Observation of the Tropical Cyclone Diurnal Cycle Using Hyperspectral Infrared Satellite Sounding Retrievals

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ABSTRACT: Hyperspectral infrared satellite sounding retrievals are used to examine thermodynamic changes in the tropical cyclone (TC) environment associated with the diurnal cycle of radiation. Vertical profiles of temperature and moisture are retrieved from the *Suomi National Polar-Orbiting Partnership (SNPP)* satellite system, *National Oceanic and Atmospheric Administration-20 (NOAA-20)*, and the Meteorological Operational (*MetOp-A/B*) satellite system, leveraging both infrared and microwave sounding technologies. Vertical profiles are binned radially based on distance from the storm center and composited at 4-h intervals to reveal the evolution of the diurnal cycle. For the three cases examined—Hurricane Dorian (2019), Hurricane Florence (2018), and Hurricane Irma (2017)—a marked diurnal signal is evident that extends through a deep layer of the troposphere. Statistically significant differences at the 95% level are observed in temperature, moisture, and lapse rate profiles, indicating a moistening and destabilization of the mid- to upper troposphere that is more pronounced near the inner core of the TC at night. Observations support a favorable environment for the formation of deep convection caused by diurnal differences in radiative heating tendencies, which could partially explain why new diurnal pulses tend to form around sunset. These findings demonstrate that the diurnal cycle of radiation affects TC thermodynamics through a deep layer of the troposphere, and suggest that hyperspectral infrared satellite sounding retrievals are valuable assets in detecting thermodynamic variations in TCs.

KEYWORDS: Diurnal effects; Hurricanes/typhoons; Tropical cyclones; Remote sensing; Soundings

1. Introduction

The daily cycle of radiation can cause significant changes to clouds, precipitation, and the circulation in tropical cyclones (TCs). While much attention has focused on documenting changes at the cloud top, observations also indicate a diurnal cycle in TC lightning activity (Stevenson et al. 2016; Ditchek et al. 2019b) and boundary layer winds and moisture (Zhang et al. 2020), which suggests that the influence of radiation extends beyond the cirrus canopy. Numerical simulations show significant changes to the TC thermodynamic environment in response to the diurnal cycle of radiation, including daily variations in temperature, humidity, and stability indices (Melhauser and Zhang 2014; Navarro and Hakim 2016; O'Neill et al. 2017; Ruppert and O'Neill 2019; Dunion et al. 2019; Evans and Nolan 2019; Trabling and Bell 2021). Observations are needed to measure these thermodynamic variations throughout the depth of the troposphere, and to understand if and how such changes manifest in TCs in nature. Atmospheric soundings are valuable tools for measuring thermodynamics throughout the atmosphere; however, few studies have utilized soundings to characterize the diurnal cycle in TCs (Frank 1977; Duran and Molinari 2016; Zhang et al. 2020). A significant challenge of using

operational rawinsonde networks or dropsondes is that these observations are sparse in both space and time, and are limited to the timing and physical location of their deployment. Remote sensing can offer enhanced spatial and temporal coverage as compared to rawinsondes and dropsondes, providing measurements in data-sparse regions such as remote oceans. These qualities make satellite sounding retrievals attractive measurements for this analysis. Here we utilize hyperspectral infrared satellite sounding retrievals derived from the National Oceanic and Atmospheric Administration (NOAA) Unique Combined Atmospheric Processing System (NUCAPS) to evaluate the diurnal variation of temperature, moisture, and stability for three TCs: Hurricane Dorian (2019), Hurricane Florence (2018), and Hurricane Irma (2017).

The TC diurnal cycle exhibits discernible changes in the upper-level clouds, with a radial expansion of the cirrus canopy observed during the day and contraction at night (Browner et al. 1977; Muramatsu 1983; Steranka et al. 1984; Lajoie and Butterworth 1984; Kossin 2002; Wu and Ruan 2016). Differences in infrared brightness temperatures reveal outward-propagating “pulses” of both colder and warmer cloud-top temperatures that proceed from the storm center over the course of the day (Dunion et al. 2014; Ditchek et al. 2019a). These “diurnal pulses” are prevalent in most Atlantic TCs from 1982 to 2017 (Ditchek et al. 2019a), and are highly predictable in both space and time (Dunion et al. 2014; Ditchek et al. 2019a). A diurnal cycle is also observed in TC rainfall (Jiang et al. 2011; Bowman and Fowler 2015; Wu et al. 2015; Leppert and Cecil 2016), with maxima observed in the early morning and minima observed in the afternoon, consistent with the overall diurnal cycle of tropical convection (e.g., Yang and Slingo 2001; Ruppert and Hohenegger 2018). Ditchek et al. (2019b)

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show that 61.1% of diurnal pulses contain lightning activity, suggesting that the majority of diurnal pulses are linked with deep convection.

Several studies have shown that diurnally varying deep convection can be supported by the diurnal cycle of the thermodynamics of the TC environment. Using large-scale diagnostics derived from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) Developmental Dataset, Knaff et al. (2019) demonstrates that greater mid- and upper-level relative humidity is the key factor for promoting robust diurnal oscillations of IR brightness temperatures. Ditchek et al. (2019a) uses SHIPS data to show that, prior to the outward propagation of a cooling diurnal pulse (i.e., a diurnal, outward-propagating trend in colder cloud-top brightness temperatures), the environment between 0000 and 0300 LT has more favorable conditions for enhanced inner-core convection, including increased moisture throughout the troposphere, stronger low-level vorticity and more upper-level divergence. Dropsonde observations also reveal that the boundary layer equivalent potential temperature is larger at night for radii greater than 150 km from the storm center (Zhang et al. 2020), which is a structure favorable for surface-based convection. While these studies show that the nighttime TC thermodynamic environment is conducive for convective development, they are limited to the analysis of either the average large-scale environment or to the boundary layer of the TC. Observations are needed, particularly in the mid- to upper troposphere, to understand how the diurnal cycle of radiation affects a deep layer of the TC.

Numerical simulations also demonstrate significant diurnal changes to the thermodynamic profile through a deep layer of the troposphere. For example, the pregenesis environment of Hurricane Karl (2010) destabilized at night due to radiative cooling, which promoted deep convection and increased the relative humidity throughout the troposphere. Daytime-only experiments, in contrast, were more stable and had increased convective inhibition (Melhauser and Zhang 2014). For mature TCs, diurnal variations in temperature in the upper troposphere and lower stratosphere are consistent with radiating gravity waves (Navarro and Hakim 2016; Navarro et al. 2017; O'Neill et al. 2017; Evans and Nolan 2019). Both Dunion et al. (2019) and Ruppert and O'Neill (2019) show substantial variations in the moisture field between daytime and nighttime, with more moist air present throughout the middle troposphere at night and drier air present in the afternoon. Dunion et al. (2019) also analyze the atmospheric stability, demonstrating higher convective available potential energy (CAPE) in the early morning hours, particularly between radii of 150–300 km from the storm center. At these radii, CAPE fluctuates by as much as 1500 J kg^{-1} . Trabing and Bell (2021) also show that the diurnal cycle of shortwave radiation in a modeling framework affects tropospheric temperature, moisture, CAPE, and precipitation type in the 150–300-km radial region. These simulations suggest that the TC diurnal cycle is active throughout the depth of the troposphere; however, it is unclear if and how these changes operate in real storms.

Although conventional atmospheric soundings provide observations of temperature and moisture throughout the depth of the troposphere, few studies have used soundings to

measure the diurnal cycle in TCs. Frank (1977) analyzed 10-yr composites of Pacific rawinsonde data and found differences of 0.5° – 1.0°C from 500 to 300 mb (1 mb = 1 hPa) between the morning and evening for temperature profiles near the inner core of the TC. These changes were much larger than for soundings which were measured in the clear-sky regions of the storm. Using high-vertical-resolution rawinsondes, Duran and Molinari (2016) determine that there is no diurnal variation in the mean static stability in the upper troposphere, but low Richardson numbers are more common in the early morning than in the early evenings, especially near 200–300 km from the storm center. Both Frank (1977) and Duran and Molinari (2016) only consider 0000 and 1200 UTC soundings. Zhang et al. (2020) demonstrate marked thermodynamic changes in the boundary layer between daytime and nighttime using composites of GPS dropsondes. This analysis, however, is limited to the lowest 2 km of the atmosphere. Understanding the TC diurnal cycle requires more observations in both space and time, which can be difficult to achieve using both rawinsondes and dropsondes; rawinsondes are limited to both a routine launch schedule and the relative location of the launch to a nearby TC, and dropsondes are limited to both the availability of aircraft reconnaissance and the physical location of the aircraft. While rawinsondes and dropsondes offer advantages such as increased spatial resolution, accuracy, and better representation of the lower atmosphere, a significant advantage of using remote sensing for this application is that the satellite constellation can offer enhanced coverage, providing more frequent measurements in difficult to observe or data-sparse regions.

This study builds upon previous work by using hyperspectral infrared satellite sounding retrievals to measure TC diurnal variations throughout the troposphere and particularly, in the mid- to upper troposphere. Satellite sounding retrievals, such as NUCAPS soundings, offer a more dense network of observations over a region as the satellite passes overhead, providing more information about the TC environment than a single radiosonde or dropsonde. NUCAPS produces vertical profiles of temperature and moisture, trace gases, and cloud properties globally using a combination of both infrared and microwave sounding instrumentation (Gambacorta 2013). This algorithm is capable of retrieving atmospheric profiles over nearly 80% of the globe under clear to partly cloudy (non-precipitating) conditions (Nalli et al. 2013, 2018; Susskind et al. 2003). NUCAPS sounding retrievals can be calculated from a variety of different satellite platforms, using the Cross-track Infrared Sounder (CrIs) and Advanced Technology Microwave Sounder (ATMS) on the *Suomi National Polar-Orbiting Partnership* (SNPP) and *NOAA-20* platforms, and the Infrared Atmospheric Sounding Interferometer (IASI) and Advanced Microwave Sounding Unit (AMSU) on the European Meteorological Operational (MetOp) satellite series. NUCAPS soundings are valuable for a variety of applications, including evaluating cold air aloft (Weaver et al. 2019); observing the pre-convective environment (Iturbide-Sanchez et al. 2018; Esmaili et al. 2020); and diagnosing extratropical transition (Berndt and Folmer 2018).

Here, composites of NUCAPS satellite sounding retrievals are binned at various radial distances from storm center and

local times to analyze the diurnal evolution of the TC thermodynamic environment. Combinations of overpasses from *SNPP*, *NOAA-20*, and *MetOp-A/B* span the diurnal cycle and capture thermodynamic fields in both the TC inner core and the surrounding environment. To our knowledge, no previous study has considered the use of hyperspectral infrared satellite soundings to measure the TC diurnal cycle.

The remainder of the paper is organized as follows: a description of the hyperspectral infrared satellite soundings observations, the compositing methodology, and a brief synoptic overview of the three case studies are given in [section 2](#). Results using remote sensing analysis are presented in [section 3](#). [Section 4](#) provides a discussion and concluding summary.

2. Data and methodology

a. NUCAPS satellite sounding retrievals

The NUCAPS algorithm is based on version 5.9 of the National Aeronautics and Space Administration (NASA) Atmospheric Infrared Sounder (AIRS) retrieval algorithm ([Susskind et al. 2003](#)) and runs operationally with global coverage in near-real time at NOAA (approx. 180-min latency) and with regional coverage in real time through direct broadcast sites (<60-min latency; [Berndt et al. 2020](#)). NUCAPS satellite sounding retrievals provide vertical profiles of temperature and moisture with a vertical resolution between 2 and 5 km under optimal conditions; this resolution can vary in regions of small temperature lapse rates or near strong horizontal gradients ([Nalli et al. 2013, 2018](#); [Sun et al. 2017](#)). Horizontal resolution is approximately 50 km near nadir and 150 km near the edge of the swath. The NUCAPS algorithm combines radiances from both infrared and microwave sounders, and is designed to work with multiple satellite platforms, including CrIS/ATMS on *SNPP* and *NOAA-20*, IASI/AMSU on *MetOp-A/B*, and AIRS/AMSU on the NASA *Aqua*¹ Earth observing system. The NUCAPS algorithm has been validated extensively against global sets of radiosondes, observations from targeted validation campaigns, and numerical weather prediction model output. It retrieves temperature information with approximately 1-K uncertainty and moisture (water vapor mixing ratio) information with approximately 18% uncertainty from 1014 to 600 mb (1.23 g kg⁻¹ absolute error), 26% uncertainty from 600 to 300 mb (0.30 g kg⁻¹ absolute error), and 72% uncertainty above 300 mb (0.02 g kg⁻¹ absolute error) ([Nalli et al. 2013, 2018](#); [Feltz et al. 2017](#)). While the fractional uncertainties for moisture appear high due to the limitations of validating moisture in low water vapor conditions, the absolute errors (e.g., 0.02 g kg⁻¹ above 300 mb) are well within Joint Polar Satellite System (JPSS) Level 1 requirements, including in the upper atmosphere.

NUCAPS performs cloud-clearing using an overlapping field of view between the infrared and microwave instruments

([Gambacorta and Barnett 2013](#)).² This cloud-clearing effectively removes the influence of clouds in the retrievals, sampling the environment located immediately surrounding the cloudy area. The combined infrared and microwave retrievals (IR+MW) can fail in regions of uniform cloudiness (e.g., where the cloud fraction within the field of regard is above 85%) and precipitation. In partly cloudy regions, errors in clear-column radiances, estimated skin temperature, and surface emissivity can also reduce the retrieval quality ([Iturbide-Sanchez et al. 2018](#); [Esmaili et al. 2020](#)). While the NUCAPS algorithm performs best in clear and partly cloudy conditions, microwave profiles can still be retrieved in cloudy or lightly precipitating regions where IR+MW retrievals fail ([Nalli et al. 2013, 2018](#)); in heavily precipitating regions, such as the eyewall of TCs, both microwave and infrared retrievals typically fail. Microwave-only (MW-only) soundings have lower vertical resolution than IR+MW retrievals, and contain approximately 2-K uncertainty for temperature ([Nalli et al. 2018](#)). For moisture, MW-only retrievals have 19.0% uncertainty from 1014 to 600 mb (1.36 g kg⁻¹ absolute error), <40% uncertainty from 600 to 300 mb (0.51 g kg⁻¹ absolute error), and approximately 61% uncertainty above 300 mb (0.02 g kg⁻¹ absolute error) ([Nalli et al. 2018](#)). Similar to the IR+MW retrievals, the fractional uncertainties for moisture appear high due to the limitations of validating moisture in low water vapor conditions, but are well within Joint Polar Satellite System (JPSS) Level 1 requirements.

NUCAPS satellite sounding retrievals are analyzed here for three TCs: Hurricane Dorian (2019), Hurricane Florence (2018), and Hurricane Irma (2017). These three cases were long-lived Atlantic hurricanes which each achieved major hurricane status [category 3 or higher on the Saffir–Simpson scale ([Simpson 1974](#))], which provides several days of data over open ocean without influence from nearby landmasses, and several days of data spanning different intensity categories. A brief synoptic overview of each TC is provided in [section 2c](#).

Examples of NUCAPS sounding retrievals for two overpasses in Hurricane Dorian are provided in [Fig. 1](#). All retrievals generated over land are removed for this and all subsequent analyses. For both overpasses, the majority of IR+MW soundings³ were successfully retrieved, meaning they are considered “good” quality (dark green circles in [Fig. 1](#)). For locations closer to the storm center (<300 km in radius), infrared retrievals fail due to the increased density of cloud cover

¹NUCAPS retrievals generated from AIRS/AMSU on the NASA *Aqua* satellite are currently under development and are not yet available to the wider scientific community.

²Using an overlapping field of view between the infrared and microwave instruments, NUCAPS performs cloud-clearing over a 3 × 3 field of regard for *SNPP*, *NOAA-20*, and NASA *Aqua* platforms ([Gambacorta 2013](#)). For NUCAPS soundings derived from IASI/AMSU on *MetOp* platforms, a 4 × 4 field of regard makes the cloud-clearing process more difficult; in addition, the instrument noise is higher in the shortwave band as compared to CrIS/ATMS, which leads to small differences in the algorithm (C. Barnett 2020, personal communication). While this contributes to more failed soundings from *MetOp* platforms, all NUCAPS systems are shown to behave in a similar way.

³The NetCDF variables used to process the IR+MW retrievals are “Temperature()” and “H2O_MR()” for temperature and water vapor mixing ratio, respectively.

FIG. 1. Examples of NUCAPS soundings from a (a) *MetOp-A/B* overpass at 1300 UTC and (b) a *SNPP/NOAA-20* overpass at 1700 UTC for Hurricane Dorian on 27 Aug 2019. Dark green circles represent combined infrared and microwave satellite (IR+MW) sounding retrievals, and filled white circles represent microwave-only (MW-only) sounding retrievals. Dashed yellow lines show 100-km radial bins centered about the storm. The orange star indicates the location of the storm center at the given time.

and intensity of precipitation. However, in both overpasses several MW-only retrievals are still available, which can be used to characterize the thermodynamics of the TC inner core region (filled white circles in Fig. 1). Although information at the innermost radii (0–100 km) may not be readily available with NUCAPS, the combination of both IR+MW retrievals and MW-only retrievals provides sufficient spatial coverage to capture diurnal variations throughout the TC environment. Moreover, while observations do indicate a diurnal cycle in cloud-top brightness temperatures at these innermost radii (Ditchek et al. 2019a), internal gravity wave dynamics suggest that the TC diurnal waves begin to propagate at radii well beyond the storm core (O’Neill et al. 2017), which are well-observed with NUCAPS data.

Table 1 summarizes the number of soundings and the quality flags for each case study. Soundings within 800 km of the storm center are considered here. In total, 66.1% of all retrievals are

good quality; 9.3% indicate a failed infrared retrieval but a successful microwave retrieval; and 24.5% are failed retrievals (i.e., both the infrared and microwave retrievals failed). Hurricane Irma exhibits roughly half the number of IR+MW retrievals as Hurricanes Dorian and Florence, with nearly 2–3 times the amount of MW-only and failed retrievals as the other two cases. Since Irma maintained category-5 hurricane status for an extended period of time (Fig. 2c), it is likely that this prolonged period as a major hurricane (and consequently the cloud and precipitation structure) led to more failed IR+MW retrievals and therefore more MW-only retrievals as compared to other case studies. Excluding the failed retrievals provides a total of 46 304 IR+MW soundings used for analysis in this study.

Figure 2 shows the time series of maximum wind speeds and the timing of the NUCAPS overpasses for the each of the three case studies. Maximum wind speeds are taken from the NHC

TABLE 1. The number of NUCAPS sounding retrievals used in this analysis based on satellite mission and case study. Soundings are categorized based on the quality of the combined infrared and microwave retrieval.

No. of NUCAPS soundings					
Sounding quality	Mission	Dorian	Florence	Irma	Total (% total)
IR+MW	<i>SNPP/NOAA-20</i>	8887	8329	4628	46 304 (66.1%)
	<i>MetOp-A/B</i>	7870	9513	7077	
MW-only	<i>SNPP/NOAA-20</i>	583	889	2867	6557 (9.3%)
	<i>MetOp-A/B</i>	402	1068	748	
Failed	<i>SNPP/NOAA-20</i>	639	627	715	17 176 (24.5%)
	<i>MetOp-A/B</i>	3025	4307	7863

FIG. 2. The 1-h interpolated maximum wind speeds (kt) for (a) Hurricane Dorian, (b) Hurricane Florence, and (c) Hurricane Irma. Blue stars indicate each UTC hour that corresponds to retrievals from a *SNPP/NOAA-20* overpass, and green stars indicate a *MetOp-A/B* overpass. Intensity categories based on the Saffir–Simpson scale are indicated by the shaded colors. Overpasses are omitted on dates prior to storm genesis, near land, and after landfall.

Automated Tropical Cyclone Forecasting (ATCF) System b-deck files (i.e., the best track intensity files; [Sampson and Schrader 2000](#)), which are linearly interpolated to each hour. Overpasses are omitted on days prior to storm genesis [defined when a tropical depression is classified by the National Hurricane Center (NHC)], when the TC is near land, and after a storm makes landfall on the U.S. mainland to isolate periods in time when a well-defined circulation is located mainly over open ocean. The TC was deemed affected by land when retrievals generated over land accounted for more than half of the profiles generated in the radial bins. Data are obtained for each storm on the following dates: 25 August–1 September 2019 for Hurricane Dorian, 1–10 September 2018 for Hurricane Florence, and 30 August–8 September 2017 for Hurricane Irma. With the combination of *SNPP*, *NOAA-20*, and *MetOp-A/B* satellites, thorough coverage is provided by

the NUCAPS soundings throughout the lifetime of each storm. For example, several overpasses occur during the rapid intensification (RI) periods of Dorian (30 August–1 September 2019 in [Fig. 2a](#)) and Florence (4–5 and 9–10 September 2018 in [Fig. 2b](#)). Irma's prolonged period as a category-5 hurricane is also well observed (5–8 August 2017 in [Fig. 2c](#)).

b. Storm-centered composites

Storm-centered composite anomalies are produced to reveal the diurnal evolution of the TC environment. Storm position information is taken from the NHC ATCF System b-deck files and are linearly interpolated to each hour. For each calendar day, NUCAPS soundings from each overpass are radially binned based on the distance from storm center, with a bin width of 100 km and extending to 800 km from the storm center. Only soundings with a quality flag of 0 (where both the

FIG. 3. Vertical profiles of temperature anomalies (K) derived from *SNPP/NOAA-20* NUCAPS satellite sounding retrievals for Hurricane Dorian. Anomalies are computed at each hour, and then averaged from 0000 to 0400 LT (blue lines) and from 1200 to 1600 LT (yellow lines). Vertical profiles are plotted every 100 km from the storm center: (a) 0–100, (b) 100–200, (c) 200–300, (d) 300–400, (e) 400–500, and (f) 500–600 km. Plus signs indicated at a specific pressure represent statistical significance at the 95% level. Shading indicates $\pm$ the standard error for each pressure layer.

infrared and microwave retrieval are successful) are retained; all other soundings are removed from this analysis.⁴ A daily mean sounding is computed for each radial bin by averaging all available soundings within each radial bin on a given day; this daily mean sounding is then subtracted from each profile on each corresponding day to yield an anomaly profile. All soundings are converted to local time (LT) and composited every 4 h (e.g., 0000–0400, 0400–0800, 0800–1200, 1200–1600, 1600–2000, 2000–0000 LT). This 4-h time interval is consistent with the variability in the location and timing of the TC diurnal pulse, indicated for a wide range of Atlantic storms using the TC diurnal clock (Dunion et al. 2014; Ditchek et al. 2019a). Composite anomaly profiles are then averaged over the lifetime of the storm to analyze the mean diurnal signal.

With local overpass times of 0130 and 1330 local time for *SNPP* and *NOAA-20* satellites and 0930 and 2230 local time for

MetOp satellites, this dataset spans the diurnal cycle. Here, the terminology describing each of the different time bins is defined as the following: 0000–0400 LT as “overnight”; 0800–1200 LT as “morning”; 1200–1600 LT as “afternoon”, and 2000–2400 LT as “evening.” Overpasses times in this dataset do not cover the time bins from 0400–0800 to 1600–2000 LT. For the Atlantic TCs considered in this study, this allows for analysis of the TC diurnal pulse when the estimated location is at 100 and 400 km for *SNPP* and *NOAA-20* satellites and 300 km from MetOp satellites, based on the TC diurnal clock (Dunion et al. 2014; Ditchek et al. 2019a). For evening MetOp overpasses, the timing allows for the assessment of the TC thermodynamic environment prior to the development of a new diurnal pulse. While the horizontal resolution and the lack of observations in regions of dense cloud cover may prevent sampling of satellite soundings in the narrow region of the pulse itself, it will capture the surrounding environments both ahead of and behind the diurnal pulse.⁵

⁴ Analysis can also be performed using only the microwave retrievals (i.e., where the infrared retrieval failed, but the microwave retrieval was successful; quality flag = 1). While such analysis does demonstrate a diurnal cycle for the three cases considered here (not shown), additional case studies are needed to interpret the value of only using the microwave retrievals.

⁵ This assumes that the diurnal pulse follows the TC diurnal clock; there are observed diurnal pulses that can be “off the clock” (Ditchek et al. 2019a). These pulses are much less frequent in storms observed from 1982 to 2017.

FIG. 4. As in Fig. 3, but for water vapor mixing ratio (g kg^{-1}).

In addition to temperature and water vapor mixing ratio, storm-centered composite anomalies of lapse rates are also analyzed. Following the methodology of Berndt et al. (2020), lapse rates can be calculated according to the Poisson equation:

$$\frac{P}{P_0} = \frac{T}{T_0} e^{\frac{-g}{Ra}}, \quad (1)$$

where P and T are the pressure and temperature at the level of interest, P_0 and T_0 are the standard pressure and temperature, g is the gravitational constant, R is the gas constant for dry air, and a is the lapse rate (K km^{-1}). Rearranging the equation and solving for a yields

$$a = \left(\frac{-g}{R} \right) \left(\frac{\ln \frac{T_2}{T_1}}{\ln \frac{P_2}{P_1}} \right), \quad (2)$$

where the temperature and pressure of the top and bottom of each layer (P_2 , T_2 and P_1 , T_1 , respectively) are substituted for P , T , P_0 , and T_0 , respectively.

Data in each radial bin are approximately normally distributed about the mean (not shown). The uncertainty in the composite mean anomalies is estimated using the standard deviation of the mean, or the standard error (Taylor 1997):

$$\sigma_x = \frac{\sigma_x}{\sqrt{N}}, \quad (3)$$

where

$$\sigma_x = \sqrt{\frac{1}{N-1} \sum (x_i - \bar{x})^2} \quad (4)$$

is the standard deviation, N is the sample size, and x_i and $\bar{x}$ are the individual anomalies and the mean of the anomalies, respectively.

c. Synoptic overview of storms

Hurricane Dorian originated from a tropical wave that emerged from the west coast of Africa on 19 August 2019 (Avila et al. 2020). Despite experiencing moderate vertical wind shear of about 15 kt ($1 \text{ kt} \approx 0.51 \text{ m s}^{-1}$) as it progressed westward, Dorian became a tropical depression at 0600 UTC 24 August and a tropical storm by 1800 UTC, about 700 n mi (1 n mi = 1.852 km) east-southeast of Barbados. After encountering both drier environmental air and interacting with the mountainous terrain in Barbados, Dorian began to intensify and became a hurricane at 1530 UTC 27 August. Dorian then encountered very favorable conditions of low wind shear, abundant moisture, and warm sea surface temperature (SST), allowing it to rapidly intensify to a category-3 hurricane at 1800 UTC 30 August, and a category 5 with peak

FIG. 5. Vertical profiles derived from *MetOp-A/B* NUCAPS satellite sounding retrievals for Hurricane Dorian. (a),(b) Temperature (K) and (c),(d) water vapor mixing ratio (g kg^{-1}). Fields represent composite anomalies computed at each hour, and then averaged from 0800 to 1200 LT (magenta lines) and from 2000 to 2400 LT (black lines). Vertical profiles are plotted (left) from 100 to 200 km and (right) from 400 to 500 km. Plus signs indicated at a specific pressure represent statistical significance at the 95% level. Shading indicates $\pm$ the standard error for each pressure layer.

estimated winds of 160 kt and minimum pressure of 910 mb on 1 September. Dorian moved very slowly westward through the Bahamas and eventually turned northward on 3 September, moving parallel to the U.S. Southeast coast. Dorian became post-tropical at 1800 UTC 7 September and was absorbed by an extratropical low at 0600 UTC 9 September over the northern Atlantic Ocean.

Hurricane Florence developed from a tropical wave that moved off the west coast of Africa on 30 August 2018 (Stewart and Berg 2019). It became a tropical depression at 1800 UTC 31 August and a tropical storm 12 h later at 0600 UTC 1 September. Moving west-northwest, Florence became a hurricane at 1200 UTC 4 September. Despite experiencing environmental conditions that are not typically associated with strengthening, such as vertical wind shear of 15–20 kt, SSTs less than 27°C , and low midlevel relative humidity, Florence underwent RI to a category-4 hurricane by 1800 UTC 5 September, followed by rapid weakening. Florence reached a peak intensity of 130 kt at 1800 UTC 11 September after a second period of RI, and made landfall as a category-1 hurricane at 1115 UTC 14 September. Florence became a tropical storm by 0000 UTC 15 September, a depression by 1800 UTC 16 September and eventually dissipated around 1200 UTC 18 September.

Hurricane Irma originated from a tropical wave that exited the west coast of Africa on 27 August 2017 (Cangialosi et al. 2018). It became a depression at 0000 UTC 30 August and a

tropical storm only 6 h later at 0600 UTC 30 August. Irma moved westward, steered by high pressure to the north, and encountered an environment favorable for intensification, including low vertical wind shear, a moist troposphere, and warm SST. Irma became a hurricane at 0600 UTC 31 August and a major hurricane by 0000 UTC 1 September, only 2 days after becoming a depression. Irma reached a peak intensity of 155 kt after a period of RI at 1800 UTC 5 September, and made several landfalls through the Caribbean before turning north-northwest toward the United States. Irma made a final landfall near Marco Island, Florida, at 1930 UTC 10 September. Irma became a remnant low by 0600 UTC 12 September and dissipated around 1200 UTC 13 September.

3. Results

All NUCAPS results use only IR+MW profiles, unless otherwise stated. Only retrievals over the ocean are analyzed. For simplicity, we start with analysis of NUCAPS satellite soundings in Hurricane Dorian. We will compare results for all three cases in section 3b.

a. Hurricane Dorian

Vertical profiles of composite temperature anomalies from *SNPP* and *NOAA-20* and for radial bins ranging from 0 to 600 km are shown in Fig. 3. Results for the 0–100-km radial bin included only one afternoon profile for comparison and are not shown. Results for profiles in radial bins > 600 km are similar

FIG. 6. Composite anomaly vertical profiles of (a),(b) temperature (K) and (c),(d) water vapor mixing ratio (g kg^{-1}) on different dates derived from *SNPP/NOAA-20* NUCAPS satellite sounding retrievals for Hurricane Dorian. Composite anomalies are computed from 200 to 300 km in radius at each hour, then averaged (left) from 0000 to 0400 LT and (right) from 1200 to 1600 LT. No soundings are indicated for this radial bin on both 28 Aug and 1 Sep 2019.

to the results shown for radial bins of 500–600 km, and are omitted from the figures. Two time periods, 12 h apart, are captured by overpasses from these satellites: a morning overpass from 0000 to 0400 LT and an afternoon overpass from 1200 to 1600 LT. For each radial bin, a clear diurnal cycle exists in temperature throughout the depth of the atmosphere. Nearly equal and opposite magnitudes are observed between the overnight and afternoon composite anomaly profiles for radial bins between 100 and 600 km (Figs. 3b–f). For radii greater than 400 km, positive anomalies between 0.1 and 0.2 K are observed from 800 to 200 mb during the day, extending through the majority of the troposphere. At night, negative anomalies of similar magnitude are observed over these same pressure layers. These profiles, which are mostly outside of the dense cloud cover in the TC inner core, describe the surrounding storm environment and represent a clear-sky radiative response. At nearly all

pressure layers, differences in the overnight and afternoon profiles are statistically significant at the 95% level, given by the Student's t test. For radial bins less than 400 km from the storm center, positive composite temperature anomalies observed between 200 and 400 mb and from 1200 to 1600 LT demonstrate absorption of solar radiation by upper-level clouds (Figs. 3b–d). Over these same pressure layers, negative temperature anomalies are observed from 0000 to 0400 LT and from 0 to 400 km, indicating longwave cooling. Statistical significance is indicated near 300 mb for radial bins of 100–200 km, and for pressure layers less than 400 mb and greater than 700 mb for radial bins of 200–400 km.

Similar daily patterns are observed for composite water vapor mixing ratio anomaly profiles (Fig. 4). Results for the 0–100-km radial bin included only one afternoon profile for comparison and are not shown. For all radii, two distinct layers are apparent in both overnight and afternoon profiles: one layer between

FIG. 7. As in Figs. 3 and 4, but for lapse rate (K km^{-1}). Note the difference in the range of the x axis for (a),(b) as compared to the other plots.

600 and 200 mb, and another from 1000 to 600 mb. Positive water vapor mixing ratio anomalies are observed from 600 to 200 mb and from 0000 to 0400 LT; these anomalies are largest for radii between 100 and 300 km, with magnitudes near $0.1\text{--}0.15 \text{ g kg}^{-1}$, which is approximately 2%–5% of the mean value at these levels (Figs. 4b,c). From 1200 to 1600 LT, all radii demonstrate negative water vapor mixing ratio anomalies from 600 to 200 mb, with the largest magnitudes at radii $< 300 \text{ km}$ (Figs. 4b,c), where afternoon composite anomaly magnitudes constitute 10%–15% of the mean value for these levels. The afternoon composite anomalies from 600 to 200 mb are similar to the midlevel (700 hPa) water vapor mixing ratio values shown in Dunion et al. (2019), which decreased in the mid- to late afternoon from 150 to 300 km in radius to values $0.5\text{--}2.5 \text{ g kg}^{-1}$ drier than morning (see their Fig. 10). For the lower layer from 1000 to 600 mb, radii from 200 to 300 km show negative water vapor mixing ratio anomalies between -0.2 and -0.1 g kg^{-1} from 0000 to 0400 LT and positive water vapor mixing ratio anomalies near 0.25 g kg^{-1} from 1200 to 1600 LT that are statistically significant at the 95% level. For radii greater than 400 km, positive anomalies between 0.1 g kg^{-1} are observed from 1200 to 1600 LT, which are approximately 2%–4% of the mean value for the lower levels. Composite water vapor mixing ratio anomalies are statistically significant at the 95% level above 600 mb for radial bins of 100–400 km (Figs. 4b–d), and throughout most of the atmosphere for radial bins from 200 to 300 km and greater than 500 km (Figs. 4c,f).

Magnitudes of composite water vapor mixing ratio anomalies from 600 to 200 mb are larger closer to the TC, likely due to the influence of clouds. From 0000 to 0400 LT, the 100–300-km radial band is more moist relative to the mean, particularly in the mid- to upper levels. Enhancement of the water vapor mixing ratio anomalies at upper levels from 100 to 300 km as compared to profiles in the external TC environment is consistent with the increase in humidity caused by the longwave cloud–radiative feedback (Ruppert et al. 2020). The influence of clouds decreases for radii $> 400 \text{ km}$.

For overpasses from MetOp satellites, composite temperature and water vapor mixing ratio anomalies show very similar results as compared to *SNPP* and *NOAA-20* overpasses (Fig. 5). For simplicity, we only compare profiles at radii from 100 to 200 km and from 400 to 500 km; results for other radial bins are consistent with those shown here. In both the near-storm and outer environments, positive temperature anomalies exist throughout the majority of the atmosphere from 2000 to 2400 LT (Figs. 5a,b). The maximum magnitude of these composite anomalies is near 0.3 K at 700 mb for radii between 100 and 200 km, and $0.25\text{--}0.3 \text{ K}$ at 900 mb for radii between 400 and 500 km. From 0800 to 1200 LT, nearly equal and opposite magnitudes are observed throughout the atmosphere from both 100–200 km and 400–500 km in radius, demonstrating a clear diurnal cycle. Composite water vapor mixing ratio anomalies also indicate a clear diurnal cycle at all pressure layers (Figs. 5c,d). Similar to *SNPP/NOAA-20* overpasses, the magnitudes of composite

FIG. 8. As in Fig. 7, but for *MetOp-A/B* NUCAPS satellite sounding retrievals. Fields represent composite anomalies computed at each hour, and then averaged from 0800 to 1200 (magenta lines) and from 2000 to 2400 LT (black lines). No soundings are available in the radial range from 0 to 100 km.

water vapor mixing ratio anomalies in the mid- to upper levels from 400 to 500 km in radius are smaller than those from 100 to 200 km in radius. Anomalies computed from *MetOp-A/B* overpasses are not statistically significant from 100 to 200 km in radius. *MetOp-A/B* had approximately 5 times as many failed sounding retrievals as *SNPP* and *NOAA-20* for Hurricane Dorian (Table 1), which leads to a smaller sample size in the 100–200-km radial range (not shown). This is expected based on the differences in the cloud-clearing algorithm discussed previously.

Temperature and moisture profiles located in the 200–300-km radial bin for each day analyzed in Hurricane Dorian are shown in Fig. 6. Numerical experiments have shown that the diurnal signal is particularly pronounced in this radial range (Dunion et al. 2019; Trabing and Bell 2021). For each date analyzed, the TC diurnal pulse archive from Ditchek et al. (2019a,b)⁶ shows that all days included a diurnal pulse, with most days exhibiting a long-lived diurnal pulse (≥ 9 h). For both composite temperature and water vapor mixing ratio anomalies, comparing the evening and overnight overpasses (Figs. 6a,c) to the morning and

afternoon overpasses (Figs. 6b,d) reveals diurnal variability on all days, with nearly equal and opposite profiles measured 12 h apart. No soundings were available for this radial bin on both August 28 and 1 September 2019. For composite temperature anomaly profiles, most profiles show negative anomalies above 400 mb and weak negative anomalies below 600 mb at night (Fig. 6a). During the day, composite temperature anomalies above 400 mb are near 0.5 K, with nearly all profiles showing weak positive below 600 mb (Fig. 6b). Composite water vapor mixing ratio anomaly profiles exhibit moistening overnight in the upper levels and drying in the lower levels (Figs. 6c,d). On 30 August 2019 (purple line) and 31 August 2019 (black line), the sign of the anomalies is reversed from 600 to 300 mb in water vapor mixing ratios as compared to the other dates; these anomalies, however, do demonstrate a diurnal signal when comparing the vertical profiles from 0000–0400 to 1200–1600 LT. While day-to-day variability is exhibited in these profiles, a diurnal cycle is clear between the profiles generated at 0000–0400 and 1200–1600 LT. Similar diurnal patterns are also seen in Hurricanes Florence and Irma; both of these storms also had TC diurnal pulses (not shown).

Composite lapse rate anomalies for all radii from 0 to 600 km and from *SNPP* and *NOAA-20* overpasses are shown in Fig. 7. Results for the 0–100-km radial bin included only one afternoon profile for comparison and are not shown.

⁶ Images of TC diurnal pulses from this database are available at http://www.atmos.albany.edu/student/sditchek/Research_PulseArchive.html.

FIG. 9. Vertical profiles of temperature (K) anomalies for Hurricane Dorian (purple line), Hurricane Irma (cyan line), and Hurricane Florence (green line). Profiles are composite averages from 200 to 300 km in radius and (a) from 0000 to 0400 LT, (b) from 0800 to 1200 LT, (c) from 1200 to 1600 LT, and (d) from 2000 to 2400 LT. Solid lines in (a) and (c) represent NUCAPS satellite sounding retrievals from *SNPP* and *NOAA-20* overpasses, respectively; and dashed lines in (b) and (d) are NUCAPS satellite sounding retrievals from *MetOp-A/B* overpasses.

There is substantial variability in lapse rate anomalies for all radial bins, and changes in lapse rates between overnight and afternoon overpasses are small. However, for radii between 200 and 400 km, larger diurnal changes in composite lapse rate anomalies are observed in the mid- to upper troposphere from 200 to 600 mb, which are statistically significant (Figs. 7c,d). Positive lapse rate anomalies between 0.1 and 0.2 K km⁻¹ are observed from 250 to 600 mb and from 1200 to 1600 LT for radii from 100 to 400 km (Figs. 7b-d). If the mean cloud top is near 200 mb, this stability tendency is consistent with the effects of shortwave warming during the day and longwave cooling at night, which both maximize near cloud top.⁷ Averaging over

⁷ We are unable to calculate the location of the cloud top using this dataset.

many profiles may also smooth the signal at these levels. In addition to radiation, convection and turbulence can significantly modify the static stability profile near the tropopause (Duran and Molinari 2019), and the relative contributions of each of these processes is difficult to ascertain. From 0000 to 0400 LT, negative lapse rate anomalies between -0.1 and -0.2 K km⁻¹ are observed from 300 to 600 mb and from 200 to 400 km in radius, consistent with decreased static stability due to longwave cooling. Although the magnitudes of the composite lapse rate anomalies appear small, the variance in these distributions from day to day is large, with standard deviations of up to 3 K km⁻¹ (not shown). During the afternoon, statistically significant negative anomalies are observed above the TC outflow layer (pressures > 200 mb) for radii between 200 and 400 km (Figs. 7c-d). Above 200 mb, negative lapse rate anomalies that occur directly above the positive lapse rate

FIG. 10. As in Fig. 9, but for water vapor mixing ratio (g kg^{-1}). Note the difference in the range of the x axis for (d) as compared to (a)–(c).

anomalies from 1200 to 1600 LT are consistent with both shortwave warming maximizing at the top of the cirrus canopy and destabilization near the top of the TC outflow due to turbulent mixing (Duran and Molinari 2019). Magnitudes of these composite lapse rate anomalies are from near -0.2 to -0.1 K km^{-1} from 200 to 400 km in radius.

Similar mid- to upper-tropospheric diurnal changes in lapse rates are observed for MetOp overpasses (Fig. 8). Overall, larger magnitudes in composite lapse rate anomalies are observed from 200 to 600 mb, and diurnal variability extends to larger radii as compared to Fig. 8. For radial bins from 200 to 400 km, negative lapse rate anomalies between -0.2 and -0.1 K km^{-1} are observed from 2000 to 2400 LT (Figs. 8c–d). Positive lapse rate anomalies are observed from 0800 to 1200 LT from 200 to 600 mb, with an average magnitude of 0.1 K km^{-1} from 200 to 400 km in radius (Figs. 8c–d). Near 200 mb, positive lapse rate anomalies of 0.1 – 0.2 K km^{-1} are observed from 200 to 400 km in radius and from 2000 to 2400 LT

(Figs. 8c–d). The larger magnitudes for mid- to upper-level composite lapse rate anomalies during the evening and morning overpasses for MetOp satellites as compared to *SNPP* and *NOAA-20* suggest that variability due to radiation at these time periods is more pronounced. Since the MetOp overpasses occur closer to the timing of sunrise and sunset, this suggests that larger diurnal changes in atmospheric stability occur closer to the daytime and nighttime transitions.

b. Comparison of all case studies

Vertical composite temperature anomaly profiles reveal similar diurnal cycles in all three storms (Fig. 9). From 0000 to 0400 LT, all NUCAPS profiles indicate negative temperature anomalies between -0.1 and -0.2 K near 200 mb, and also below 800 mb (Fig. 9a). Weak positive anomalies near 0.1 K are observed from 600 to 300 mb for Hurricanes Irma and Florence. The sign of these anomalies is reversed 12 h later at each pressure layer (Fig. 9c). In the mid- to lower troposphere,

FIG. 11. As in Figs. 9 and 10, but for lapse rate (K km^{-1}). Note the difference in the range of the x axis for (a) and (c) as compared to (b) and (d).

largest composite temperature anomaly magnitudes are observed in the morning (0800–1200 LT) and evening (2000–2400 LT) for all cases (Figs. 9b, d). Cooling from -0.4 to -0.2 K relative to the mean is observed during the morning for Dorian and Florence (Fig. 9b), which transitions to a warming of 0.2 – 0.4 K relative to the mean in the early evening (Fig. 9d). Differences in cloud-top height between the storms and throughout the lifetime of each storm could cause the shallow anomalies near the tropopause to be smoothed out when the observations are averaged.

Composite water vapor mixing ratio anomalies also reveal a clear diurnal signal for all cases at a radius of 200–300 km (Fig. 10). From 0000 to 0400 LT, negative anomalies exist near -0.2 g kg^{-1} from 1000 to 600 mb, with positive anomalies near 0.1 g kg^{-1} indicated from 600 to 200 mb in Hurricane Dorian (Fig. 10a), consistent with Fig. 4. The sign of these anomalies is reversed 12 h later, with nearly equal and opposite magnitudes observed for each case (Fig. 10c). From 0800 to 1200 LT, positive anomalies exist between 1000 and 600 mb for

Hurricanes Dorian and Irma, with weak negative anomalies from 600 to 200 mb (Fig. 10b). Comparing these morning profiles to those from 2000 to 2400 LT (Fig. 10d) indicates a diurnal signal. The diurnal cycle seems to be reversed for Hurricane Florence, however, as compared to Dorian and Irma (Figs. 10b,d). The reason for this difference at this time is unknown; however, future work should consider variability in the TC environment and internal variability (e.g., eyewall replacement cycles) as possible causes for the difference in composite water vapor mixing ratio anomalies.

The largest changes in stability for all three case studies are observed in the mid- to upper troposphere in both the morning and evening (Fig. 11). From 0800 to 1200 LT, all three cases indicate positive anomalies between 600 and 200 mb, with magnitudes of 1.0 K km^{-1} (Fig. 11b). In the early evening (2000–2400 LT), Dorian and Florence indicate negative lapse rate anomalies from 600 to 200 mb (Fig. 11d). Irma demonstrates more variability overall from 2000 to 2400 LT as compared to

FIG. 12. Number of IR+MW-only profiles in each radial bin for all TC intensities (purple bars), intensities ranging from tropical storm to category-2 strength, as defined by the Saffir–Simpson scale (cyan bars), and intensities ranging from category-3–5 strength (green bars).

the other two cases, and shows positive anomalies near 0.2 K km^{-1} and near 400 mb; this is due to the increased amount of failed retrievals in Irma for *MetOp-A/B* overpasses, leading to a smaller sample size (Table 1). Dorian and Irma exhibit negative anomalies with magnitudes near -0.1 K km^{-1} and between 600 and 200 mb from 0000 to 0400 LT (Fig. 11a). The anomalies are reversed from 1200 to 1600 LT, with positive values near 0.1 K km^{-1} shown between 600 and 200 mb (Fig. 11b). Florence shows similar patterns to Dorian and Irma near 300 mb in Figs. 11a–b; however, anomalies for Florence differ from the other two case studies between 600 and 400 mb. The decreased stability in the mid- to upper troposphere in evening and overnight followed by enhanced stability in the morning and afternoon suggests that anomalous convection forms in the overnight hours; latent heat released by anomalously strong convection leads to positive midlevel lapse rate anomalies in the morning. Near 200 mb, similar to Fig. 3c, all profiles indicate positive anomalies from 0000 to 0400 LT and negative anomalies from 1200 to 1600 LT (Figs. 11a,c).

c. Sensitivity to storm intensity

Figure 12 demonstrates the number of IR+MW soundings as a function of both radial bin and storm intensity. Intensities are split into two categories: 1) “weaker storms,” defined as storms with intensities ranging from tropical storm strength to category-2 strength on the Saffir–Simpson scale (Figs. 13b,e); and 2) “stronger storms,” defined as storms with intensities from categories 3 and above (Figs. 13c,f). The number of soundings retrieved increases with increasing radial bin for all categories, which is a result of the decreasing density of cloud cover with distance from the storm center, as well as the larger area within each radial bin at larger

radii. Soundings are generated in all radial bins for both weaker and stronger storms. For radial bins $< 400 \text{ km}$, the majority of soundings retrieved pertain to TCs of weaker intensity, especially for radial bins between 100 and 300 km. For radial bins $> 400 \text{ km}$, stronger storms contribute approximately one-third of all profiles.

Vertical profiles of composite temperature anomalies generated from *SNPP* and *NOAA-20* as a function of storm intensity are shown in Figs. 13a–f. Results are shown for all radial bins in Hurricane Dorian. For both intensity categories, a diurnal cycle exists in both the 200–300 km radial range (Fig. 13b,c) and in the 400–500-km radial range (Figs. 13e,f). Similar to Fig. 3, in the upper troposphere from 200 to 400 mb both weaker and stronger storms exhibit positive temperature anomalies of $0.2\text{--}0.4 \text{ K}$ during the day and negative temperature anomalies near -0.2 K at night, which reflects the absorption and emission of radiation by upper-level clouds near center of the TC (Figs. 13b,c). Similar to Figs. 3e,f, for radii from 400 to 500 km both intensity categories demonstrate nearly equal and opposite anomaly profiles that extend through the depth of the troposphere, suggesting less influence from clouds (Figs. 13e,f). Comparison of composite temperature anomaly profiles for weaker storms (Figs. 13b,e) to those for all intensity categories (Figs. 13a,d) demonstrates very close agreement at all pressure layers, suggesting that the composite temperature anomalies for all intensities largely reflect patterns from weaker storms. For all intensity categories in the 200–300-km radial range, composite temperature anomaly profiles from 1000 to 700 mb are influenced by the stronger storms, which demonstrate larger magnitudes for both overnight and afternoon profiles in the lower troposphere (Fig. 13c).

Similar sensitivity patterns to storm intensity are observed for composite water vapor mixing ratio anomaly profiles

FIG. 13. Vertical profiles of temperature (K) derived from *SNPP/NOAA-20* NUCAPS satellite sounding retrievals for Hurricane Dorian for (a),(d) all intensities; (b),(e) intensities from tropical storm strength to category-2 intensity; and (c),(f) category-3–5 intensity. Fields represent composite anomalies computed at each hour, and then averaged from 0000 to 0400 LT (blue lines) and from 1200 to 1600 LT (yellow lines). Composite averages (top) from 200 to 300 km, and (bottom) from 400 to 500 km. Plus signs indicated at a specific pressure represent statistical significance at the 95% level. Shading indicates $\pm$ the standard error for each pressure layer. “Tropical Storm” is abbreviated “TS” in the titles of (b) and (e).

(Figs. 14a–e). Overall, composite water vapor mixing ratio anomalies for all intensity categories (Figs. 14a,d) largely reflect the diurnal patterns of weaker storm intensities, which demonstrate a clear diurnal cycle throughout the depth of the troposphere (Figs. 14b,e). For stronger storms, the influence of the diurnal cycle is less clear, especially for radial ranges from 400 to 500 km (Figs. 14c,e). Uncertainty shading shows much larger variability for stronger storms at these radial ranges.

Comparing the composite water vapor mixing ratio anomaly profiles for weaker storms and stronger storms from 200 to 300 km in radius and from near 600–300 mb shows that, while both intensity categories exhibit a diurnal pattern in water vapor mixing ratio from day (1200–1600 LT) to night (0000–0400 LT), the sign of the anomalies is reversed; for weaker storms, positive water vapor mixing ratios near $0.1\text{--}0.2\text{ g kg}^{-1}$ are observed at night from 400 to 600 mb (Fig. 14b); stronger storms exhibit

FIG. 14. As in Fig. 13, but for water vapor mixing ratio (g kg^{-1}).

negative water vapor mixing ratios near -0.05 g kg^{-1} in these same pressure layers (Fig. 14c). Similarly, during the day, negative temperature anomalies with a maximum magnitude of -0.3 g kg^{-1} near 600 mb are observed for weaker storms, while positive temperature anomalies with a maximum value near 0.1 g kg^{-1} are observed for stronger storms. This difference in pattern between the weaker and stronger storms is masked by the composite averaging across all intensity categories. The sample size of soundings for storms with intensities of category 3 and above is much smaller for those of lower intensity for radii from 200 to 300 km (Fig. 12), which could affect the composite averages. Further case studies are needed to

understand this sensitivity to the diurnal response in moisture in the upper troposphere based on storm intensity, and to determine if other TC structural changes, such as eyewall replacement cycles, could also affect these composite averages.

4. Discussion and conclusions

The goal of this work is to investigate the usefulness of hyperspectral infrared satellite sounding retrievals in observing the TC diurnal cycle. Vertical profiles of temperature, water vapor mixing ratio, and lapse rate anomalies are composited in a storm-centered framework for three different TCs—Hurricanes

Dorian (2019), Florence (2018), and Irma (2017)—to analyze the thermodynamic evolution of both the TC inner core and surrounding environments. For each case study, composites of temperature, moisture, and stability anomalies at various time intervals and radii from the storm center demonstrate a coherent diurnal cycle that extends throughout the depth of the troposphere. For Hurricane Dorian, composite temperature, water vapor mixing ratio, and lapse rate anomalies are significant at the 95% level in the upper troposphere for radii > 100 km and throughout the troposphere for radii > 400 km.

The diurnal thermodynamic evolution observed in NUCAPS satellite soundings suggests that changes in temperature, moisture, and stability are closely related to the absorption of solar radiation in both cloudy and clear-sky environments. Near the TC inner core (< 300 km in radius), cooling of the mid- to upper levels after sunset coincides with moistening of the mid- to upper levels and steepening of mid- to upper-level lapse rates relative to the mean environment, promoting an environment favorable to convection. This enhancement of inner-core moisture at upper levels overnight is consistent with the increase in humidity caused by the longwave cloud-radiative feedback (Ruppert et al. 2020), and has been shown to accelerate both TC genesis and intensification (Ruppert et al. 2020; Nicholls 2015). Warming induced by the absorption of longwave radiation within deep convective clouds near the core of the TC drives upward motion and promotes moistening of the atmosphere (Ruppert et al. 2020). The overnight increase in both low-level radial and tangential winds shown in both observational (Zhang et al. 2020) and numerical studies of the TC diurnal cycle (Navarro and Hakim 2016; Navarro et al. 2017; Dunion et al. 2019; Evans and Nolan 2019) is also consistent with this intensification. In the clear-sky environment, warming is observed throughout the depth of the troposphere during the day as solar radiation is absorbed; moistening is also observed in the low to midtroposphere. Above 600 mb, diurnal variations of water vapor mixing ratio anomalies in the clear-sky atmosphere are much smaller in comparison to the cloudy atmosphere. Diurnal variability of both temperature and water vapor mixing ratio anomalies are much larger for cloudy regions closer to the inner core of the TC.

Stability changes are largest near sunrise and sunset in the mid- to upper troposphere near the TC inner core, with destabilization relative to the mean environment at night and stabilization during the day. This pattern in static stability corresponds to the diurnal variability described in a numerical simulation, where increased CAPE is observed after local sunset (Dunion et al. 2019). Moreover, new diurnal pulses are observed to form from 0 to 100 km in radius and from 0000 to 0400 LT (Ditchek et al. 2019a), many of which are electrically active (Ditchek et al. 2019b). The soundings shown here reveal an environment more favorable to the development of convection following local sunset, which persists through the early morning. The close correspondence of stability patterns between the TC observational datasets and the numerical simulation lends support to the numerical results, and could partially explain why new diurnal pulses tend to form after local sunset (Dunion et al. 2014).

While stronger storms (defined as category 3 and above on the Saffir–Simpson scale) do demonstrate a clear diurnal signal, more profiles are generated for weaker storms, which comprise the majority of the composite averages. For water vapor mixing ratio anomalies, the sign of the diurnal signal is reversed between weaker and stronger storms, and much larger variability in anomalies is exhibited for stronger storms, suggesting that the diurnal cycle of moisture is not consistent among storms of varying intensity. More case studies are needed to further understand the diurnal cycle in water vapor mixing ratios.

The true magnitude of the diurnal cycle is likely not fully captured using remote sensing. Moreover, composite averaging smooths the variability, particularly near the tropopause where large fluctuations can occur over thin layers. Similar studies using either radiosondes or dropsondes where possible to measure the diurnal variability in temperature, moisture, and stability are needed to understand the full extent of these diurnal changes. Studies relating these anomalies to the location of the cloud top may also be fruitful avenues for future work. However, given the capabilities and reliability of NUCAPS soundings as demonstrated in previous studies in a variety of thermodynamic environments, especially in the mid- to upper levels of the atmosphere, we expect that the results presented here do accurately demonstrate the diurnal thermodynamic variability of the three analyzed TCs.

These results demonstrate that both satellite sounding retrievals and remote sensing from polar-orbiting satellites are useful tools in examining diurnal changes in the TC thermodynamic environment. Moreover, hyperspectral infrared satellite soundings in general can be a valuable additional tool for measuring thermodynamics in the TC environment, especially in the absence of aircraft reconnaissance. The three cases considered here were similar in that they all had favorable conditions for intensification and reached major hurricane status; future work should assess the sensitivity of these results to differences in the large-scale environment, such as changes in the magnitudes of vertical wind shear or the presence of dry air; other avenues include relating these thermodynamic changes to observed diurnal changes in convection and precipitation.

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Data availability statement. SNPP, NOAA-20, and MetOp-A/B NUCAPS satellite sounding products are publicly available

using the NOAA Comprehensive Large Array-Data Stewardship System (CLASS) Website (<https://www.bou.class.noaa.gov/saa/products/welcome>).

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