# EARLY STAGE EXPERIMENT
*Science Description*

---

**Experiment/Module:** Gravity Wave

**Investigator(s):** Jun Zhang, David Nolan (U. Miami)

**Requirements:** TD, TS, Category 1

**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.

**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 [*IFEX Goals 1, 3*].

**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).

These waves can be observed by research aircraft and surface instruments (Nolan and Zhang 2017). The flight-level data reveal waves with radial wavelengths of 2–10 km, and by compositing the data from inbound and outbound flight legs separately, an outward phase speed of 20-25 m $s^{-1}$ can be inferred. Data from a research buoy in the Pacific also show evidence for the effects of the gravity waves on surface pressure and wind speed, with periods around 1000 s and 2000 s. Numerical simulations reproduce these waves and indicate distinct vertical structures for the dominant modes, with peaks in amplitude of vertical velocity near the tropopause and in the lower troposphere (Nolan and Zhang 2017). The simulations also indicate that TC intensity can be correlated with the amplitudes of these wave signals. Thus, analysis of atmospheric gravity waves may be a more direct approach for remote monitoring of TC intensity.

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

**Hypotheses:**

1. TCs that have a deeper boundary layer, stronger inflow, larger boundary-layer convergence, larger surface enthalpy fluxes, and less degree of asymmetry in boundary-layer enthalpy and inflow, tend to intensify faster in a sheared environment.

**Objectives:**

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.

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

**P-3 Pattern 1:**
For early stage TCs, after completing Figure-4 pattern, at the end of the last leg, continue outward to 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-real quadrant.

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

**Links to Other Early Stage Experiments/Modules:** The Gravity Wave module can be flown in conjunction with the following Early Stage experiments: AIPEX and Synoptic Flow Experiment.

**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 (55 n mi) 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:**

Bryan, G. H., 2012: Effects of surface exchange coefficients and turbulence length scales on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev.*, **140**, 1125–1143.

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.