MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Tropical Cyclone Diurnal Cycle Experiment

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Requirements: Categories 2–5

Plain Language Description: This experiment aims to collect observations that improve the understanding of how day-night fluctuations in radiation affect the intensity and structure of hurricanes. One component of these oscillations is a phenomenon called the tropical cyclone diurnal cycle where the cloud field of storms are seen to expand and contract each day. These daily expansions are associated with a pulse of thunderstorms and rain that travel hundreds of kilometers away from the storm center and will be observed using aircraft observations.

Mature Stage Science Objective(s) Addressed:

1) Collect observations targeted at better understanding internal processes contributing to mature hurricane structure and intensity change [*IFEX Goals 1, 3*]

2) Collect observations targeted at better understanding the response of mature hurricanes to their changing environment, including changes in vertical wind shear, moisture and underlying oceanic conditions [*IFEX Goals 1, 3*]

Motivation: The objectives are to obtain quantitative information of the 3-dimensional kinematic and thermodynamic structure and evolution of TC diurnal pulses/waves and examine their effect on TC structure, intensity and the environment surrounding the storm. The TC diurnal cycle (TCDC) may additionally manifest as a substantial midlevel radial return flow underneath the primary TC outflow region during daytime, causing a temporary two-celled overturning circulation. This oscillatory return flow temporarily converges subsiding TC air back toward the storm core at midlevels, increasing midlevel ventilation. Spatio-temporal variability of radiative processes, including but not limited to the TCDC and associated TC diurnal pulses/waves, and their co-variability with TC kinematic and thermodynamic structures may be an important and fundamental TC process.

Background: Although numerous studies have documented the existence of diurnal maxima and minima associated with tropical oceanic convection and the TC upper-level cirrus canopy, we lack a thorough understanding of the nature and causes of these variations and especially the extent to which these variations are important for TCs. It is well known that the coherent diurnal cycle of deep cumulus convection and associated rainfall is different over the land and ocean (Gray and Jacobson 1977; Yang and Slingo 2001), with a peak over land in the late afternoon/early evening due to daytime boundary layer heating and a peak in the early morning over the ocean. In addition, Gray and Jacobson (1977), Mapes and Houze (1993), and Liu and Moncrieff (1998) found that the oceanic peak was more prominent when the preexisting convection was more intense and associated with an organized weather system such as an African easterly wave or mesoscale convective system. Browner et al. (1977) found that the areal extent of the TC cirrus canopy was a minimum at 0300 LST and a maximum at 1700 LST and suggested that this diurnal oscillation might be important for the TC. More recently, Kossin (2002) used storm-centered GOES infrared imagery to calculate azimuthally averaged brightness temperatures and create Hovmöller-type diagrams of brightness temperature diurnal oscillations over time.

Dunion et al. (2014) examined all North Atlantic major hurricanes from 2001 to 2010 and documented a phenomenon they referred to as the TCDC and associated TC diurnal pulses in mature TCs. They examined infrared (IR) geostationary satellite imagery and found a diurnal pulsing pattern in the cloud field that appears to occur with remarkable regularity through a relatively deep layer of the TC. One prominent characteristic of these oscillations is an IR cooling trend that begins forming in the storm's inner core (R~≤150 km) near the time of sunset each day. This cooling takes on a ring-like shape (i.e., TC diurnal pulse) as it continues to move away from the storm overnight, reaching areas several hundred kilometers from the circulation center by the following afternoon. A marked warming of the cloud tops occurs behind this propagating feature and structural changes in the storm are noted as it moves away from the inner core, suggesting that it may have implications for TC intensity change and structure.

Navarro et al. (2017) and O'Neill et al. (2017) showed evidence in numerical TC simulations that these diurnal pulses are internal inertial gravity waves. Ruppert and O'Neill (2019) found in addition that simulated TCs oscillate daily between a single-celled overturning circulation and a stacked two-cell overturning circulation, a balanced response in concert with the diurnal wave response. The diurnal and inertial frequencies can be very similar depending on the environmental flow, and so better understanding of this radial oscillation at midlevels will help disentangle diurnal impacts from dynamic impacts on mechanical work available for driving the primary cyclonic circulation. Additionally, Dunion et al. (2019) examined a hurricane nature run and found strong radially propagating diurnal signals in temperature, winds, and precipitation throughout the depth of the troposphere in that simulated TC.

Chavas et al. (2015) and Chavas and Lin (2016) developed a physical model for the complete radial structure of the TC low-level wind field and showed that it can reproduce the wind structure and its variability of TCs in nature. This model is also able to capture variability in the wind field in models across a wide range of climate states (Reed and Chavas 2015, Cronin and Chavas 2019). The model combines theory for the inner-core convecting region circulation (Emanuel and Rotunno 2011), where the low-level wind-field is dynamically linked to the upper-level turbulent outflow, and the outer non-convecting circulation (Emanuel 2004), where the low-level wind field depends on the radiative-subsidence rate within the free tropopshere. The timescales of both model components are very fast (O(<12 hr)) suggesting that the model may also be able to explain variations in the wind field induced by TC diurnal pulses/waves.

Beyond the influence of the TCDC specifically, radiative feedbacks more generally have been shown in numerical TC simulations to accelerate TC intensification (Nicholls 2015, Wing et al. 2016, Muller and Romps 2018, Smith et al. 2020). These feedbacks result from interactions between spatially and temporally varying radiative heating and the developing TC, in which differential heating between deep convection and the surrounding cloud-free region favors rising motion and moistening in the region of deep convection and generates a circulation response that favors TC intensification. These feedbacks can be quantified by considering the co-variability of column moist static energy, radiative heating, and surface fluxes (Wing et al. 2016, Wing et al. 2019).

Goal(s): Collect observations targeted at better understanding how radiative processes, particularly the TCDC, affect hurricane intensity and structure and the environment surrounding the storm. This experiment will also investigate how the TCDC impacts day-night oscillations of the full 3-D circulation of these storms, particularly winds in the lower and middle levels (inflow and outflow) and the upper-level cirrus canopy (outflow).

Hypotheses:

1. Radially propagating TC diurnal pulses/waves are associated with periods of enhanced upper-level outflow and lower-level inflow that extend through a relatively deep layer of the troposphere, potentially out to large radii.
2. TC diurnal pulses/waves also generate periods of enhanced tangential winds that extend to large radii via changes in the overturning circulation, consistent with theory.
3. Large outflow boundaries (i.e., arc clouds) are favored to form along the leading edge of TC diurnal pulses/waves when low to mid-level dry air is present in the surrounding storm environment (e.g., TPW ≤45 mm located at R~200-400 km/R~110-215 nm) and can stabilize the low to mid-level environment as they propagate away from the storm.
4. Deep midlevel inflow/outflow oscillations at or near the diurnal cycle are more likely with a more axisymmetric storm and may also potentially occur immediately under a highly asymmetric outflow jet (and not elsewhere azimuthally from the center of the storm).
5. Dropsonde-based calculations of radial gradients of column moist static energy can be used in concert with other available observations to estimate radiative feedbacks on TC intensification.

Objectives:

1. Measure the full 3-D circulation, especially radial gradients of low-level inflow and upper-level outflow ahead of and behind outwardly propagating diurnal pulses/waves.
2. Measure radial gradients of low to mid-level (~500 hPa to the surface) temperature and moisture ahead of and behind large (100s of km in length) arc cloud features that are favored to form along the leading edge of outwardly propagating diurnal pulses/waves.
3. Measure wind and quantities that comprise moist static energy calculation for wide transect of TC, including a wide transect of an outflow jet, in order to characterize TC environment vs. outer tropical environment.

4. Measure wind and quantities that comprise moist static energy calculation along an outflow jet (close to natural coordinates of jet as possible), in order to compare to transect and characterize outflow jet mixing rate with environment.

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information):

The experimental UW-CIMSS/HRD TCDC web page:
http://tropic.ssec.wisc.edu/real-time/tc_diurnal_cycle/tc_diurnal_cycle.php
will be used to monitor the development and propagation of TC diurnal pulses/waves for storms of interest. Figure 1 shows the TCDC clock that predicts the approximate times that the diurnal pulse/wave passes various radii and will be used in concert with the UW-CIMSS/HRD TCDC page to plan optimal aircraft sampling strategies and takeoff times.

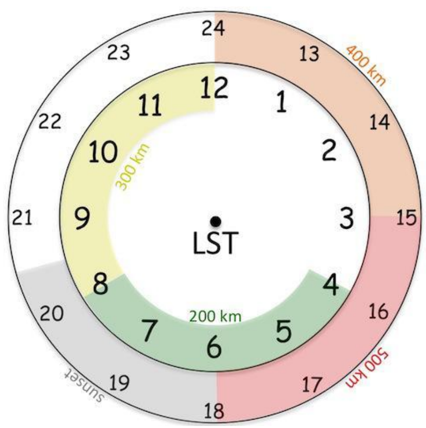

Fig. 1. Conceptual 24-hr TCDC clock that estimates the radial location of TC diurnal pulses/waves propagating away from the storm. TC diurnal pulses typically form around local sunset (~ 1800-2030 LST, gray shading) and begin to propagate away from the inner core, passing R~200 km the following morning (~0400-0800 LST, green shading) and R~400 km by the early to middle afternoon (~1200-1500 LST, orange shading).

The circular outer band convective features depicted in Fig. 2 show examples of TC diurnal pulses/waves as seen by the P-3 LF radar during missions into 2010 Earl and 2014 Edouard. These convectively active (25-45 dBZ) outer band features should be high priority targets during the mission. In order to adequately sample their 3-dimensional structure with the TDR, the P-3 and/or G-IV should completely transect orthogonally across to these outwardly propagating features (at least 20 km/10 n mi beyond their inner and outer edges) during inbound and/or outbound legs or ferries to/from the storm. Since large arc cloud events (100s of km in length, Fig. 3) often appear along the leading edge of diurnal pulses/waves, the P-3 and/or G-IV LPS should monitor the UW-CIMSS TCDC infrared satellite imagery, visible satellite imagery, and the P-3 multi-mode radar (MMR) throughout the mission.

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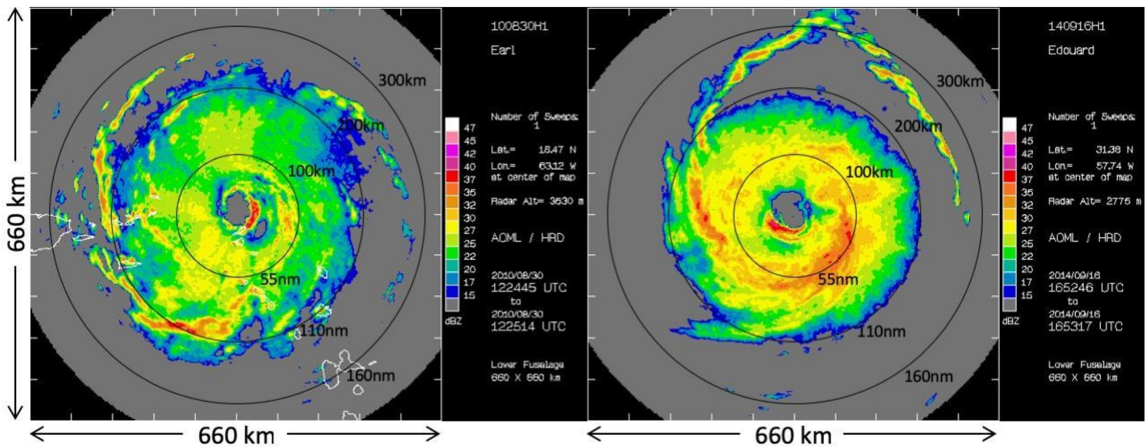

Fig.2. P-3 lower fuselage radar showing 25-40 dBZ circular convective bands in the environments of (left) 2010 Hurricane Earl (R=~200-250 km) at ~830 LST and (right) 2014 Hurricane Edouard (R=~150-300 km) at ~1300 LST. These circular outer band features are often coincident with TC diurnal pulses/waves and may be linked to the TC diurnal cycle.

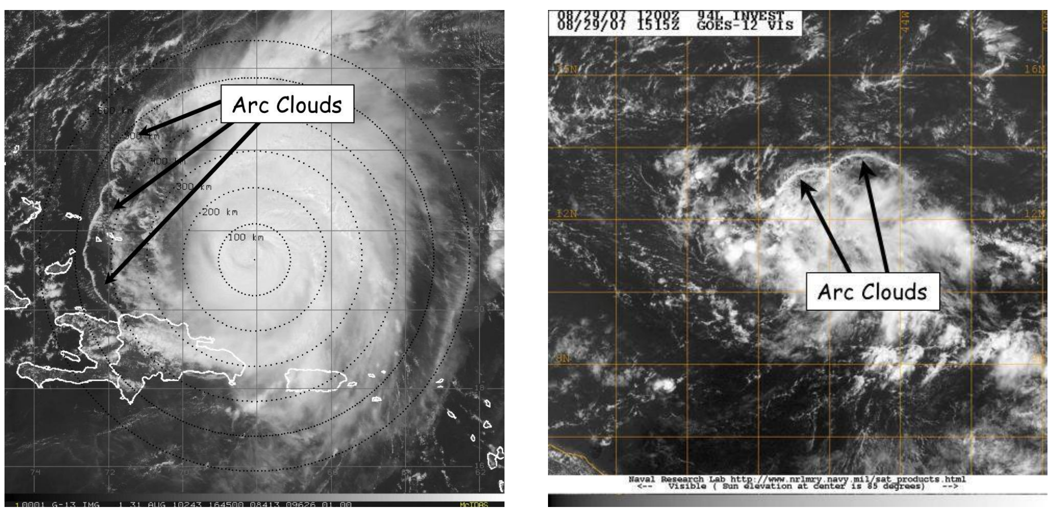

Fig. 3. GOES visible satellite imagery showing arc clouds racing away from the convective cores of (left) 2003 Hurricane Isabel and (right) 2007 Pre-Tropical Depression Felix.

P-3 Pattern 1: This preferentially would be coordinated with the G-IV or can be a stand-alone pattern and takes ~2.5-5.0 hr to complete. Any standard pattern can be flown that provides symmetric coverage (e.g., Rotated Figure-4, Figure-4 butterfly, etc.) with leg lengths adjusted as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulse/wave targets that are indicated by satellite imagery and/or the P-3 MMR. Since this pattern is mainly focused on the TC inner core and near environment, leg lengths should generally not be extended beyond 135-160 n mi (250-300 km). For TC diurnal pulse/wave targets beyond this radius, the ferry to/from the storm can be used to optimize sampling.

The LPS should confirm that the TDR and MMR are operating and collecting data if larger radius features are targeted during a ferry.

P-3 Module 1 (Arc Cloud Module): This is a stand-alone module that takes 0.5-1 hr to complete. When arc clouds emanating from the periphery of the TC convective core are identified using satellite imagery and/or P-3 MMR, perform this break-away pattern by transecting orthogonally across to these outwardly propagating features (Figs. 2 and 3). Since arc clouds typically form when the leading edge of TC diurnal pulses/waves reach areas of low to mid-level dry air (TPW ≤45 mm) in the periphery of the storm [R~160-215 n mi (300-400 km)], targets will tend to be favored in the late morning to mid-afternoon local time (Fig. 1).

G-IV Pattern 1: This preferentially would be coordinated with the P-3 or can be a stand-alone pattern and takes ~4-5.25 hr to complete. A standard G-IV Star with Circumnavigation (optimal) or Star (minimal) pattern will be flown and leg lengths should be adjusted as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulses/waves that are indicated by satellite imagery and/or the P-3 MMR (if available). TC diurnal pulse/wave targets can also be sampled during ferries to/from the storm.

G-IV Module 1 (Arc Cloud Module): This is a stand-alone module that takes 0.5-1 hr to complete. When arc clouds emanating from the periphery of the TC convective core are identified using satellite imagery and/or P-3 MMR (if available), perform this break-away pattern by transecting orthogonally across to these outwardly propagating features (Figs. 2 and 3). Since arc clouds typically form when the leading edge of TC diurnal pulses/waves reach areas of low to mid-level dry air (TPW ≤45 mm) in the periphery of the storm [R~160-215 n mi (300-400 km)], targets will tend to be favored in the late morning to mid-afternoon local time (Fig. 1).

G-IV Module 2 (Transect Module): This is an add-on module that takes 1-1.5 hr to complete. It can be done as a combination of a ferry to-from the storm and a breakaway from a different pattern, in order to get a large-radius cross section of the storm that includes strong outflow in at least one leg (avoiding the eye/eyewall region). Preferable back-to-back missions that capture midnight LST and once shortly after 1200 LST.

G-IV Module 3 (Outflow Axis Module): This is a stand-alone module that takes 1.5-2 hr to complete. Minimal requirement is to fly along the principal outflow axis of the primary outflow jet (described in *Flight Patterns* document). Then cut across same axis perpendicularly in at least one transect at large radii [≥160 n mi (≥300 km)]. This can potentially be flown as a modified ferry to/from another pattern. Ideally this will be done shortly after 1200 LST in order to catch a potential diurnal pulse/wave along-axis. The outflow jet location will be determined using the methodology in the *Flight Patterns* document.

Links to Other Mature Stage Experiments/Modules: The TC Diurnal Cycle Experiment and Modules can be flown in conjunction with following *Mature Stage* experiments and modules: Eye-Eyewall Mixing, Gravity Wave, Convective Burst Structure and Evolution, Rainband Complex Survey, RICO SUAVE, Surface Wind Speed and Significant Wave Height Validation, Synoptic Flow, NESDIS JPSS Satellite Validation, ADM-Aeolus Satellite Validation, and NESDIS Ocean Winds.

Analysis Strategy: This experiment seeks to observe the formation and evolution of the TCDC and associated TC diurnal pulses/waves. Specifically, GPS dropsonde and radar (TDR and MMR) observations will be used to analyze both the inner-core and environmental kinematics and thermodynamics that may lead to the formation of TC diurnal pulses/waves and to document the kinematics, thermodynamics, and precipitation patterns that are associated with radially propagating TC diurnal pulses at various stages of their evolution. GPS dropsonde and radar observations will also be used to place radial gradients of thermodynamic properties in the context of the 3-dimensional kinematic structure of the TC and other available observations of relevant processes. GPS dropsonde observations will be quality controlled and transmitted to the GTS in real-time for assimilation into numerical models. TDR data will also be transmitted to NOAA EMC in real-time.

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