MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Gravity Wave

Investigator(s): Jun Zhang (PI) and David Nolan (co-PI)

Requirements: Categories 2–5

Plain Language Description: Hurricane convection produces gravity waves that propagate both upward and outward. The observational data collected from this module will be analyzed to quantify the characteristics of the gravity waves in early-stage hurricanes and their relationship with storm intensity and intensity change. These data would also provide valuable information for model evaluation and physics improvement.

Mature Stage Science Objective(s) Addressed:

1) Collect observations targeted at better understanding internal processes contributing to mature hurricane structure and intensity change [*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 mature hurricanes. These measurements include improved three-dimensional representation of the hurricane wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds and underlying oceanic conditions [*APHEX Goal 2*]

Motivation: Internal gravity waves are ubiquitous in the atmosphere and are continuously generated by deep moist convection around the globe. Gravity waves play a critical role in the dynamical adjustment processes that keep the atmosphere close to hydrostatic and geostrophic wind balance, by redistributing localized heating over larger distances. Numerical simulations show gravity waves radiating from the eyewall region to the outer core in TCs. TC convection produces gravity waves that propagate both upward and outward. This module is designed to observe smaller scale gravity waves, with radial wavelengths of 2 to 20 km, that radiate outward from the TC core with phase speeds of 20 to 30 m s^{-1}. The goal is to quantify how the characteristics of these waves are tied to TC intensity and intensity change.

Background: Gravity waves exist due to the natural restoring force associated with the static stability of the atmosphere (Markowski and Richardson 2010; Sutherland 2010). Most gravity wave generation is associated with three processes: 1) the interaction of the atmospheric flow with topography, 2) rapidly evolving imbalances of the large-scale flow, and 3) disruptions to the atmosphere by moist convection. Visual evidence for these waves existing in TCs was documented in the early study by Black (1983), who analyzed features in cloud tops using stereoscopic analysis of photographs taken from hand-held cameras on the Skylab space station. Simulations with mesoscale atmospheric models have reproduced these features, which generally have wavelengths of tens to hundreds of km (Kim et al. 2009). These waves propagate long distances and their influences on the atmospheric boundary layer have also been observed (Niranjan-Kumar et al. 2014).

Goal(s): Collect observations for improving our understanding of the characteristics of gravity waves in mature-stage hurricanes. Quantify how the characteristics of these waves are related to hurricane intensity and intensity change.

Hypotheses:

1. The wavelengths of the outward radiating mid-tropospheric gravity waves can be related to the angular propagation speed of the inner-core convective asymmetries.

Objectives:

1. Fly back and forth across individual waves so that both their wavelength and phase speed can be measured.

P-3 Pattern 1 (Internal Processes):
For mature stage TCs, after completing Figure-4 pattern, at the end of the last leg, continue outward to a distance of 160 n mi (295 km) from the center, or further, if possible. Then turn P-3 back to the eye. This module ideally should be conducted in quadrant with the least rainband activity, typically the upshear right or right-rear quadrant.

P-3 Pattern 2:
For mature stage TCs, after completing an outbound or downwind leg in Figure-4 pattern, continue outward to a distance of 90 n mi (165 km) from the center, or further, if possible. Then turn P-3 back to the previous end point. This module ideally should be conducted in quadrant with the least rainband activity, typically the upshear right or right-rear quadrant.

Links to Other Mature Stage Experiments/Modules: The Gravity Wave module can be flown in conjunction with the following Mature Stage experiments: TCDC Experiment, Synoptic Flow Experiment, and NESDIS Ocean Winds.

Analysis Strategy: This module seeks to observe the characteristics of the TC gravity waves. Flight-level wind observations will be used to analyze the wavelengths and amplitudes of these waves. The vertical velocity will be quality controlled by correcting the attack angle and dynamical pressure using specially designed modules conducted by calibration flights before each hurricane season (Zhang 2010; Zhang and Drennan 2012). To avoid the contamination of the spectra by convection near the eyewall, only data from at least 100 km away from the storm center are used. The power spectrum will be computed using a fast Fourier Transform (FFT) algorithm to estimate the peak wavelengths of these waves.

References:

Browner, S. P., W. L. Woodley, and C. G. Griffith, 1977: Diurnal oscillation of cloudiness associated with tropical storms. *Mon. Wea. Rev.*, **105**, 856–864.

Black, P. G., (1983), Tropical storm structure revealed by stereoscopic photographs from Skylab. *Adv. Space Res.*, **2**, No. 6, 115–124.

Kim, S.-Y., H.-Y. Chun, and D. L. Wu (2009), A study on stratospheric gravity waves generated by Typhoon Ewiniar: Numerical simulations and satellite observations. *J. Geophys. Res.*, **114**, D22104.

Markowski, P., and Y. Richardson (2010), *Mesoscale meteorology in mid-latitudes*. Wiley-Blackwell, Hoboken, New Jersey, 430 pp.

Niranjan Kumar, K., Ch. Kanaka Rao, A. Sandeep, and T. N. Rao (2014), SODAR observations of inertia-gravity waves in the atmospheric boundary layer during the passage of tropical cyclone. *Atmos. Sci. Lett.*, **15**, 120–126.

Nolan, D.S., and J.A. Zhang, 2017: Spiral gravity waves radiating from tropical cyclones. Geophysical Research Letters, 44(8):3924–3931, doi:10.1002/2017GL073572.

Sutherland, B. R., *Internal Gravity Waves* (2010). Cambridge University Press, New York, 377 pp.

Zhang, J. A., (2010), Spectral characteristics of turbulence in the hurricane boundary layer over the ocean between the outer rainbands. *Quart. J. Roy. Meteorol. Soc.*, **136**, 918–926.

Zhang, J. A., and W. M. Drennan (2012), An observational study of vertical eddy diffusivity in the hurricane boundary layer. *J. Atmos. Sci.,* **69**, 3223–3236.