EARLY STAGE EXPERIMENT
Science Description

Experiment/Module: Impact of Targeted Observations on Forecasts (ITOFS) Experiment

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Requirements: No requirements: flown at any stage of the TC lifecycle

Plain Language Description: This experiment will use advanced guidance from multiple sets of forecast models to determine locations where aircraft observations could potentially improve forecasts of tropical cyclone track, intensity and structure.

Early Stage Science Objective(s) Addressed:

1. Collect datasets that can be used to improve the understanding of intensity change processes, as well as the initialization and evaluation of 3-D numerical models, particularly for TCs experiencing moderate vertical wind shear [*APHEX Goals 1, 3*].

Motivation: Operational G-IV Synoptic Surveillance missions have resulted in average GFS track-forecast improvements of 5–10% and statistically significant intensity improvements through 72 h (Aberson 2010). However, the basic G-IV flight-track design and observational sampling strategies have remained largely unchanged for the past decade while the model, ensemble and data-assimilation systems have been upgraded considerably. ITOFS is designed to investigate new strategies for optimizing the use of aircraft observations to improve numerical forecasts of TC track, intensity, and structure.

Background: Accurate numerical TC forecasts require the representation of meteorological fields on a variety of scales, and the assimilation of the data into realistic models. Based on this requisite, HRD re-designed synoptic surveillance in 1998 to improve track predictions of TCs during the watch and warning period by targeting GPS dropsonde observations in the storm environment and assimilating those data into numerical models. Optimal sampling was attained using a fully nonlinear technique that employed the breeding method, the operational NCEP ensemble-perturbation technique at the time, in which initially random perturbations in the model were repeatedly evolved and rescaled. This technique helped define the fastest growing modes of the system, where changes to initial conditions due to additional data grow (decay) in regions of large (small) perturbation in the operational NCEP Ensemble Forecasting System. Although this approach provided a good estimate of the locations in which supplemental observations are likely to have the most impact by identifying locations of probable error growth in the model, it did not distinguish those locations which impact the particular TC forecast of interest from those which do not. The G-IV flight-track designs and targeting techniques developed from the series of 1996–2006 HRD Synoptic Flow Experiments were transitioned to operations at NOAA NHC and AOC in 2007 and have continued to be an integral part of operations since then. These operational missions resulted in average GFS track-forecast improvements of 5–10% and statistically significant intensity improvements through 72 h (Aberson 2010). While overall improvements have been achieved, literature indicates that synoptic-scale dropsonde observations do not consistently improve TC track forecasts due to an increased use of satellite data in operational models (Wu et al. 2006, 2007, Yamaguchi et al. 2009, Harnisch and Weissmann 2009, Majumdar et al. 2011).

In 2018, HRD conducted a cost/benefit analysis for G-IV dropsonde targeting through an extensive literature review and OSE/OSSE studies. This analysis evaluated the relative impact of dropsonde data sampling the TC, near the TC, and in large-scale environmental conditions towards identifying optimal dropsonde deployment locations for TC prediction. Data denial experiments using NCEP's Global Forecast System (GFS), European Center's Medium-range Forecast (ECMWF) system, the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Japanese Meteorological Agency's Global Spectral Model (GSM) have shown that of these three regions, measurements near the TC provided the largest improvement in track forecasts (Harnisch and Weissmann 2009, Wu et al. 2006 and 2007, Yamaguchi et al. 2009). Finally, results from sensitivity experiments performed using HRD's regional OSSE system concluded that G-IV dropsondes located nearest to the TC vortex provide the largest impact on track forecasts using a research version of HWRF (Ryan et al. 2019). Additional OSSEs conducted in an ensemble-based version of this system broadly assessed the characteristics of assimilating profiles of wind measurements and showed that TC forecast outcomes depend on radial location of profiler coverage in the region of a TC (Bucci et al. 2020), supporting the findings above. Thus, while G-IV synoptic surveillance has traditionally focused on the large-scale environment for improved performance in TC track forecasts, HRD suggested the addition of a ring of dropsondes closer to the TC inner core in an effort to improve hurricane model performance. NHC implemented the change to add a ring of dropsondes deployed at a radius of 90 n mi (165 km) from the TC center and continues this strategy for TC surveillance when possible.

Results from HRD's aforementioned OSSE sensitivity study on G-IV dropsonde targeting further revealed that systematic changes to the radial distance of dropsondes locations demonstrated a dependence on sampling the boundary between the core and near-TC regions, the "gradient region" (Ryan et al. 2019). This suggests using the size of the target TC to scale dropsonde deployment locations by wind-field extent. This ensures that the observations consistently sample the conditions in the near-storm environment regardless of natural size increases through time. While NHC tasks concentric rings for the G-IV when possible, the radii at which dropsondes deploy are fixed at 1.5 and 3 earth-degrees.

Recently, an ensemble-based targeting method has emerged that can provide an a priori estimate of the impact of hypothetical observations on forecast metrics, including TC track and intensity (e.g., Ancell and Hakim 2007, Torn and Hakim 2008, Torn 2014). This technique is advantageous because it can compute target locations for metrics directly tied to TCs, combines the data assimilation system with forecast sensitivity analyses, and is inexpensive. It also combines sensitivity information with forecast uncertainty, which makes it more likely that assimilating observations in a target region will reduce forecast uncertainty for the particular metric of interest (e.g., 72-hr track uncertainty). During the 2015-2016 NOAA SHOUT and 2017 NOAA UAS field campaigns, the ensemble-based sensitivity method was applied to real-time ensemble forecasts to determine optimal locations for Global Hawk-deployed GPS dropsonde observations (Wick et al. 2020). These analyses were derived from experimental 80-member HWRF and 51-member ECMWF model ensembles.

Adjoint models can provide insight into the practical limitations of our ability to predict the path of tropical cyclones and their strength (e.g., Doyle et al. 2011, 2012). An adjoint model can be used for the efficient and rigorous computation of numerical weather forecast sensitivity to changes in the initial state. Rapid growth of small perturbations can lead to errors on multiple scales that conspire to limit the forecast accuracy of the path and intensity of tropical cyclones (Doyle et al. 2012). The magnitude of the sensitivity has been shown to provide an estimate of the potential for forecast error (Doyle et al. 2019; Reynolds et al. 2019), and similar methods have been shown to provide the best forecasts (Aberson et al. 2011).

Goal(s): Investigate new sampling strategies for optimizing the use of aircraft observations to improve model forecasts of tropical cyclone track, intensity, and structure.

Hypotheses:

1. New, more advanced targeting techniques that optimize aircraft sampling of the TC environment can improve numerical forecasts of TC track, intensity, and structure, and could potentially be transitioned to operations.

Objectives:

1. Produce real-time targeting guidance derived from the ECMWF, GEFS, and possibly HAFS models that can be used to design optimal aircraft flight tracks for improving TC track, intensity, and structure. Utilize the NRL COAMPS-TC adjoint sensitivity when available as part of TCRI to provide additional targeting guidance.
2. Design aircraft missions that sample model sensitive regions with GPS dropsondes.
3. Explore options for conducting data denial experiments to assess the impact of Synoptic Flow GPS dropsondes on model forecasts of track, intensity, and structure.

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

P-3 Pattern 1: When ensemble prediction systems (and NRL COAMPS-TC adjoint system when available) suggest sensitivity of TC-related forecast metrics (e.g., track, intensity, and structure) in/near the inner core [i.e., R≤105 n mi (≤195 km)], fly any standard pattern that provides symmetric coverage (e.g., Figure-4, Rotated Figure-4, Butterfly, P-3 Circumnavigation). P-3 legs should be extended to reach the radius of 34 kt winds whenever possible [R~125 n mi (~230 km) for Atlantic hurricanes] and/or to sample sensitivity targets.

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G-IV Pattern 1: When ensemble prediction systems (and NRL COAMPS-TC adjoint system when available) suggest sensitivity of TC-related forecast metrics (e.g., track, intensity, and structure), fly a non-standard pattern that will vary from storm-to-storm and be defined by regions that are identified using model targeting techniques. These patterns will typically resemble a Lawnmower pattern and can be flown at any time during the mission, including during the ferries to/from the storm. The over-storm or near-storm portion of the pattern could incorporate the following standard patterns: Figure-4, Rotated Figure-4, Butterfly, Lawnmower, Square Spiral, G-IV Circumnavigation, G-IV Star, or G-IV Star with Circumnavigation. In order to maintain consistency with NOAA NHC operational Synoptic Surveillance missions, an outer circumnavigation at R=180 n mi (335 km) should also be flown. If time and conditions permit, a second inner circumnavigation is also desirable. This inner radius should be the smaller of the following two radii:

1. 90 n mi (165 km), the standard inner radius used by NHC.
2. NHC's analyzed R34 winds multiplied by 1.5 (addresses storms with small R34 winds). For reference, an observed value of R34 for a small Atlantic hurricane is 50 n mi (90 km), equating to a G-IV inner circumnavigation radius of ~75 n mi (~140 km).

G-IV Pattern 2: When 2 or more TCs (or invests) are interacting with each other, fly a multi-part pattern in addition to G-IV Pattern 1 which focuses on the non-priority TC in the interaction. This pattern must be flown in coordination with P-3 and G-IV sampling for the priority TC. The plans will vary depending on the interacting TCs, their distance apart, and mission turn-around time. The two parts include symmetric, storm-centered sampling of the near-TC/outer-core conditions (R≥90-105 n mi (≥165-195 km)), and sampling in the joint environment through which the TCs are interacting.

Links to Other Early Stage Experiments/Modules: This experiment can be flown in conjunction with nearly all HFP *Genesis*, *Early*, and *Mature Stage* experiments. P-3 and/or G-IV GPS dropsonde targeting can also be performed during ferries to/from targets of interest (e.g., African easterly wave, invest or TC).

Analysis Strategy: Guidance from ensemble prediction systems (e.g., ECMWF, GEFS, and HAFS) (and NRL COAMPS-TC adjoint system when available) will be used to compute the sensitivity of TC-related forecast metrics (e.g., track, intensity and structure) and will be used to guide GPS dropsonde sampling of the TC and its environment. Retrospective data denial experiments will be conducted post mission to assess the impact of the GPS dropsonde, TDR, and HDob data on model forecasts of TC track, intensity and structure.

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