Towards a Theory of Turbulence Spectra of Tropical Cyclones

Boris Galperin, College of Marine Science, University of South Florida

Alexander K. Nickerson, Gregory P. King, Jun A. Zhang, and Semion Sukoriansky

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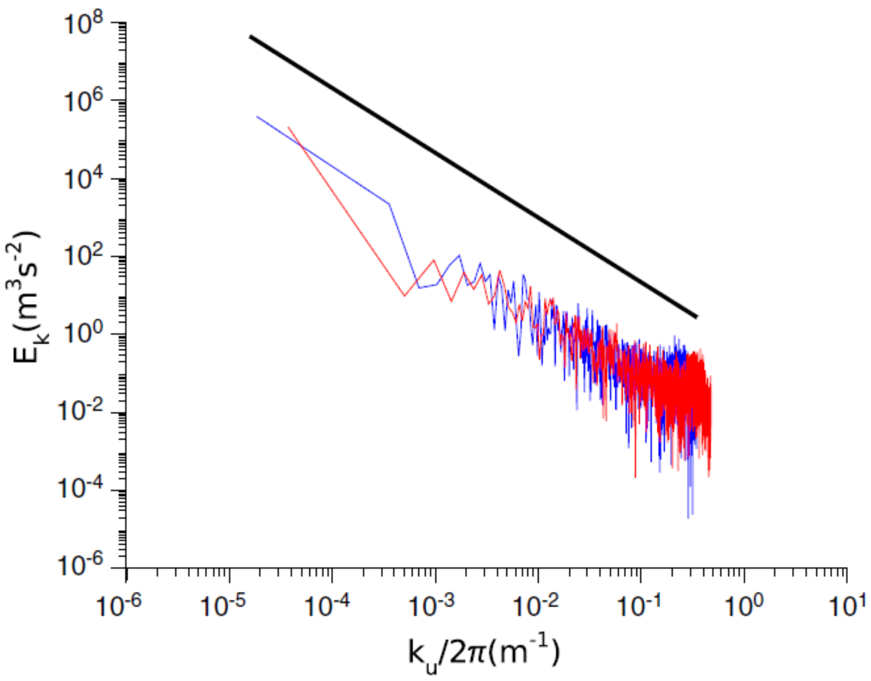
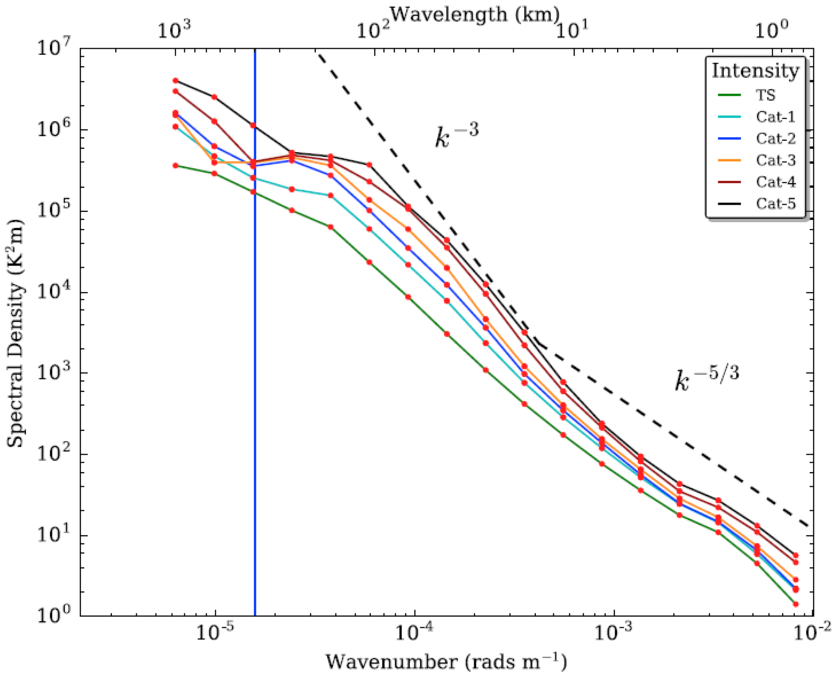
What is known?

- Tropical cyclones' (TC) 1D spectra have been computed from airplane reconnaissance missions



Wavenumber spectrum of kinetic energy for flight legs at heights of 88m (red) and 194m (blue). From: Byrne & Zhang (2013), GRL



Spectral composites of three datasets. Flight legs are not truncated at RMW. From: Vonich & Hakim (2018), JAS

- The 1D spectra resemble those found in the troposphere and stratosphere (Nastrom & Gage)
- Let us try to follow the physics of the NG spectra to explain the TC ones

So, what is the physics of the NG spectra?

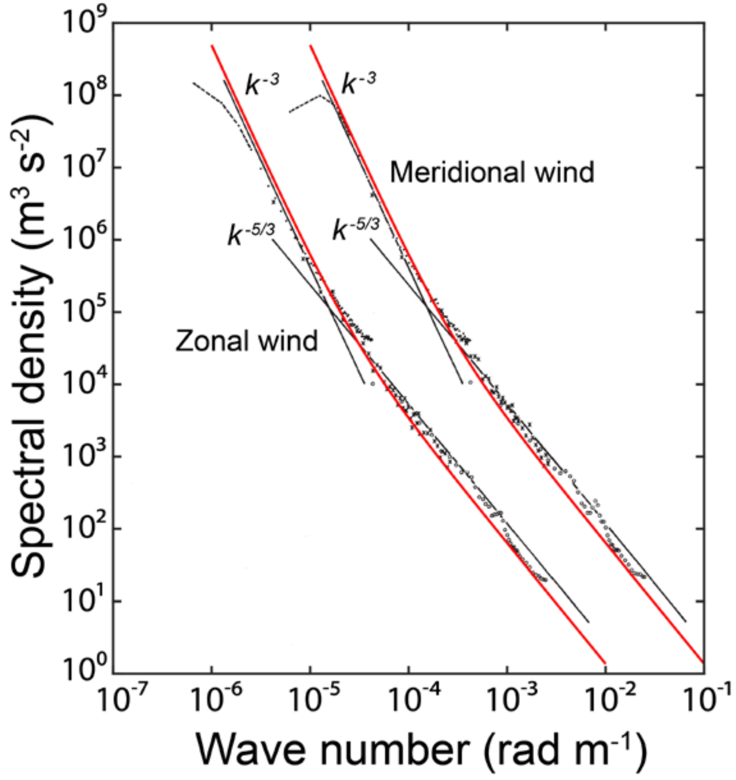
- The -5/3 slope points to Kolmogorov turbulence although it is too strongly anisotropic to be 3D
- If it is 2D, then the -5/3 slope → inverse cascade
- Then, the small-scale energy source is problematic
- The 3rd-order structure function analysis by Lindborg (1999) points to direct cascade
- The issue is still unresolved and being debated
- The -3 slope is attributed to direct enstrophy cascade $(\text{rate}\ \Pi_\omega)$ of 2D turbulence
- The connection between spectral amplitude and Π_ω was not shown
- Most studies deal with slopes, but the physics is in the amplitudes
- If we cannot explain the NG spectra, how can we deal with the TC ones?

- We have developed an analytical theory of rotating turbulence, QNSE, that produces expressions for 1D longitudinal and transverse spectra:

$$E_L(k_1) = \frac{18}{55} C_K \Pi_\varepsilon^{\frac{2}{3}} k_1^{-\frac{5}{3}} + 0.0926\, f^2 k_1^{-3}$$

$$E_T(k_1) = \frac{24}{55} C_K \Pi_\varepsilon^{\frac{2}{3}} k_1^{-\frac{5}{3}} + 0.24\, f^2 k_1^{-3}$$

- The theory predicts slopes and amplitudes and accurately describes the NG spectra

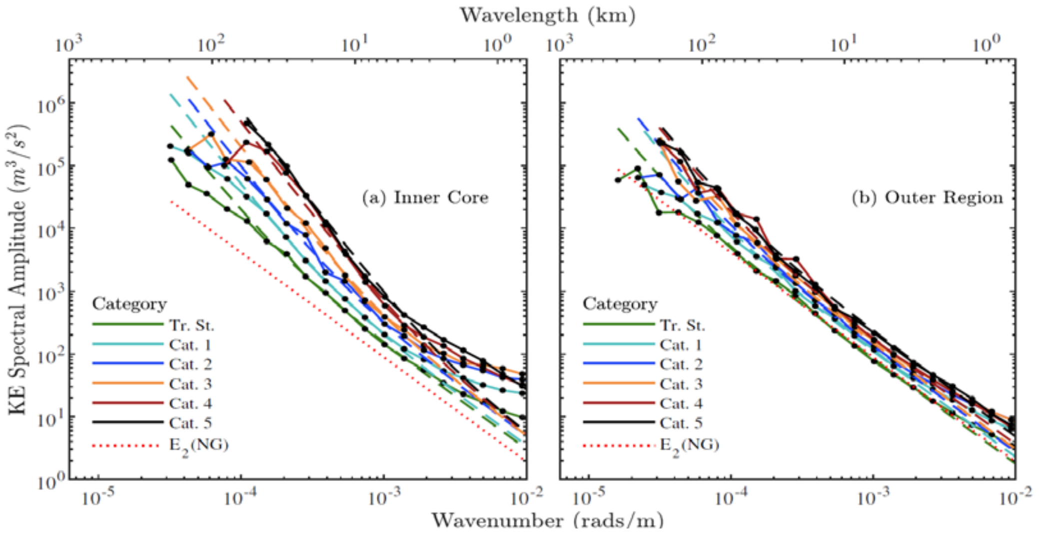


- How can we use QNSE for tropical cyclones for which $f \simeq$ constant?
- Tropical cyclones feature strong cyclostrophic rotation, and so their ***effective*** Coriolis parameter is $\tilde{f} = \hat{f} + f$, where $\hat{f} = 2\alpha \frac{U_m}{R_m}$, $\alpha = O(1)$

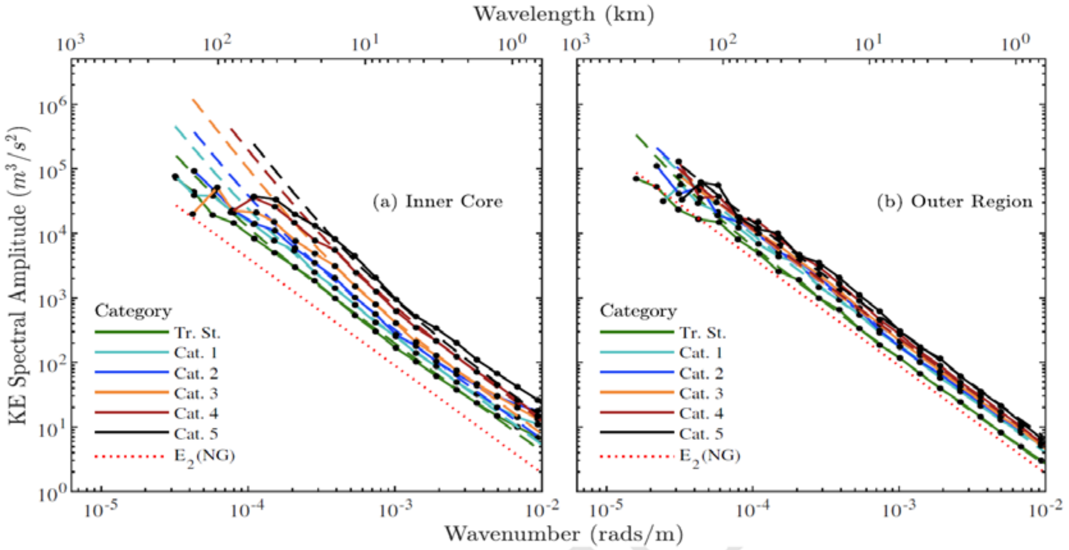
Storm Category	ϕ °N	f $10^5 s^{-1}$	$\hat{f}$ $10^5 s^{-1}$	$\tilde{f}$ $10^5 s^{-1}$
TS	24.9	6.2	40.9	47.1
1	25.8	6.3	72.9	79.2
2	25.5	6.3	88.9	95.2
3	23.3	5.8	124.6	130.4
4	21.6	5.4	169.0	174.4
5	20.5	5.1	194.0	199.1

- The cyclostrophic addend provides for observed dependence on TC category
- Inside the inner core ⇒ solid body rotation ⇒ turbulence is homogeneous ⇒ QNSE applies
- In the outer region ⇒ turbulence is inhomogeneous; $\hat{f} \to 0, \tilde{f} \to f$, spectra rebound to NG

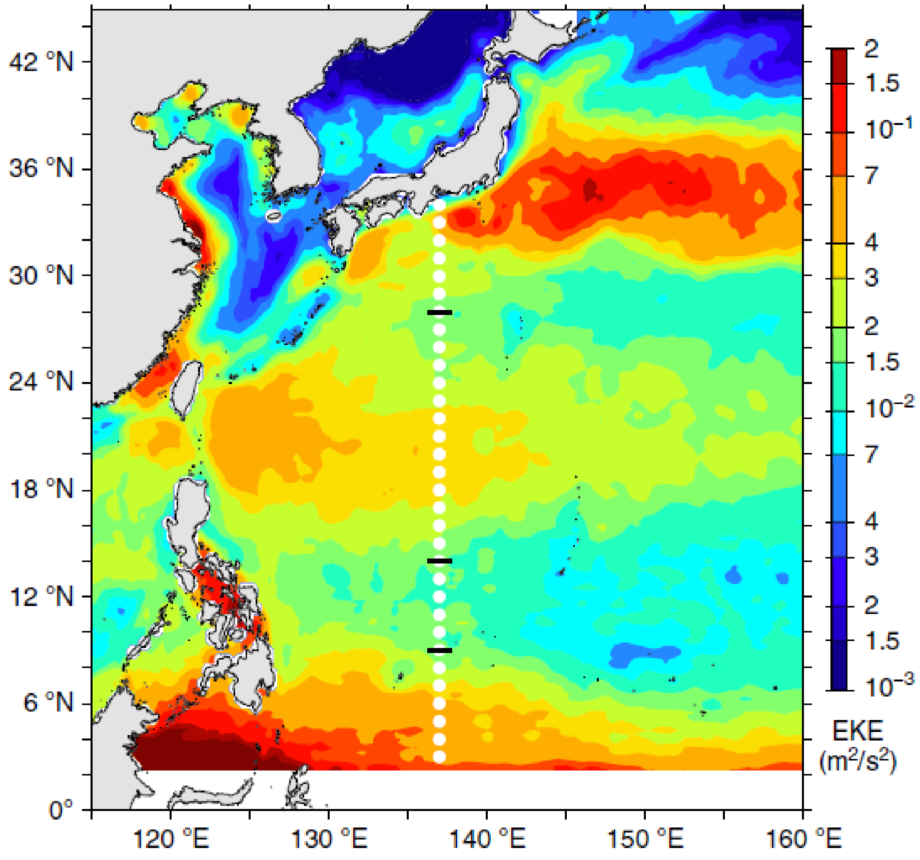
- The data has been collected from 1979 to 2019 by reconnaissance flights into tropical systems in the North Atlantic and Eastern Pacific Oceans
- We processed 655 flights into 138 storms conducted by the NOAA Hurricane Hunters

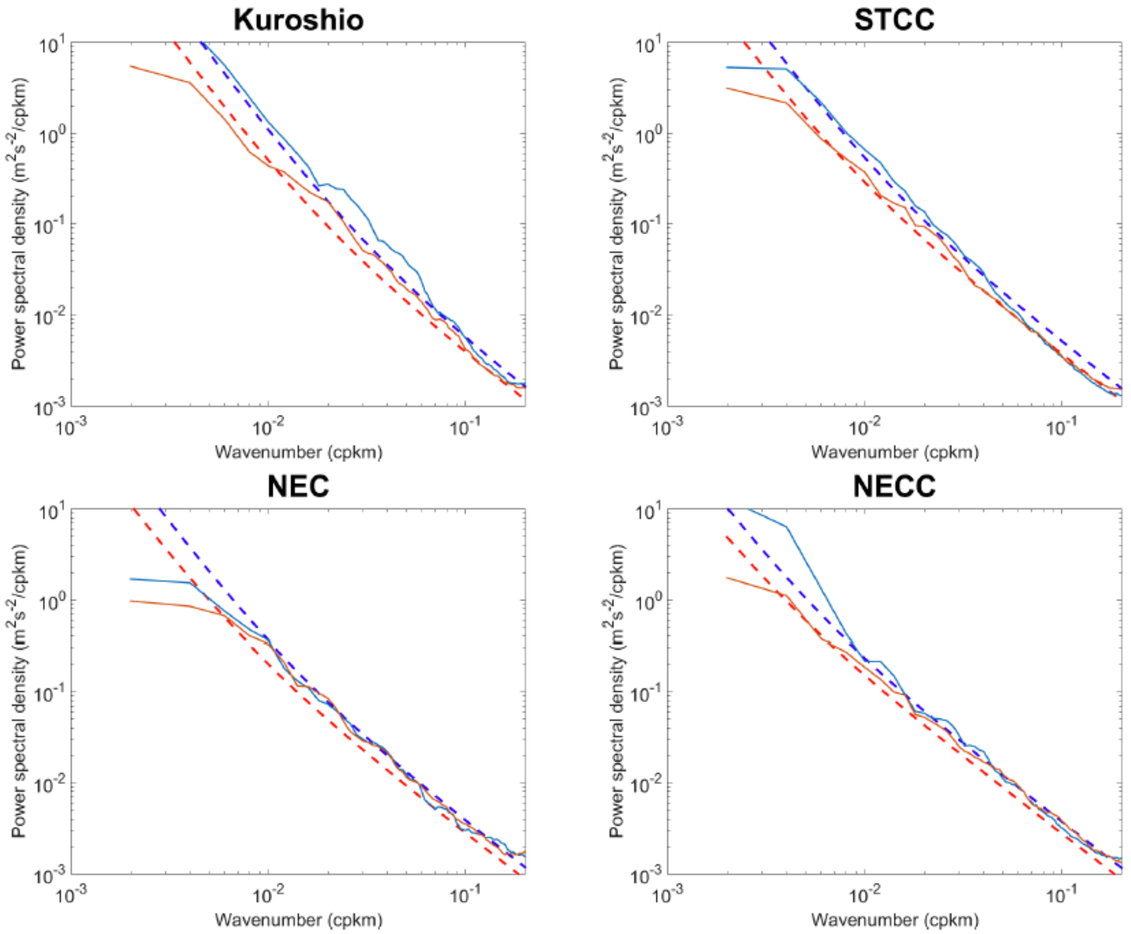


Transverse (azimuthal) spectra



Longitudinal (radial) spectra





Same QNSE expressions describe longitudinal and transverse spectra in the Northwest Pacific ocean

Conclusions (only a few):

- QNSE replicates amplitudes and slopes of TC turbulence
- Estimates energy flux to subsynoptic scales (Π_ε)
- Clarifies the physics and underscores the symbiosis of TC and NG spectra
- Outside the TC vortex, the spectra rebound to NG
- Dependence of spectral amplitudes on f rather than Π_ω points to a key weakness of Charney's theory
- Spectra are insensitive to cascade direction; may harbor double cascade
- Large-scale geophysical turbulence is not 2D but quasi-2D in 3D space
- The theory can be used to test models and supplement measurements
- The affinity of the TC, tropospheric and ocean spectra exposes the unity of physical laws governing a broad variety of geophysical flows