MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Tropical Cyclone Diurnal Cycle Experiment

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Requirements: Categories 2–5

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 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. The TC diurnal cycle and associated TC diurnal pulses/waves 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 TC diurnal cycle 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.

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.
2. 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.
3. TC diurnal pulses/waves co-manifest with full-depth modulations of TC overturning circulation, and a strong diurnal or near-diurnal signal may be detected in radial winds at large radii and midlevels.
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).

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 TC diurnal cycle 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.

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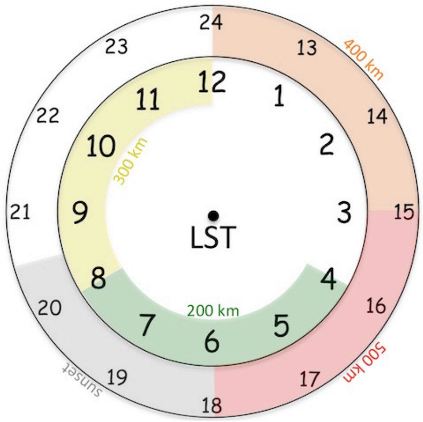

Fig. 1. Conceptual 24-hr TCDC clock that estimates the radial location of TC diurnal pulses/waves propagating away from the storm. TC diurnal pulses typically form around local sunset (~ 1800-2030 LST, gray shading) and begin to propagate away from the inner core, passing R~200 km the following morning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

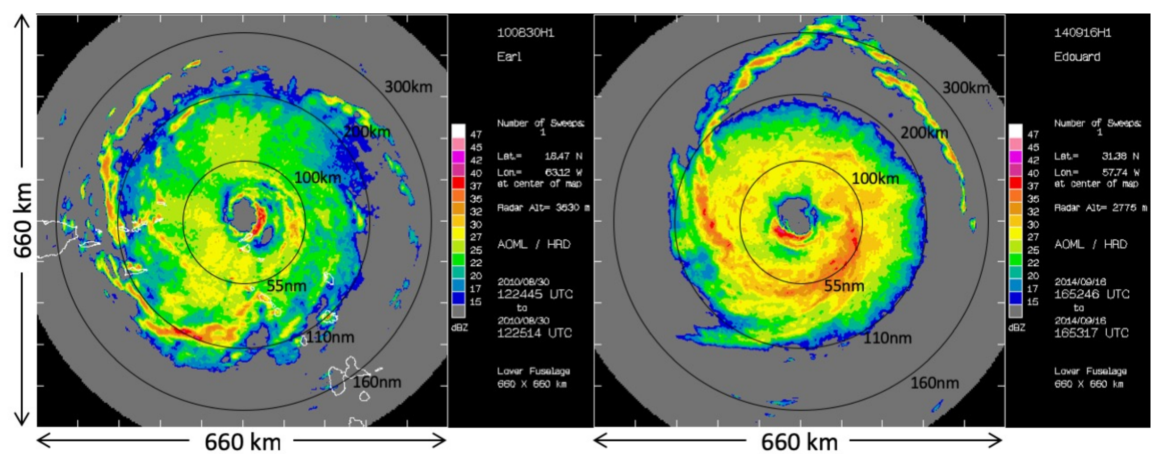

Fig.2. P-3 lower fuselage radar showing 25-40 dBZ circular convective bands in the environments of (left) 2010 Hurricane Earl (R=~200-250 km) at ~830 LST and (right) 2014 Hurricane Edouard (R=~150-300 km) at ~1300 LST. These circular outer band features are often coincident with TC diurnal pulses/waves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

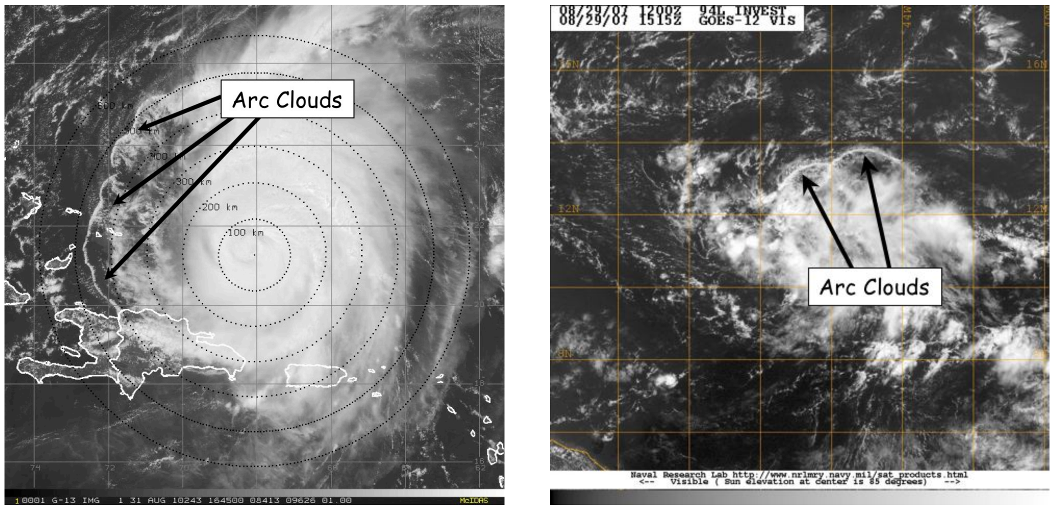

Fig. 3. GOES visible satellite imagery showing arc clouds racing away from the convective cores of (left) 2003 Hurricane Isabel and (right) 2007 Pre-Tropical Depression Felix.

P-3 Pattern 1: This can be a stand-alone pattern or can be coordinated with the G-IV 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 be 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 can be a stand-alone pattern or can be coordinated with the P-3 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, SEF, and SFMR Modules, TC in Shear Experiment, TDR Experiment, Synoptic Flow Experiment, NESDIS JPSS Satellite Validation Experiment, ADM-Aeolus Satellite Validation Module, and NESDIS Ocean Winds.

Analysis Strategy: This experiment seeks to observe the formation and evolution of the TC diurnal cycle 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 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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