

MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Gravity Wave Module

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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*]

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 showed 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.

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Hypotheses:

1. Gravity waves radiating from the TCs inner core are prevalent in TCs and their wave amplitudes correlate with TC intensity.

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

P-3 Module 1: For mature stage TCs, after completing Figure-4 pattern, at the end of the last leg, continue outward to distance of 160 n mi (300 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.

Links to Other Mature Stage Experiments/Modules: The Gravity Wave module can be flown in conjunction with the following *Mature Stage* experiments: TCDC Experiment, TC in Shear Experiment, TDR 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:

- 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.

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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.