END STAGE EXPERIMENT
Science Description

Experiment/Module: Tropical Cyclones at Landfall

Investigators: Heather Holbach, John Kaplan, Jun Zhang, Ghassan Alaka, Frank Marks, Lew Gramer, Lev Looney, George Alvey, Forrest Masters (University of Florida), Michael Biggerstaff (University of Oklahoma), David Nolan (University of Miami), Xiaomin Chen (University of Alabama Huntsville), Johna Rudzin (Mississippi State University), John Schroeder (Texas Tech University)

Requirements: TC making landfall, approaching the coastline, undergoing rapid weakening, or extratropical transition.

Plain Language Description:

Landfalling tropical cyclones (TCs) often produce a variety of high impact weather over land including tornadoes and damaging winds (particularly gusts) for which there exists limited objective forecast guidance. Thus, our experiment seeks to utilize P-3 aircraft, land-based mobile research team instrumentation, and ocean-based uncrewed surface vehicles to collect data in landfalling TCs to improve both our understanding and capability to predict the dangerous phenomena often associated with these landfalling systems.

End Stage Science Objective(s) Addressed:

1. Collect observations targeted at better understanding changes TCs undergo at landfall. Objectives include validation of surface wind speed estimates and model forecasts, understanding factors that modulate intensity changes near and after landfall, and to understand processes that lead to tornadoes in outer rainbands [*APHEX Goals 1, 3*].

2. Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in landfalling TCs, rapidly weakening TCs, and TCs undergoing extratropical transition. These measurements include improved three-dimensional representation of the TC wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds [*APHEX Goal 2*]

Motivation:

During a tropical cyclone (TC) landfall threat, the size of the warned area typically depends on the forecast track, the extent and storm-relative location of hurricane- and tropical storm-force winds, and the required evacuation lead-times. Since significant improvements in track forecasts have been observed in recent years, the goal of our experiment is to improve the accuracy of the observed and forecast surface wind speeds (sustained and gusts) both at and after the time of TC landfall to further optimize the warnings that forecasters issue. Tornadoes spawned by landfalling TCs are another dangerous hazard for those that reside near a tropical cyclone's track. Thus, improvements in the forecasting of each of the above phenomena (extent and structure of maximum wind, wind gusts, and TC-spawned tornadoes) are required to aid with the protection of life and property.

Background:

Uncertainties in surface wind-speed estimates derived from flight-level and SFMR data collected near the coast continue to exist. This may be due to changes in bathymetry near the coastline which could alter the breaking-wave field thereby changing the roughness length and microwave emissions at high wind speeds (Holbach et al. 2018). Evaluation of these effects in tropical cyclones approaching the coastline may lead to adjustments to the operational SFMR-derived surface wind-speed algorithms. Additionally, uncertainty in planetary boundary layer (PBL) parameterizations at high-wind speeds remains elusive, mostly due to scarce observations (Chen et al. 2021b). Understanding the response of PBL structure to the complex surface roughness variations near the coastline is crucial for PBL physics improvements.

Although wind gusts produced by landfalling TCs can have a significant impact on both life and property, explicit numerical model forecasts of wind gust magnitudes are presently quite limited. Thus, forecasters have typically estimated TC wind gusts in real-time by multiplying gust factors obtained in previous observational studies to the sustained wind speed. Gust factors have been explicitly studied in TCs by several researchers (e.g., Durst 1960; Powell et al. 1991;1996, Krayer and Marshall 1992; Harper et al. 2009; Masters et al. 2010; Tyner et al. 2015, Giammanco et al. 2016). While many of those studies suggest that gust factors can vary as a function of such factors as roughness, convection, and mean wind speed, a single gust factor value is often applied for a given averaging period or sustained wind speed. The rate of decay of the sustained TC winds over land is another factor that has important forecast implications and that previous studies have found can vary depending on a range of factors (Kaplan and DeMaria 1995; Alford et al. 2020, Hlywiak and Nolan 2021). Additionally, the coherent structure in hurricane boundary layer (HBL), which is known to affect the surface enthalpy exchange and HBL turbulent mixing, was found to be linked directly to the surface wind gusts over land (e.g., Kosiba et al. 2013), but the thermodynamic and dynamic factors controlling the formation of these coherent structures are not well understood. One important reason is the lack of high temporal resolution observations of the HBL characteristics during the landfall, especially over the ocean Thus, this experiment seeks to collect data before, during, and after landfall to better understand and predict both the wind gusts and maximum sustained winds produced by landfalling TCs.

Severe weather, including tornadoes, is often associated with landfalling TCs. However, the basic dynamic and thermodynamic structures found in TC supercells are not well-understood. While some studies have shown that TC tornadoes have characteristics that are like those of Great Plains tornadoes, some key differences exist, such as the height and amplitude of the vortices. Most TC tornadoes occur in the front-right quadrant of the TC primarily from 12 h prior to 48 h after landfall (Schultz and Cecil 2009). Additionally, the most damaging TC tornadoes occur in rainbands. While TC tornadoes are typically weaker than their Great Plains counterparts, they account for at least 10% of all tornadoes from Louisiana to Maryland (Schultz and Cecil 2009). Unlike Great

Plains tornadoes, TC tornadoes are typically associated with relatively small values of CAPE, relying instead on frictionally-induced convergence that accompanies landfalling TCs. The sudden deceleration of the wind as it encounters the rough land surface helps drive vertical motion, which promotes the development of embedded mesovortices and severe weather.

The sea surface temperature (SST) response of a TC as it is approaching landfall is more complex than that in open ocean environments (e.g., Seroka et al., 2017; Miles et al., 2017; Dzwonkowski et al., 2020; Gramer et al., 2022). Gramer et al. (2022) showed that convergence of the ocean surface flow over shallower coastal shelves is often associated with downwelling, and, therefore, SST is maintained or even increases. Recent observations in a landfalling TC (Hurricane Ida, 2021) showed that the TC inflow was dominated by land-sea gradients in surface friction, with the strongest inflow occurring on the offshore flow side of the TC. A similar pattern was found in the landfall simulations presented in Hlywiak and Nolan (2022). This contrasts with open ocean conditions where inflow asymmetries are dependent on vertical wind shear and the direction of storm motion. Given this knowledge, it is of interest to identify how sensitive the TC boundary layer thermodynamics and kinematics are to coastal SST changes as favorable TC boundary layer conditions are linked to changes in TC intensity (e.g., Zhang et al., 2017; Chen et al., 2021; Wadler et al. 2021).

Goal(s):

This experiment seeks to employ P-3 aircraft, land-based observation platforms, and ocean-based uncrewed surface vehicles (saildrones) to collect thermodynamic and kinematic observations in landfalling tropical cyclones. These data can be utilized to better understand and reduce the uncertainty in SFMR wind speed estimates and PBL parameterizations in coastal regions, investigate the factors that influence HBL coherent structure, wind gust and sustained wind magnitudes, as well as TC size, near the time of landfall, and improve our understanding of the mechanisms that modulate TC generated tornadoes.

Hypotheses:

1. Shoaling of waves near the coastline artificially increases the retrieved wind speeds from the SFMR.
2. The datasets collected utilizing aircraft, land-based, and ocean-based instrumentation can be used to better understand and predict both the sustained and gust wind-speeds produced by landfalling TCs. A special high-temporal-resolution dataset collected utilizing both aircraft, land-based, and ocean-based instrumentation can be used to better understand the factors controlling the formation of coherent structures in landfalling TCs that can contribute to wind damage and TC intensity changes.
3. The airborne data collected can be used to compute traditional environmental parameters (e.g., CAPE, vertical shear, helicity) that will aid in distinguishing sectors of the storm that are most supportive of supercell development. This data will be helpful for optimizing Storm Prediction Center issued severe weather watches and validating numerical-model output.

4. The boundary layer thermodynamic and kinematic structure of a TC, whose outer rain bands are already experiencing landfall and undergoing the influence of surface friction gradients, may be determined by the shelf and coastal ocean SST response.

Objectives:

1. Collect Doppler, flight-level, WSRA, and SFMR surface wind-speed data both within the core and near storm environment (within about 160 n mi/300 km of the TC center) as the TC approaches the coastline to help improve and validate real-time surface wind-speed estimates.
2. Collect observations that provide a measure of three-dimensional TC structure prior to and near the time of landfall to aid with the understanding and prediction of the mechanisms that modulate the sustained and gust wind speeds of landfalling TCs.
3. Collect kinematic and thermodynamic data in rainbands that have the potential to produce severe weather, including tornadoes.
4. Collect collocated observations of the atmospheric and oceanic boundary layer prior to landfall to identify the relative importance of the coastal ocean SST on the thermodynamic and kinematic TC boundary layer subject to frictionally forced asymmetries, its influence on the kinematic boundary layer, and its contribution to the intensity changes of landfalling TCs.

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

P-3 Pattern #1: SFMR Coastal

A break-away/non-standard pattern in which the P-3 flies perpendicular to the coastline, across the bathymetry gradient, in a region with near constant surface winds. After flying away from the coast for about 27 n mi (50 km), the P-3 would turn downwind and then back towards the coast, repeating a similar line as the first leg. A dropwindsonde and AXBT, if available, would be released at the midpoint of the leg. This pattern can also be flown in reverse with the first leg flown while flying towards the coast. It would be ideal to have the WSRA collecting surface wave spectra data as well. Further, it would be beneficial to coordinate with saildrones, if any are in the domain.

P-3 Pattern #2a: Coastal Survey (Standard)

A break-away/non-standard pattern in which the P-3 flies parallel, but ~20-25 n mi (35-45 km) offshore so that the SFMR, IWRAP, and WSRA or KaIA, if available, footprints are out of the surf zone. The second pass should be parallel and just offshore ~5 n mi (10 km) from the coast or as close to the coastline as safety permits to aid in the evaluation of the changes in the kinematic and thermodynamic storm structure as the TC approaches the coastline and to provide in-situ data for synthesis and comparison with land-based mobile team data. Finally, a short leg would be flown from the coast spiraling towards the storm center to evaluate the boundary layer recovery of the offshore flow.

P-3 Pattern #2b: Coastal Survey (Rapid Sampling of Onshore Flow)

A break-away/non-standard pattern in which the P-3 flies a box pattern centered on the dual-Doppler analysis domain of ground-based mobile radars, with the E-W coastal leg 3-4 nm offshore, safety permitting and far enough from the coastline such that deployed dropsondes splash over water. Each leg is ~25 n mi (46 km), with two dropsondes released in the one-third and middle points of the E-W coastal leg. Repeat the flight pattern 4-6 times to collect a few hours of data; in that case, drops will be released only in the middle of the first leg each time. The SFMR, IWRAP, KaIA, and DWL should be turned on, if available.

P-3 Pattern #3: Offshore Intense Convection

A break-away/non-standard pattern in which the P-3 crosses the target rainband (safety permitting) 10-15 n mi (20–30 km) downwind of intense convective cells and then proceeds to about 15 n mi (30 km) outside the rain band axis while maintaining at ~5 n mi (10 km) separation from the outer edge of the rainband for safety. The aircraft then turns upwind and proceeds along a straight track parallel to the band axis. When the P-3 is ~10-15 n mi (20–30 km) upwind of the target cells, the aircraft turns and proceeds along a track orthogonal to the band axis until the P-3 is 15 n mi (30 km) inside the rainband then turns downwind and flies parallel to the rainband axis all the while maintaining a ~5 n mi (10 km) separation from the edge of the rainband for safety. Additionally, this pattern may minimally consist of a single downwind leg parallel to the rainband axis while maintaining a ~5 n mi (10 km) separation from the edge of the rainband for safety (i.e., orthogonal and/or upwind legs are not flown). However, it is desirable that the entire flight pattern still be flown to capture the evolution of the rainband and to collect observations on each side of the rainband axis.

P-3 Pattern #4: Coastal Air-Sea Interaction

The P-3 would fly a rotated figure-4 pattern with leg lengths of 110 n mi (205 km) with the initial point (IP) at the coastline flying inbound toward the center perpendicular to the coastline. Leg 2 would be oriented parallel to the coastline to sample the onshore and offshore flow. Dropsonde and AXBT combo drops would be made at all endpoints except the IP and final endpoint along with midpoints between the RMW and endpoint inbound and outbound on leg 2, outbound on leg 3, and inbound on leg 4. There would also be combo drops at the inbound and outbound RMW on leg 2. Combo drops outside of points between the endpoints on leg 2 may be augmented to align with any coastal ocean surface measurements that may be present from Ocean Observing modules (i.e., drifters, surface or bottom moorings, gliders, ALAMO floats). Additionally, the pattern can be adjusted such that only combo drops at the midpoints, endpoints, and the RMW on leg 2 need to be deployed if assets are low. However, it is desirable that the entire flight pattern still be flown for radar coverage. Lastly, it would be beneficial to coordinate with saildrones, if any are in the domain of interest.

Links to Other End Stage Experiments/Modules:

1. Sustained and Targeted Ocean Observation Module
2. Stratiform Spiral Module
3. Gravity Wave Module
4. Surface Wind Speed and Wave Validation Module
5. Rainband Complex Module

Analysis Strategy:

SFMR Coastal

By flying this module in a region of nearly constant winds, with the wind speed measured by a dropwindsonde and SST measured by an AXBT if available, the effects of bathymetry on SFMR measurements can be identified by comparing the brightness temperature measurements for each frequency along the leg. If the winds are not constant, but multiple dropwindsonde measurements are available along the leg, then any wind-speed change can be accounted for in the comparison. Flying one leg towards the coast and one away will also allow for the impact of wave-breaking direction to be evaluated. WSRA or KaIA surface wave spectra data will provide information on the wave characteristics pertinent to the wind-wave relationship.

Coastal Survey (a)

Three-dimensional wind-field analyses and vertical profiles will be compared with dropwindsonde, SFMR, IWRAP, WSRA, KaIA, and/or LIDAR data and land-based mobile team doppler, tower and profiler data to aid with the evaluation of changes in TC kinematic and thermodynamic structure as the TC approaches the coastline. Additionally, the in-situ data collected will provide a database for refinement of existing ground-based team algorithms that utilize doppler data to estimate sustained surface winds and to validate real-time empirical and numerical model wind gust forecasts.

Coastal Survey (b)

This repeated U-shape flight pattern within the ground-based Dual-Doppler radar lobes will generate high-frequency (~15 min) three-dimensional boundary layer kinematic and thermodynamic observations upstream of the land-based instruments. An integration of this high-frequency flight data and ground-based observations can facilitate the study of evolution of HBL coherent structure as well as their impact on wind gusts during landfall.

The three-dimensional wind-field analyses and vertical profiles will be compared with dropwindsonde, SFMR, IWRAP, KaIA, and/or LIDAR.

Offshore Intense Convection

Three-dimensional wind-field analyses and vertical profiles will be made from Doppler datasets. Dropwindsonde and flight-level data will be analyzed and combined with any available rawinsonde and surface (e.g., buoys, CMAN, etc.) observations to establish the kinematic and thermodynamic environment of targeted cells. Any available land-based radar will be used to augment airborne observations of cell evolution. Observations of TC supercells will be used to validate numerical models, to assess the ability to predict signatures of tornadic activity, and to compare TC tornadoes with those from mid-latitude supercells.

Coastal Air-Sea Interaction

This pattern is used to sample the coastal and near-shelf ocean vertical temperature structure, SST, and concurrent atmospheric boundary layer thermodynamic and kinematic structure to evaluate how these conditions change under the influence of surface friction gradients near landfall. Leg 2 will sample the inflow in the offshore and onshore flow regions. Combo drops of dropsondes and AXBTs, together with SFMR near-surface wind velocities, will help estimate the air-sea fluxes and to evaluate the thermodynamic structural changes of the hurricane boundary layer. TDR and SFMR observations will be used to identify kinematic structural changes of the hurricane boundary layer near the time of landfall.

Note: As part of the data collection and analysis procedures for each of the above flight modules, P-3 flight-level, SFMR, dropsonde, TDR and AXBT data will be transmitted from the aircraft in real-time via the GTS for assimilation into the numerical models and for validation of model forecasts of wind speed, temperature, moisture, and rainfall. A complete set of these data will also be made available at the AOC ftp site shortly after the conclusion of each mission.

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