-m qa (g kg^{-1})	14.9/22.9	**19.41**	1.46	127	12.8/21.7	**18.27**[a,c]	1.93	112
10-m RH (%)	79.9/100	**92.7**	5.30	58	65.9/89.2	**79.7**	5.91	115
10-m RH (%)	75.2/1000	**94.5**	6.27	60	67.1/96.5	**81.7**	7.29	75
10-m RH (%)	80.9/100	**94.4**	5.24	127	63.0/93.6	**79.6**	6.45	112
qSST − 10-m qa (g kg^{-1})	1.58/6.30	4.31[a,b]	1.06	58	−0.1/9.03	4.79[a]	1.93	115
qSST − 10-m qa (g kg^{-1})	1.41/7.00	**3.62**[b]	1.24	60	1.49/7.73	**4.70**[c]	1.99	75
qSST − 10-m qa (g kg^{-1})	0.20/7.92	**3.23**[a,b]	1.67	127	1.42/9.24	**5.98**[a,c]	1.84	112
SST − 10-m Ta (°C)	0.9/4.8	**2.47**	1.01	58	−2.8/3.7	**0.26**[a]	0.91	115
SST − 10-m Ta (°C)	0.0/4.5	**2.28**	1.08	60	−1.2/3.2	**0.31**[c]	0.74	75
SST − 10-m Ta (°C)	0.1/4.8	**2.03**	1.11	127	−0.8/4.4	**1.20**[a,c]	1.02	112
$SST_{IC} - SST_{amb}$ (°C)	−1.2/0.0	−0.46[a,b]	0.27	40	—	—	—	—
$SST_{IC} - SST_{amb}$ (°C)	−2.5/0.0	−1.06[b]	0.75	60	—	—	—	—
$SST_{IC} - SST_{amb}$ (°C)	−1.2/0.0	−1.37[a]	1.11	127	—	—	—	—
Buoy latitude (°N)	15.0/25.8	22.79	3.53	58	14.5/25.9	23.47	3.73	115
Buoy latitude (°N)	26.0/28.9	27.39	0.92	60	26.0/28.9	27.54	1.08	75
Buoy latitude (°N)	29.2/32.5	30.21	1.32	127	29.2/32.5	30.33	1.13	112

[a] Statistically significant mean differences at the 95% level or higher between the lowest-latitude and highest-latitude samples.
[b] Statistically significant mean differences at the 95% level or higher between the lowest-latitude and midlatitude samples.
[c] Statistically significant mean differences at the 95% level or higher between the midlatitude and highest-latitude samples.

the widely held OHC contention, which suggests that at SSTs below 26°C, the available thermal energy stored in the upper ocean is insufficient to support and maintain a hurricane. Individual observations from many hurricanes spanning several decades show this assertion to be incorrect as is highlighted by the 15 sub-26°C hurricane events illustrated in Fig. 2a. In each of these cases, both ΔT and Δq were found to be positive.

3. The meridional variability of near-surface temperature and moisture differences in hurricanes

a. Radial structure of SST, surface moisture, and Δq

As previously mentioned, inner-core Td_{10m} exhibits very little variability as a function of latitude for the storms sampled in this study (see Table 1; Fig. 3a). As noted by the 95% confidence intervals shown in Fig. 3a, statistically significant differences between average Td_{10m} for DT, ST, and LML systems were not observed within the hurricane inner core. In addition, Fig. 3a and Table 1 also illustrate that statistically significant differences in mean Td_{10m} were not found between ST and DT ambient samples or between ambient and core ST and DT samples, respectively. These results, which were not found when ambient SST and Ta_{10m} samples were compared with inner-core mean conditions, suggest that on average, near-surface moistening that typically occurs during inflow (e.g., ocean evaporation, sea spray interactions, precipitation) is likely to be largely counterbalanced by drying processes associated with convective downdrafts outside the hurricane inner-core environment. These results are consistent with earlier findings (e.g., Barnes et al. 1983; Powell 1990; Cione et al. 2000, 2013).

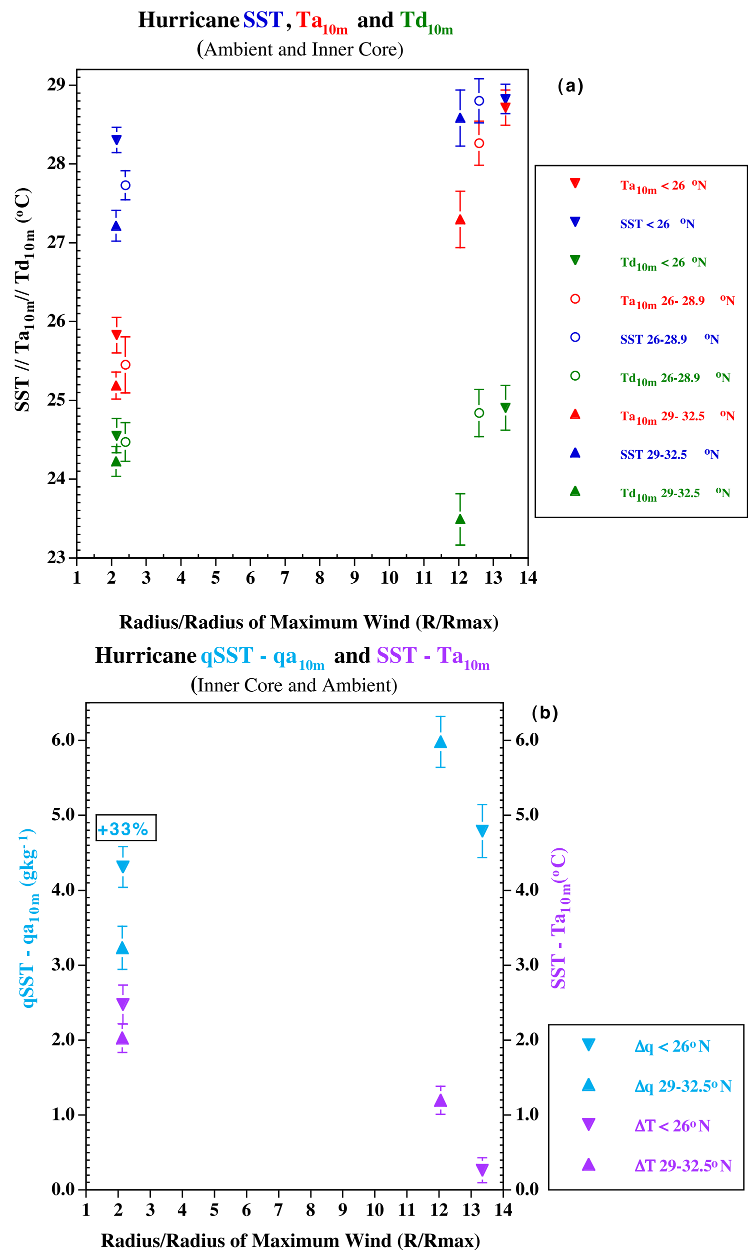

FIG. 3. (a) SST (blue), 10-m air temperature (Ta_{10m}, red), and 10-m dewpoint temperature (Td_{10m}, green) as a function of radius to the storm center divided by the storm radius of maximum wind (R/Rmax). Both ambient inner-core mean values (with 95% confidence intervals) are illustrated. SST, Td, and Ta ambient-core pairings are shown for observations south of 26°N (solid line), between 26° and 28.9°N (dotted), and between 29° and 32.5°N (dashed). SST, Ta_{10m}, and Td_{10m} are given in °C. (b) qSST − qa_{10m} (light blue) and SST − Ta_{10m} (purple) as a function of radius to the storm center divided by the storm radius of maximum wind (R/Rmax). Both ambient inner-core mean values (with corresponding 95% confidence intervals) are illustrated. qSST − qa_{10m} (Δq) and SST − Ta_{10m} (ΔT) ambient-core pairings are shown for observations south of 26°N (solid line) and between 29° and 32.5°N (dashed). As noted in the illustration, average core Δq values were found to be 33% greater for the lower-latitude sample. Here Δq is measured in g kg^{-1} while the units for ΔT are in °C.

In contrast, low-latitude SST near the storm center was found to be statistically significantly greater than inner-core SST observed for higher-latitude hurricanes. This finding is not surprising since most storms tend to experience (relatively) cooler upper ocean conditions as they travel northward (e.g., Palmen 1948; Price 1981; Lloyd and Vecchi 2011). Nevertheless, the results found in Table 1 and Fig. 3a are significant since they help quantify the impact latitude can have on inner-core SST (SST_{IC}). It is also worth noting that average ambient SSTs (SST_{amb}) were not found to vary appreciably as a function of latitude. In fact, unlike inner-core SSTs, statistically significant differences between average ambient SST samples were not found. These results suggest that ocean cooling (i.e., $SST_{IC} - SST_{amb}$) resulting from wind-driven turbulent mixing is likely to exhibit a strong latitudinal dependence, which is consistent with the notion that shallower mixed layers and stronger stratification is associated with higher-latitude systems.

Using values presented in Table 1, Fig. 3b depicts Δq (and ΔT) for the lowest and highest latitude hurricane samples. This figure illustrates how the magnitude of Δq decreases as a function of radial distance to the storm. This trend, which is especially noticeable for higher-latitude storms, is due to the combined effects of SST cooling (and hence reductions in qSST) as well as a radially constant (or increasing) qa_{10m} term. The statistically significant differences (33%) in inner-core Δq depicted in Fig. 3b are largely a result of cooler (warmer) ocean conditions found within the inner core for higher- (lower-) latitude storm systems. All other factors being equal, these findings suggest that the average magnitude of surface moisture flux is approximately 1/3 greater for DT hurricanes (<26°N) relative to conditions found for LML storms (29°–32.5°N).

b. Radial structure of surface air temperature and ΔT

While Δq is the dominant thermodynamic parameter that impacts the magnitude of surface enthalpy fluxes in hurricanes, it is also of interest to examine the behavior of ΔT within the tropical cyclone environment. From Table 1 and Fig. 3a, we see that comparisons between ambient and inner-core Ta_{10m} values generally resemble the ambient-to-core cooling patterns observed for SST. However, depending on storm latitude, the average ambient-to-inner-core differences in Ta_{10m} are 1.5–6 times greater than $SST_{IC} - SST_{amb}$ values shown in Table 1. As a result of this factor, ambient-to-core ΔT values *increase* as observations approach the storm center (see Fig. 3b). In addition, and unlike statistically significant results found for inner-core Δq, average inner-core ΔT for low- and high-latitude storm samples were not found to be appreciably different due to compensating cooling trends observed for both SST and Ta_{10m}. It is also worth noting that differences between ambient and inner-core ΔT increase as a function of storm latitude, while the opposite trend is found for Δq samples used in this study. In addition, results highlighted in Table 1 show that ambient-to-core mean RH differences are statistically significant for each of the three latitude-stratified storm samples. However, ambient-to-core mean Td_{10m} and qa_{10m} differences were observed to be negligible for deep-tropic and subtropic hurricanes. This finding highlights the danger of using RH to ascertain (absolute) moisture content given the parameter's dependence on temperature. These findings, in addition to results illustrated in Fig. 3a, should provide value for future efforts attempting to evaluate the physical performance of regional- and global-scale forecast models.

4. Thermodynamic controls on inner-core surface latent heat flux: Ocean versus atmosphere

The qSST − qa_{10m} or "Δq" term illustrated in (2) represents the primary thermodynamic parameter controlling surface latent heat flux (L_H). In this section, we investigate how observations of qSST and qa_{10m} near the storm center individually correlate with Δq as a function of storm latitude. A primary objective is to quantify the relative roles the atmosphere (qa_{10m}) and ocean (qSST) each have on Δq variability within the high wind hurricane inner-core environment.

Figure 4a depicts qSST (blue) and qa_{10m} (green) as a function of Δq for all LML hurricane events between 29° and 32.5°N. Here, all TCBD observations illustrated were within 111 km from the analyzed storm center. From this figure we see that the explained variance (r^2) for inner-core qSST is slightly greater than that of qa_{10m} (0.345 vs 0.284). Figure 4b is similar to Fig. 4a except that observations shown are valid for DT hurricanes south of 26°N. Here, the explained variance for Δq associated with the near-surface atmosphere (qa_{10m}; 0.570) is far greater than the observed r^2 found for the ocean (qSST; 0.084). Figure 4c highlights the relationship found between Δq explained variance and latitude for both qSST (ocean) and for qa_{10m} (atmosphere) for DT (<26°N), ST (26°–28.9°N), and LML (29°–32.5°N) hurricanes. This illustration clearly depicts the reduced (increased) influence inner-core qSST (qa_{10m}) has on the critical Δq term for DT and ST storm samples. At higher latitudes, contributions from oceanic and atmospheric forcing are observed to be similar. An additional factor worth noting in Fig. 4b is the reduced scatter found for both qSST and qa_{10m} (relative to Fig. 4a). This reduction is quantified in Table 1 and illustrated in Fig. 4d. Here, inner-core oceanic and atmospheric air–sea thermodynamic

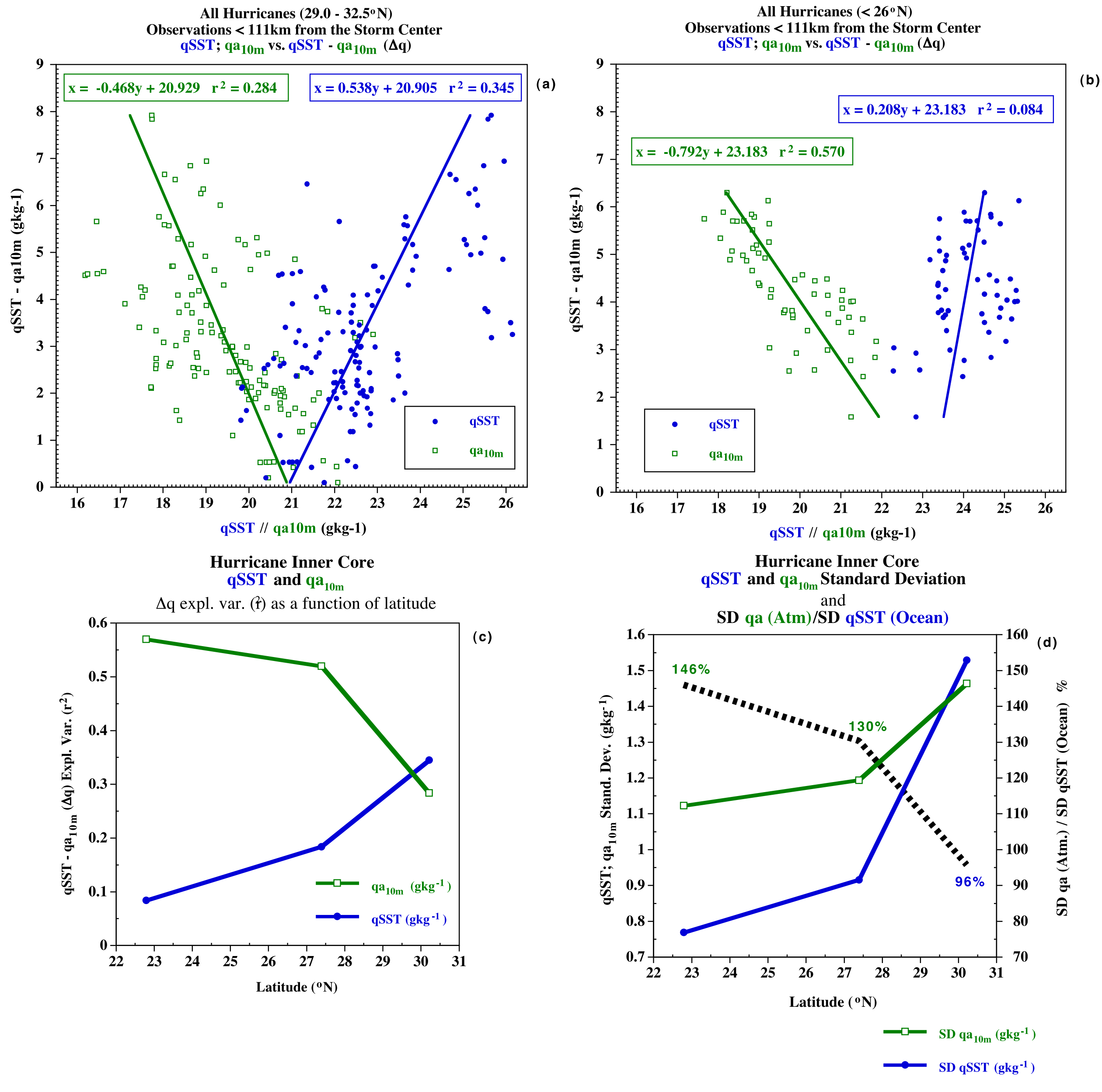

FIG. 4. (a) Surface specific humidity (qSST, blue) and 10-m specific humidity (qa_{10m}, green) variability as a function of qSST − qa_{10m} (Δq) for Tropical Cyclone Buoy Database (TCBD) hurricanes between 29.0° and 32.5°N. Only qSST and qa_{10m} values within 1° radius (<111 km) of the storm center were included for this analysis. The solid lines represent least squares best-fit estimates for both samples. Information on slope, intercept, and explained variance (r^2) are also provided for each curve. Both qSST and qa_{10m} are given in g kg^{-1}. (b) As in (a), but for Tropical Cyclone Buoy Database (TCBD) hurricane observations south of 26°N. (c) The explained variance (r^2) of inner-core Δq as a function of latitude for both surface specific humidity (qSST, blue) and 10-m specific humidity (qa_{10m}, green) for deep-tropic (<26°N), subtropic (26°–28.9°N), and lower midlatitude (29°–32.5°N) hurricanes. As in (a) and (b), only qSST and qa_{10m} values within 1° radius (<111 km) of the storm center were included for this analysis. Both qSST and qa_{10m} are given in g kg^{-1}. (d) The variability (standard deviation) of inner-core qSST (blue) and qa_{10m} (green) as a function of latitude. The ratio of atmospheric variability (SD qa_{10m}) divided by oceanic variability (SD qSST) is also shown (dashed black curve). As in (a)–(c), only qSST and qa_{10m} values within 1° radius (<111 km) of the storm center were included for this analysis. SD qSST and SD qa_{10m} are given in g kg^{-1}, while the ratio of atmospheric to oceanic variability is illustrated as a percentage. Percentage values in blue (green) depict average conditions where oceanic (atmospheric) variability is greatest.

variability is shown to be noticeably reduced for lower-latitude hurricanes. Figure 4d also illustrates that the ratio of atmospheric to oceanic variability dramatically increases with decreasing latitude. This is likely an important factor responsible for the relatively high (low) Δq explained variance found for qa_{10m} (qSST) for the DT hurricane sample (Fig. 4c). These results suggest that for hurricanes south of 29°N, near-surface atmospheric specific humidity is much more likely to influence Δq, and, therefore, the magnitude of surface latent heat flux observed within the hurricane inner-core environment.

5. Summary

Analyses from this study reconfirm the decades-old, empirically driven linkage between 26°C and hurricane activity. However, the assumption that SSTs of 26°C or greater are required in order to supply the energy necessary to maintain hurricane intensity is not supported by observations used in this study. As illustrated here [and in Cione and Uhlhorn (2003)] the energy required to maintain a nonstationary hurricane amounts to approximately 2%–8% (depending on storm speed and intensity) of the ocean heat content available to the system. Results from this study also illustrate that hurricanes can (and occasionally do) maintain hurricane intensity even when SSTs are at or below 26°C. This occurs, despite the fact that OHC is less than zero in cases where surface ocean temperatures do not exceed 26°C.

Instead of focusing on absolute SST thresholds and/or incomplete upper-ocean thermal energy storage diagnostic terms, this research utilizes a more direct approach to assess how near-surface thermodynamic conditions affect storm maintenance by monitoring the relative difference between the near-surface dewpoint temperature and the SST within the high wind hurricane environment. When inner-core SST is lower than the atmospheric dewpoint temperature, surface enthalpy flux would, by definition, ‘‘shut down’’ since SST $-$ Ta_{10m} (ΔT) and qSST $-$ qa_{10m} (Δq) would both be negative. Even if other factors remained favorable for hurricane maintenance, extended periods of zero surface enthalpy flux would ultimately end up significantly weakening the system. Observations from this study show that the maximum inner-core surface dewpoint temperature (observed at any latitude for any storm) was 26.5°C. As such, when SSTs exceed 26°C, in the overwhelming majority of cases, both Δq and ΔT would be greater than zero, which in turn *would ensure positive surface enthalpy flux conditions* within the hurricane inner-core environment. This conclusion regarding the criticality of 26°C runs counter to the widely held OHC assertion that the available thermal energy stored in the upper ocean is insufficient to maintain hurricane intensity when inner-core SSTs fall below 26°C. Observations from this multidecadal hurricane study do not support this contention given the 15 sub-26°C hurricane events that have been documented. Instead, the results presented support the ‘‘positive enthalpy flux condition’’ given the fact that in each of the 245 cases sampled, positive values for ΔT and Δq were observed.

Results show that inner-core SST, on average, ranged between 28.3°C (for storms south of 26°N) and 27.2°C (for systems between 29° and 32.5°N). In contrast, mean inner-core 10-m surface dewpoint temperatures were found to be largely insensitive to changes in latitude, and varied between 24.2° and 24.5°C. As a result of these combined effects, the magnitude of inner-core Δq exhibits a significant latitude signal that is largely driven by inner-core SST cooling. As depicted in earlier illustrations, the net effect is that deep-tropic hurricanes (south of 26°N) on average exhibit Δq values 33% higher relative to systems observed at higher latitudes (29°–32.5°N).

For storm systems observed between 29° and 32.5°N, the explained variance associated with Δq directly attributable to the ocean (qSST) and atmosphere (qa_{10m}) was found to be roughly similar. However, for hurricanes south of 29°N, atmospheric forcing was observed to dominate. Analyses from this study also illustrate that the ratio of atmospheric variability (i.e., std dev qa_{10m}) to oceanic variability (i.e., std dev qSST) increased with decreasing latitude. Combined, these results suggest that for hurricanes south of 29°N, the atmosphere, not the ocean is much more likely to influence the key thermodynamic parameter (Δq) controlling surface moisture flux within the hurricane high wind environment.

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REFERENCES

Barnes, G. M., E. J. Zipser, D. Jorgensen, and F. Marks Jr., 1983: Mesoscale and convective structure of a hurricane rainband. *J. Atmos. Sci.,* **40,** 2125–2137, doi:10.1175/1520-0469(1983)040<2125:MACSOA>2.0.CO;2.

Black, P. G., and Coauthors, 2007: Air–sea exchange in hurricanes: Synthesis of observations from the Coupled Boundary Layer Air–Sea Experiment. *Bull. Amer. Meteor. Soc.,* **88,** 357–374, doi:10.1175/BAMS-88-3-357.

Byers, H. R., 1959: *General Meteorology.* McGraw Hill, 540 pp.

Chan, J. C. L., Y. Duan, and L. K. Shay, 2001: Tropical cyclone intensity change from a simple ocean–atmosphere coupled model.

J. Atmos. Sci., **58,** 154–172, doi:10.1175/1520-0469(2001)058<0154:TCICFA>2.0.CO;2.

Cione, J. J., and E. Uhlhorn, 2003: Sea surface temperature variability in hurricanes: Implications with respect to intensity change. *Mon. Wea. Rev.,* **131,** 1783–1796, doi:10.1175/2562.1.

——, P. Black, and S. Houston, 2000: Surface observations in the hurricane environment. *Mon. Wea. Rev.,* **128,** 1550–1561, doi:10.1175/1520-0493(2000)128<1550:SOITHE>2.0.CO;2.

——, E. A. Kalina, J. Zhang, and E. Uhlhorn, 2013: Observations of air–sea interaction and intensity change in hurricanes. *Mon. Wea. Rev.,* **141,** 2368–2382, doi:10.1175/MWR-D-12-00070.1.

Dare, R. A., and J. McBride, 2011: The threshold sea surface condition for tropical cyclogenesis. *J. Climate,* **24,** 4570–4576, doi:10.1175/JCLI-D-10-05006.1.

Dengler, K., 1997: A numerical study of the effects of land proximity and changes in sea surface temperature on hurricane tracks. *Quart. J. Roy. Meteor. Soc.,* **123,** 1307–1321, doi:10.1002/qj.49712354109.

Gilhousen, D. B., 1988: Quality control of meteorological data from automated marine stations. Preprints, *Fourth Int. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology,* Miami, FL, Amer. Meteor. Soc., 113–117.

——, 1998: Improved real-time quality control of NDBC measurements. Preprints, *10th Symp. on Meteorological Observations and Instrumentation,* Phoenix, AZ, Amer. Meteor. Soc., 363–366.

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, doi:10.1029/2003EO510001.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.,* **96,** 669–700, doi:10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2.

Hong, X. H., S. Chang, S. Raman, L. Shay, and R. Hodur, 2000: The interaction between Hurricane Opal (1995) and a warm core ring in the Gulf of Mexico. *Mon. Wea. Rev.,* **128,** 1347–1365, doi:10.1175/1520-0493(2000)128<1347:TIBHOA>2.0.CO;2.

Jacob, S. D., and L. K. Shay, 2003: The role of oceanic mesoscale features on the tropical cyclone–induced mixed layer response: A case study. *J. Phys. Oceanogr.,* **33,** 649–676, doi:10.1175/1520-0485(2003)33<649:TROOMF>2.0.CO;2.

——, ——, and A. Mariano, 2000: The 3D oceanic mixed layer response to Hurricane Gilbert. *J. Phys. Oceanogr.,* **30,** 1407–1429, doi:10.1175/1520-0485(2000)030<1407:TOMLRT>2.0.CO;2.

Leipper, D., and D. Volgenau, 1972: Hurricane heat potential of the Gulf of Mexico. *J. Phys. Oceanogr.,* **2,** 218–224, doi:10.1175/1520-0485(1972)002<0218:HHPOTG>2.0.CO;2.

Lin, I.-I., C.-C. Wu, K. A. Emanuel, I.-H. Lee, C.-R. Wu, and I.-F. Pun, 2005: The interaction of Supertyphoon Maemi (2003) with a warm ocean eddy. *Mon. Wea. Rev.,* **133,** 2635–2649, doi:10.1175/MWR3005.1.

——, ——, I.-F. Pun, and D.-S. Ko, 2008: Upper ocean thermal structure and the western North Pacific category-5 typhoons. Part I: Ocean features and category-5 typhoon's intensification. *Mon. Wea. Rev.,* **136,** 3288–3306, doi:10.1175/2008MWR2277.1.

——, M.-D. Chou, and C.-C. Wu, 2011: The impact of a warm ocean eddy on Typhoon Morakot (2009): A preliminary study from satellite observations and numerical modeling. *Terr. Atmos. Oceanic Sci.,* **22,** 661–671, doi:10.3319/TAO.2011.08.19.01(TM).

Liu, J., J. Curry, C. Clayson, and M. Bourassa, 2011: High-resolution satellite surface latent heat fluxes in North Atlantic hurricanes. *Mon. Wea. Rev.,* **139,** 2735–2747, doi:10.1175/2011MWR3548.1.

Lloyd, I. D., and G. Vecchi, 2011: Observational evidence for oceanic controls on hurricane intensity. *J. Climate,* **24,** 1138–1153, doi:10.1175/2010JCLI3763.1.

Mainelli, M., M. DeMaria, L. Shay, and G. Goni, 2008: Application of oceanic heat content estimation to operational forecasting of recent Atlantic category 5 hurricanes. *Wea. Forecasting,* **23,** 3–16, doi:10.1175/2007WAF2006111.1.

Mao, Q., S. W. Chang, and R. L. Pfeffer, 2000: Influence of large-scale initial oceanic mixed layer depth on tropical cyclones. *Mon. Wea. Rev.,* **128,** 4058–4070, doi:10.1175/1520-0493(2000)129<4058:IOLSIO>2.0.CO;2.

Miller, B. I., 1958: On the maximum intensity of hurricanes. *J. Meteor.,* **15,** 184–195, doi:10.1175/1520-0469(1958)015<0184:OTMIOH>2.0.CO;2.

Palmen, E., 1948: On the formation and structure of tropical cyclones. *Geophysica,* **3,** 184–195.

Perlboth, I., 1967: Hurricane behavior as related to oceanographic environmental conditions. *Tellus,* **19A,** 258–268, doi:10.1111/j.2153-3490.1967.tb01481.x.

Powell, M. D., 1990: Boundary layer structure and dynamics in outer hurricane rainbands. Part II: Downdraft modification and mixed layer recovery. *Mon. Wea. Rev.,* **118,** 918–938, doi:10.1175/1520-0493(1990)118<0918:BLSADI>2.0.CO;2.

Price, J. F., 1981: Upper ocean response to a hurricane. *J. Phys. Oceanogr.,* **11,** 153–175, doi:10.1175/1520-0485(1981)011<0153:UORTAH>2.0.CO;2.

——, 2009: Metrics of hurricane-ocean interaction: Vertically integrated or vertically-averaged ocean temperature? *Ocean Sci.,* **5,** 351–368, doi:10.5194/os-5-351-2009.

Ramage, C. S., 1959: Hurricane development. *J. Meteor.,* **16,** 227–237, doi:10.1175/1520-0469(1959)016<0227:HD>2.0.CO;2.

Rodgers, E., W. Olson, J. Halverson, J. Simpson, and H. Pierce, 2000: Environmental forcing of Supertyphoon Paka's (1997) latent heat structure. *J. Appl. Meteor.,* **39,** 1983–2006, doi:10.1175/1520-0450(2001)040<1983:EFOSPS>2.0.CO;2.

Shay, L. K., J. Goni, and P. G. Black, 2000: Role of a warm core ocean feature on Hurricane Opal. *Mon. Wea. Rev.,* **128,** 1366–1383, doi:10.1175/1520-0493(2000)128<1366:EOAWOF>2.0.CO;2.

Yablonsky, R. M., and I. Ginis, 2013: Impact of a warm ocean eddy's circulation on hurricane-induced sea surface cooling with implications for hurricane intensity. *Mon. Wea. Rev.,* **141,** 997–1021, doi:10.1175/MWR-D-12-00248.1.