Zonostrophic Turbulence in Hurricanes

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Quasinormal scale elimination (QNSE) theory

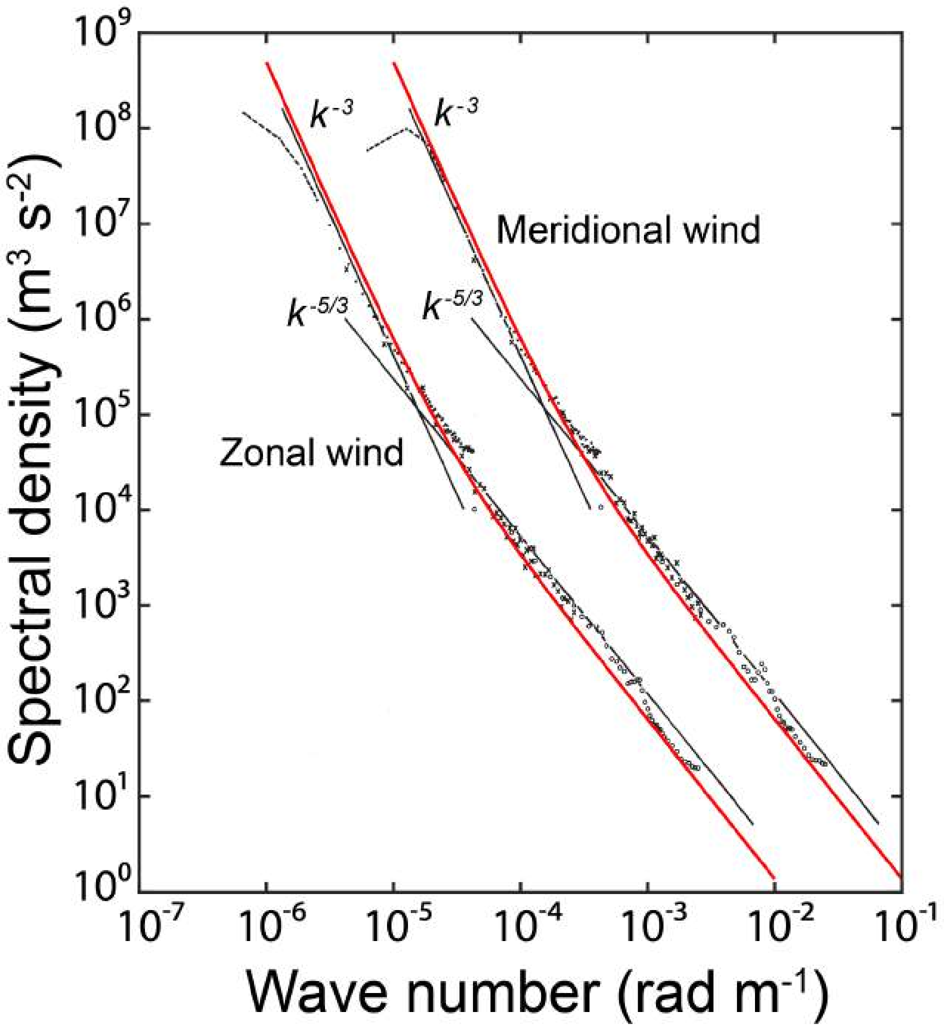
- Galperin and Sukoriansky (2020) developed an analytical theory that produces expressions for 1D anisotropic energy spectra of atmospheric and oceanic turbulence.

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

(Longitudinal)

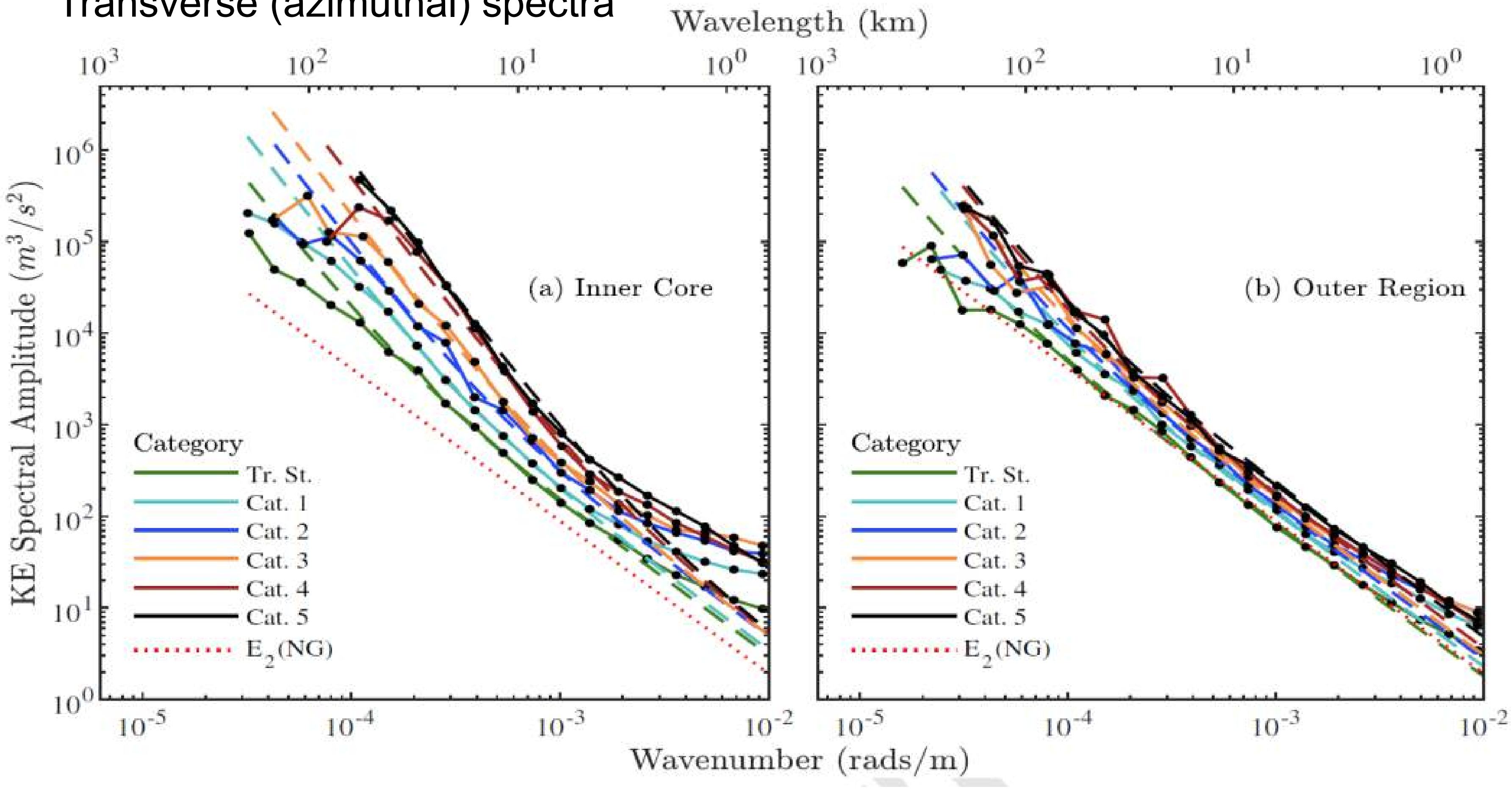
$$E_T(k) = \frac{24}{55} C_K \Pi_\varepsilon^{\frac{2}{3}} k^{-\frac{5}{3}} + 0.24\, f^2 k^{-3}$$

(Transverse)



Can QNSE be applied in hurricane conditions?

Transverse (azimuthal) spectra



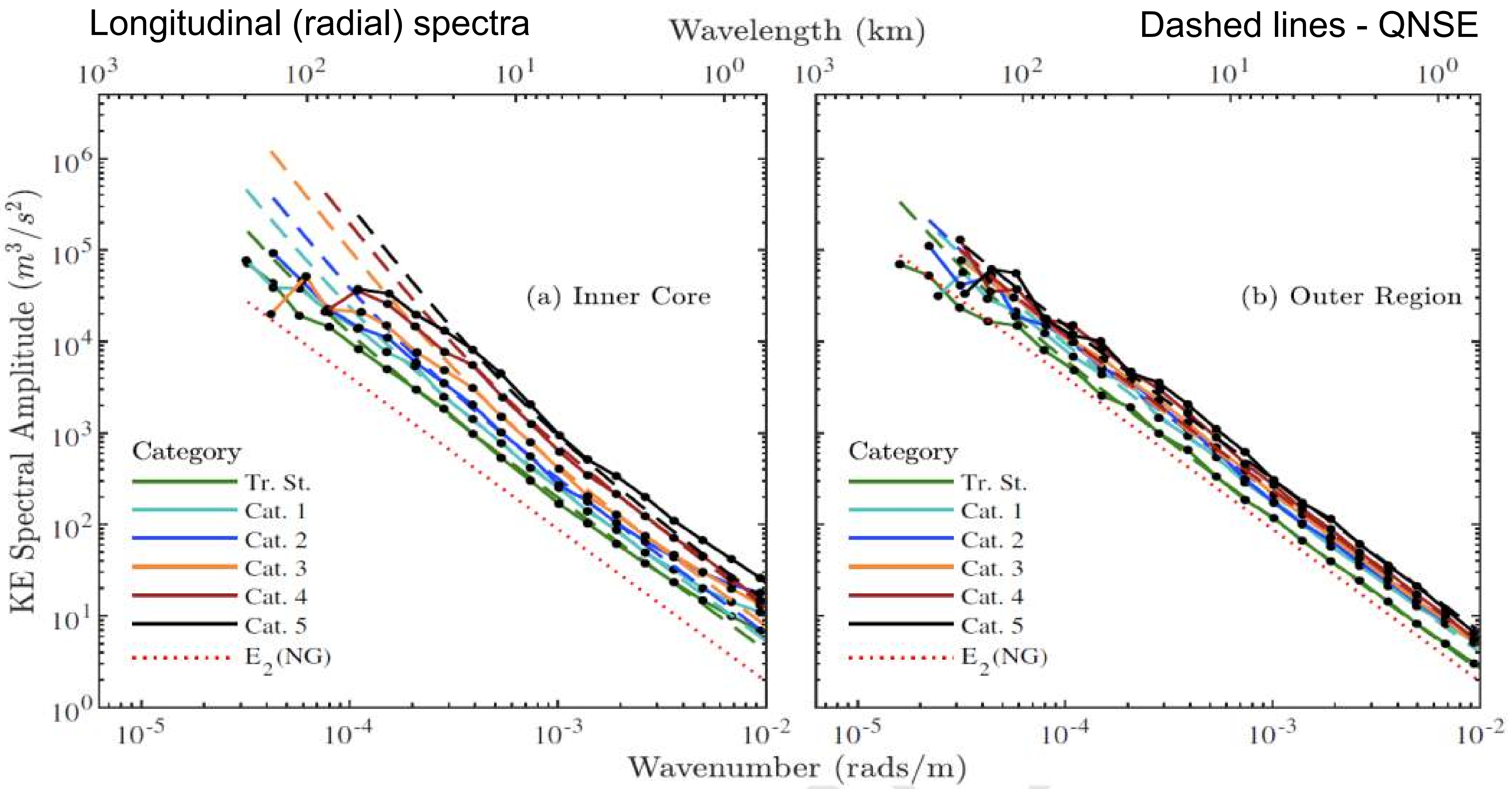
Solid lines – aircraft observations

Dashed lines - QNSE

Red dots– NG spectrum of tropospheric and stratospheric turbulence (Nastrom & Gage (1981, 1984, 1986)

- Flight-level Data from a total of 655 flights (into 138 storms from 1997 to 2019) were analyzed to study the characteristics of kinetic energy spectra in comparison to theory

Can QNSE be applied in hurricane conditions?



Summary of Zonostrophic Turbulence

- The QNSE theory of rotating turbulence is capable of reproducing both the amplitudes and slopes of observed turbulence spectra in tropical cyclones (TCs)
- Outside the TC vortex (outer core), the TC spectra rebound to NG spectra for weak storms
- The affinity of the TC, tropospheric and ocean spectra exposes the unity of physical laws governing a broad variety of geophysical flows

Turbulent flux Parameterization

Vertical eddy diffusivity for momentum transfer (K_m):

$$K_m = k\,(u_*/\Phi_m)\,z\,(1 - z/h)^2$$

Momentum flux (τ):

$$\tau = -\rho(\overline{u'w'}^2 + \overline{v'w'}^2)^{1/2} = K_m \rho \frac{\partial \bar{u}}{\partial z}$$

$k = 0.4$

u_* : friction velocity

Φ_m : stability function ~1

h : PBL height determined by critical Richardson number method

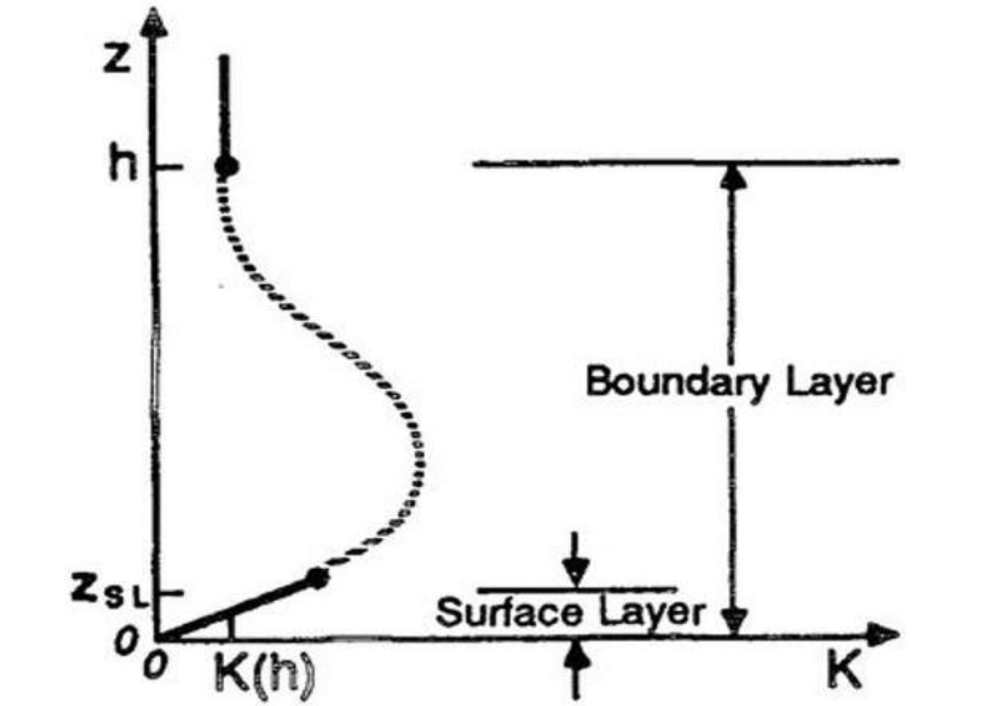
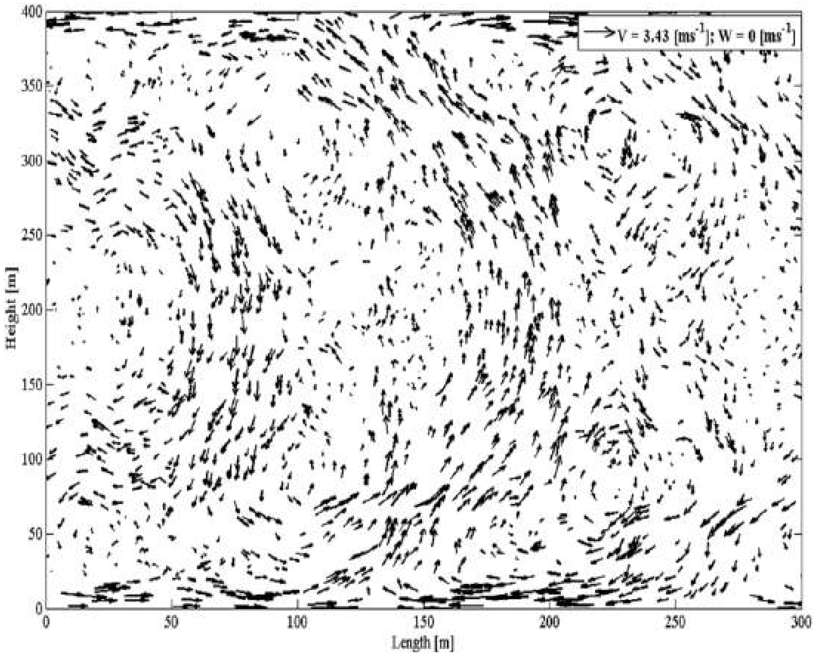
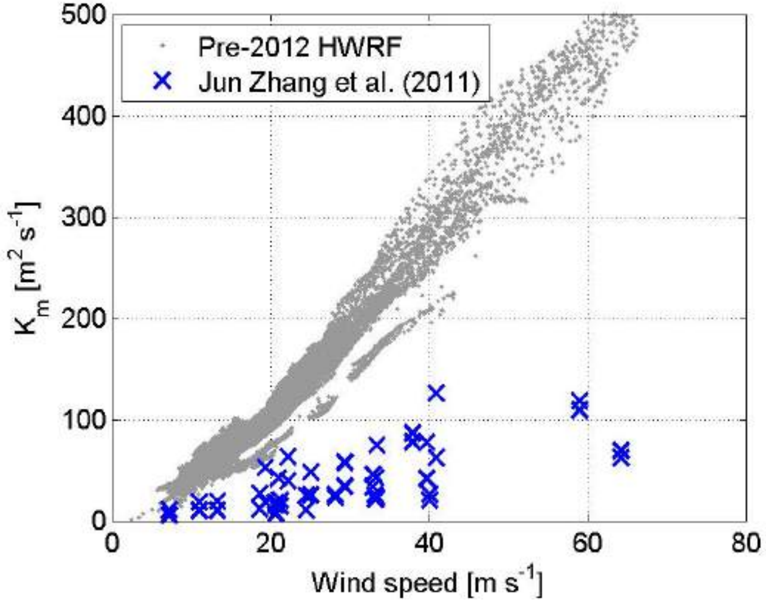


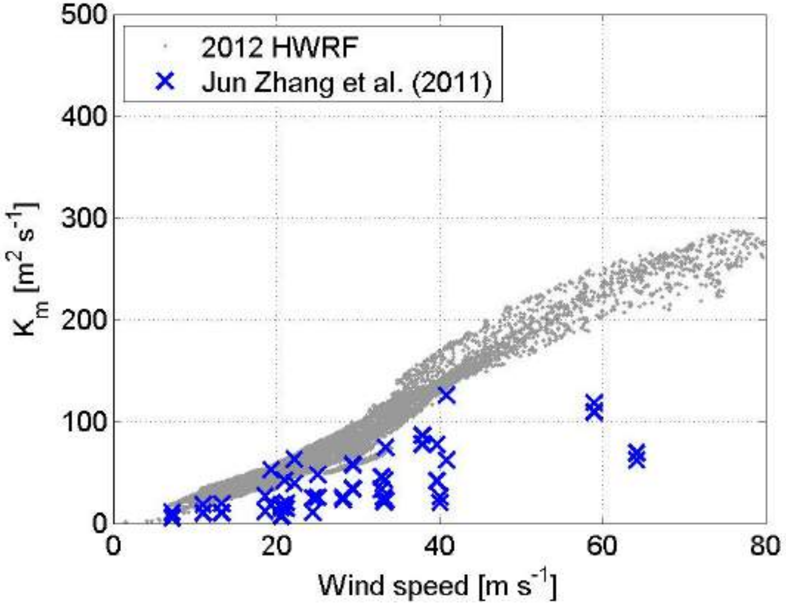
FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

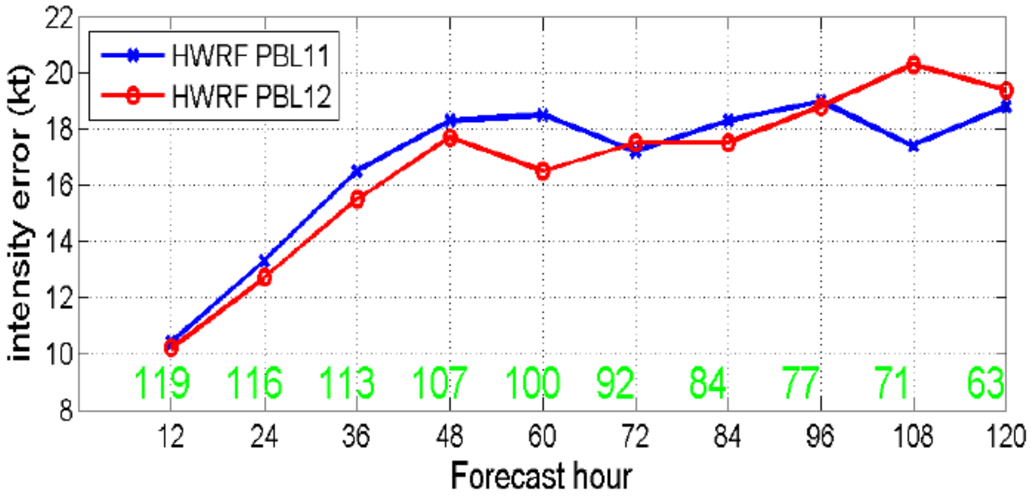


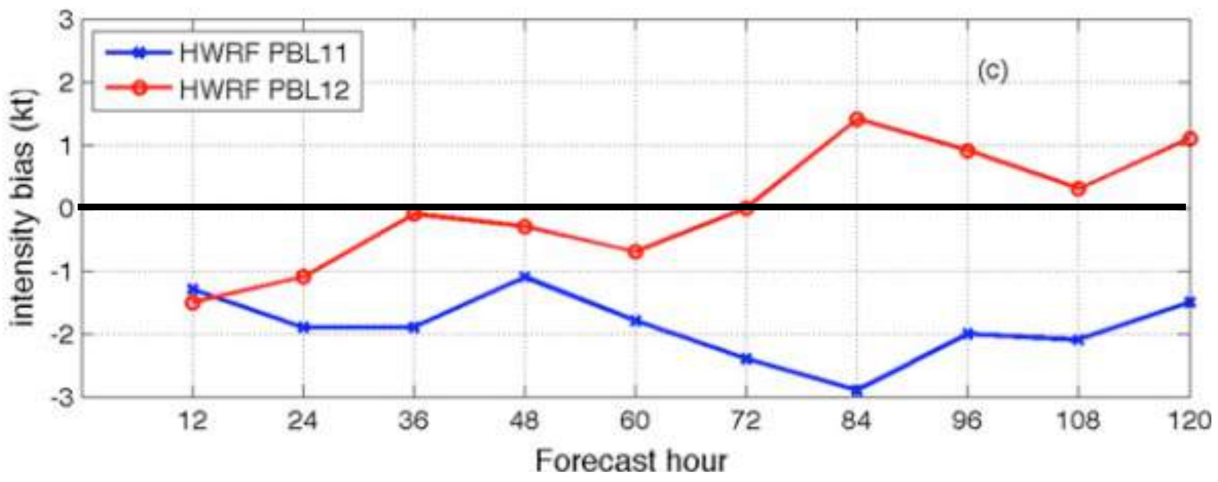
Improving turbulence parameterization in hurricane forecast models



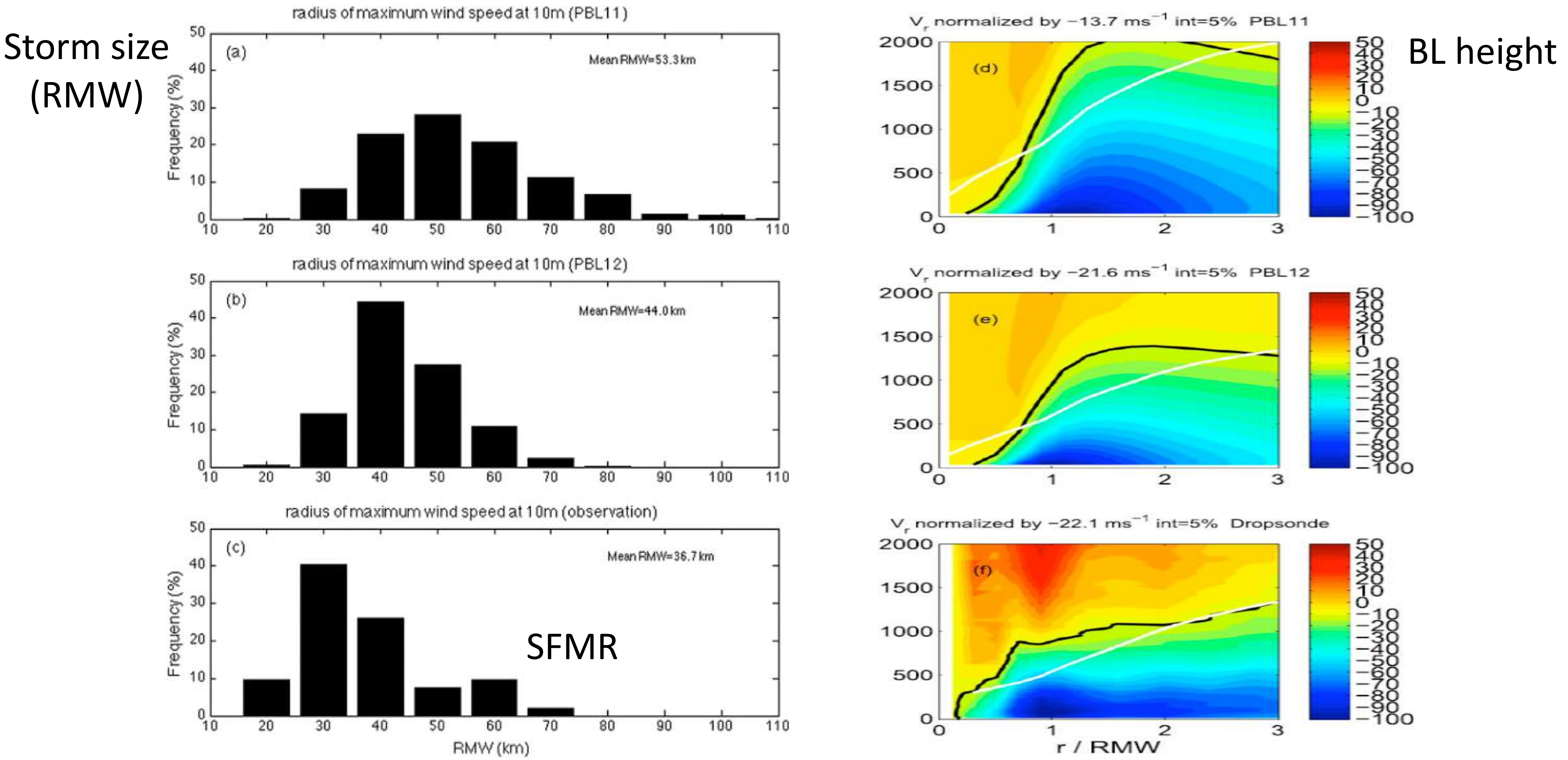
Observations (x) from limited P3 flights in the hurricane boundary layer







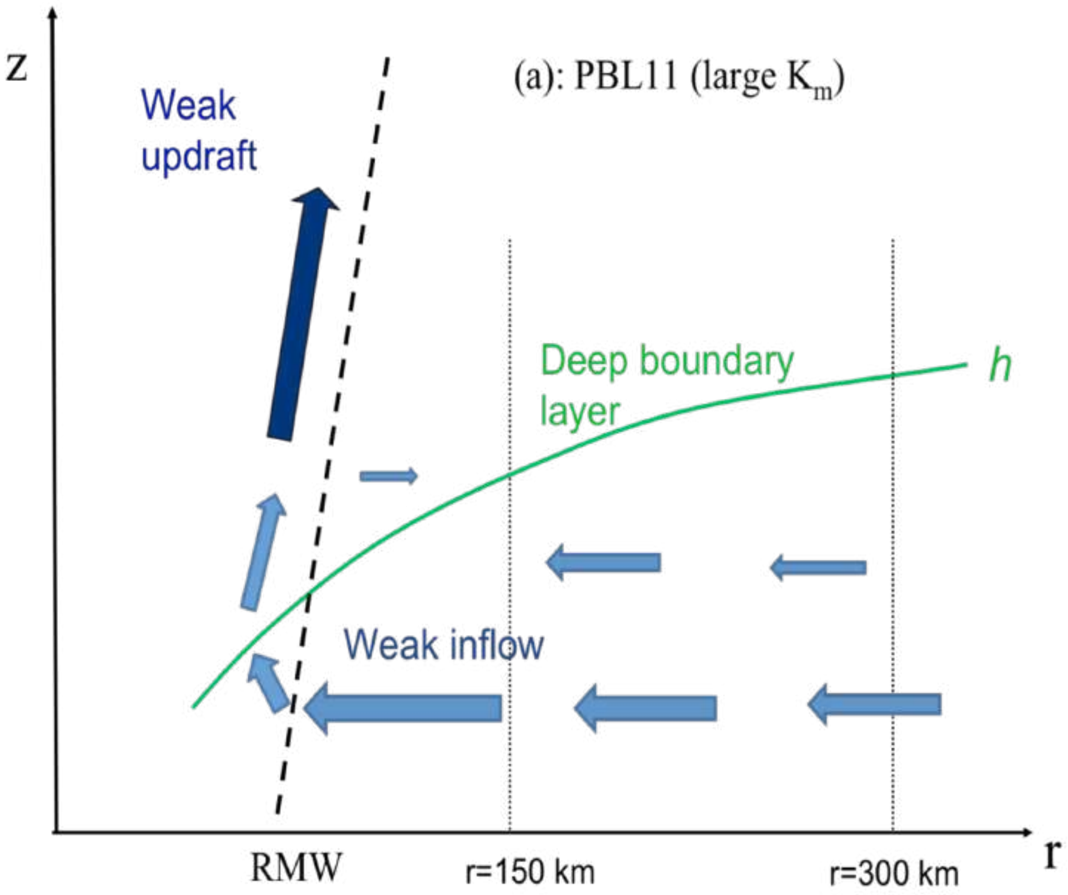
Improving turbulence parameterization in hurricane forecast models



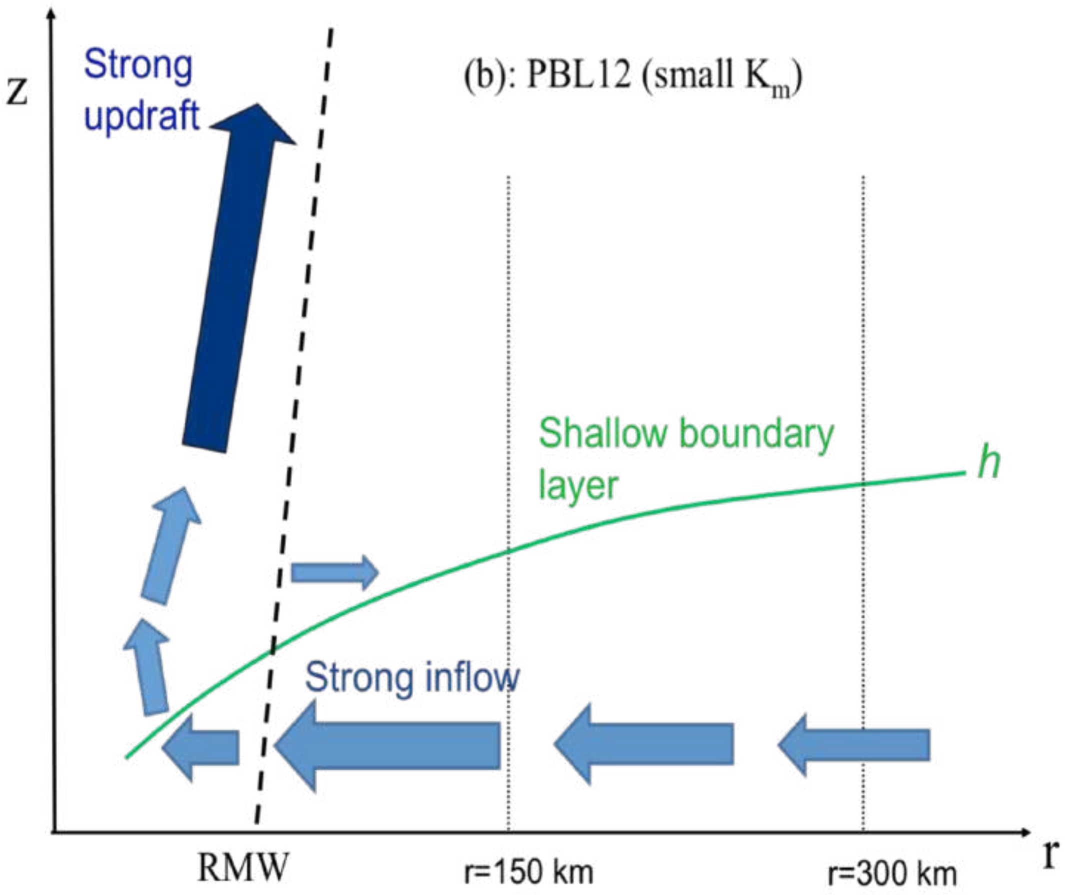
Effects of Turbulent Mixing on Hurricane Structure and Intensity

(J. A. Zhang et al. 2015, 2017)

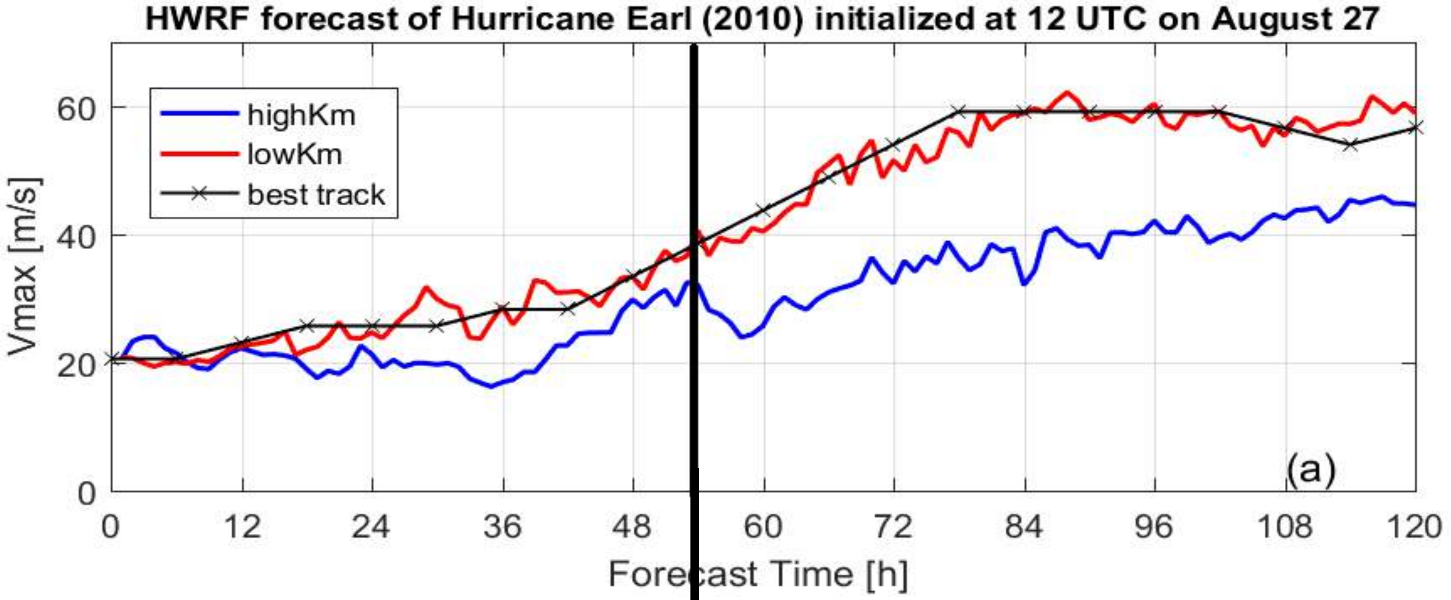
Large eddy diffusivity

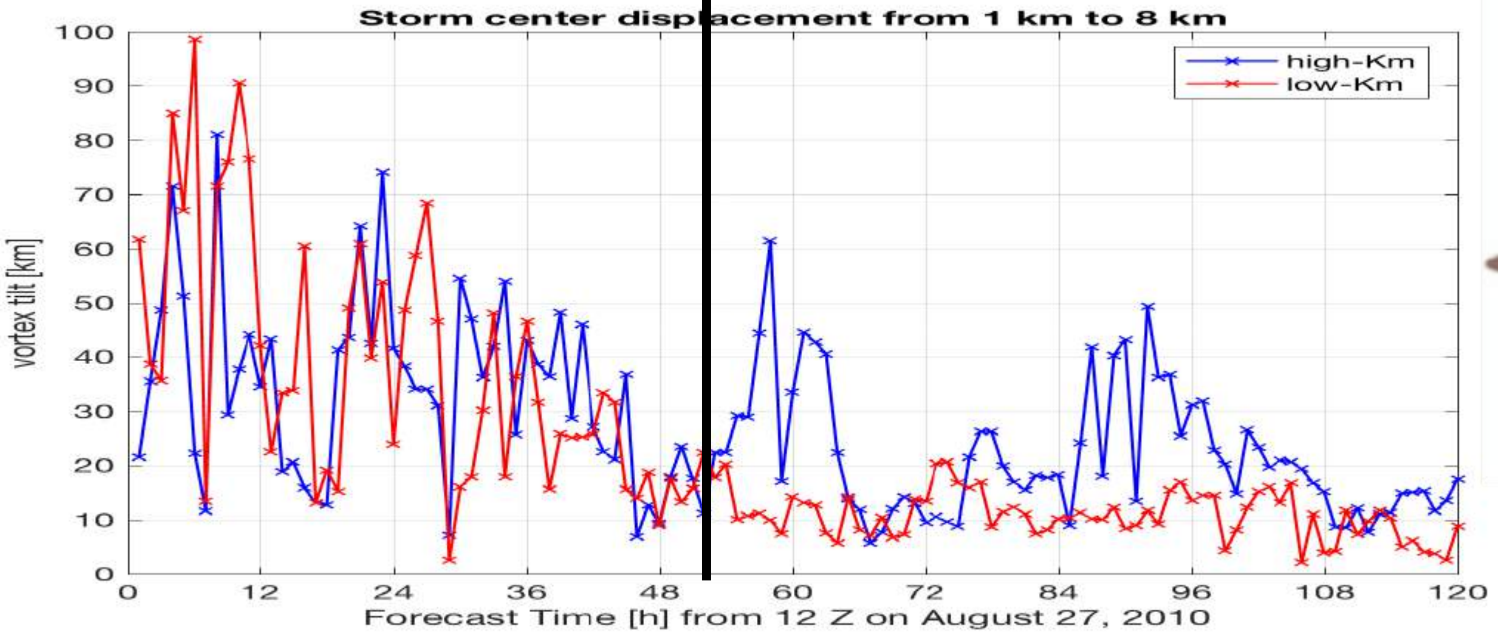


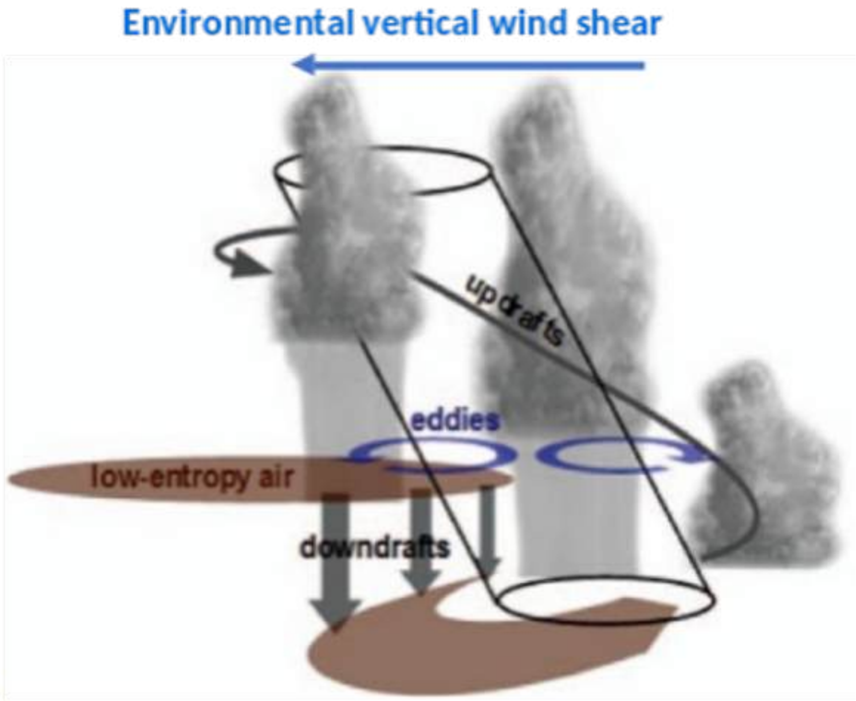
Small eddy diffusivity



Impacts of PBL scheme on Vortex Tilt







More Conclusions

1. Successful Examples of Research to Operations (R2O) are shown in terms of using observational data to improve boundary-layer parameterization in operational models (e.g., HWRF)

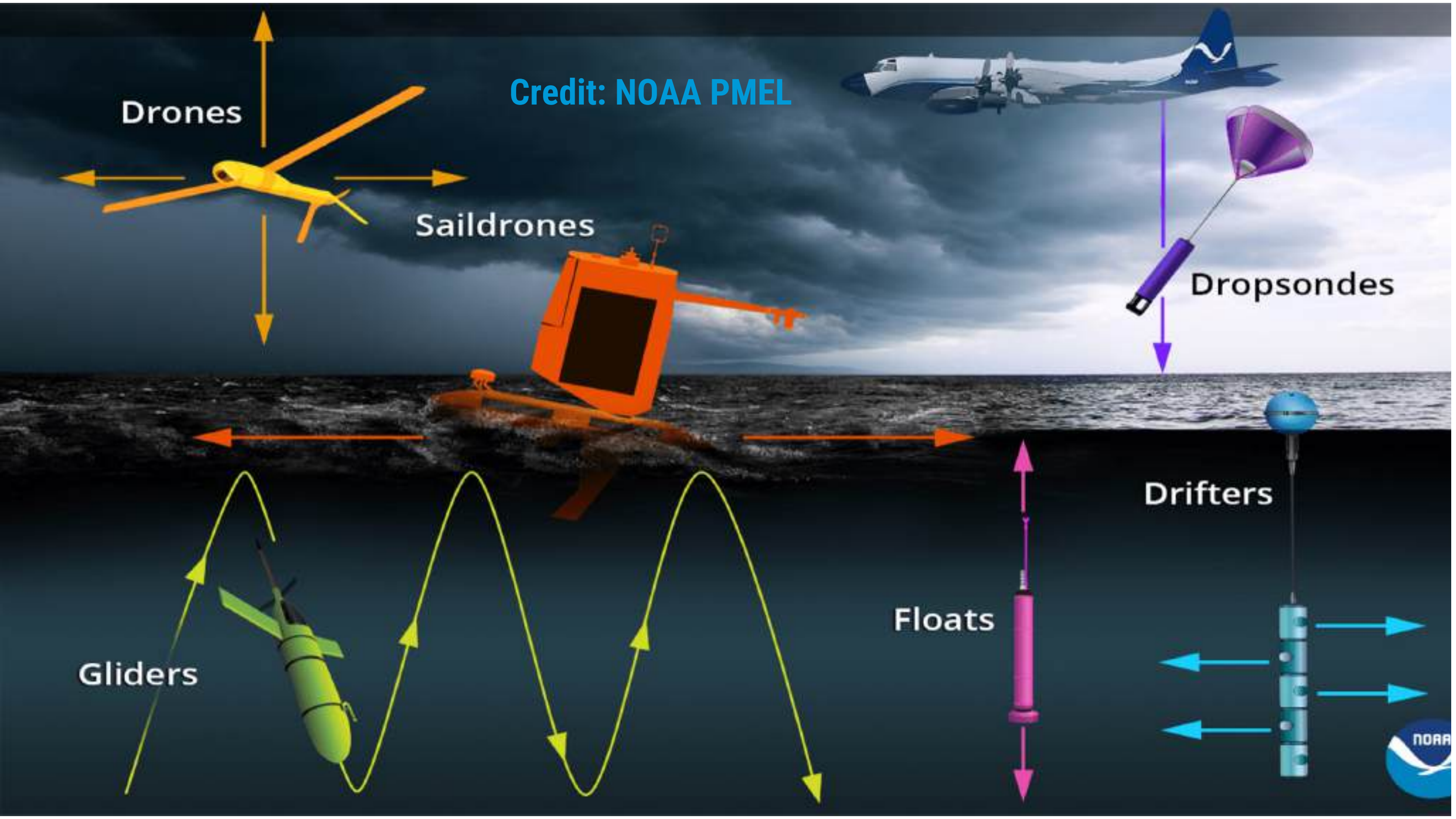
2. Model deficiency can be identified through model diagnostics of TC structures based on observations

3. Observation-based model physics upgrades led to improvements in hurricane intensity and structure forecasts

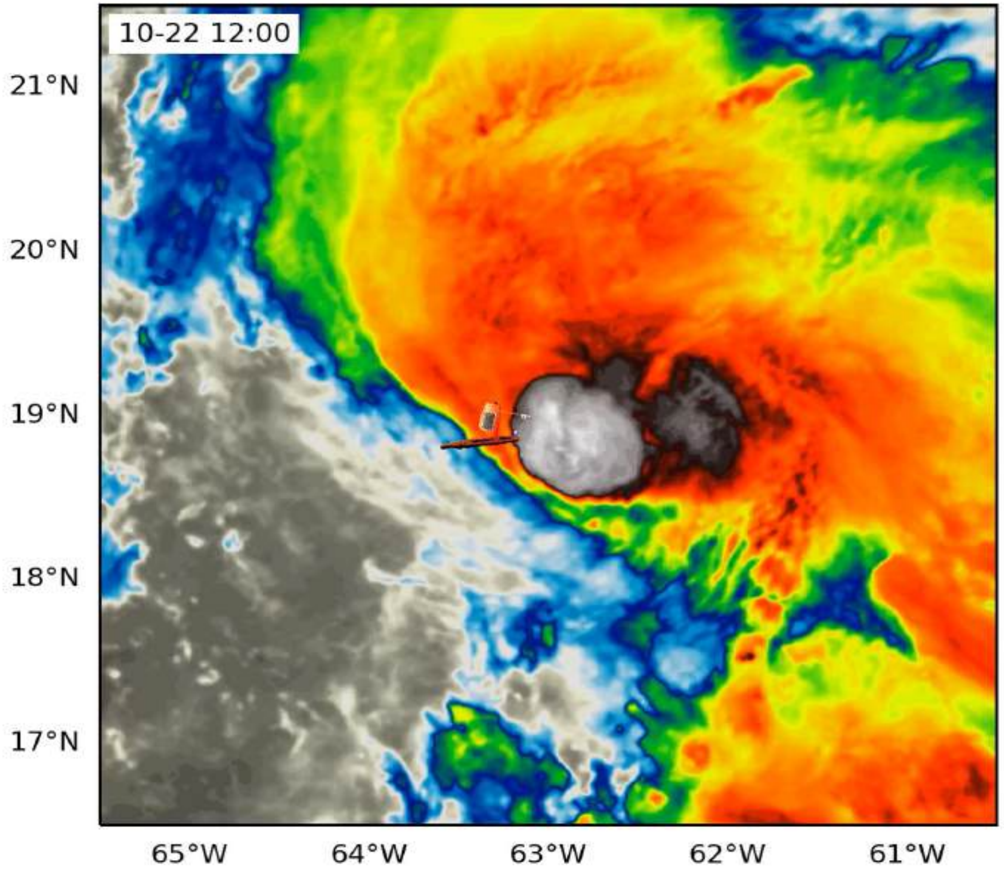
4. Analyses of retrospective forecasts helped understand how and why changes in the PBL schemes affect hurricane intensity and structure

Coordinated Hurricane Atmosphere-Ocean Sampling (CHAOS) Experiment

PIs: Jun Zhang, Lev Looney (NOAA/U Miami), Cheyenne Stienbarger (NOAA GOMO)



Hurricane Tammy (2023)



https://www.aoml.noaa.gov/wp-content/uploads/2024/04/2024HFP_OceanObserving_Science_Description_CHAOS.pdf

Thanks!

Questions?

Contact: jun.zhang@noaa.gov

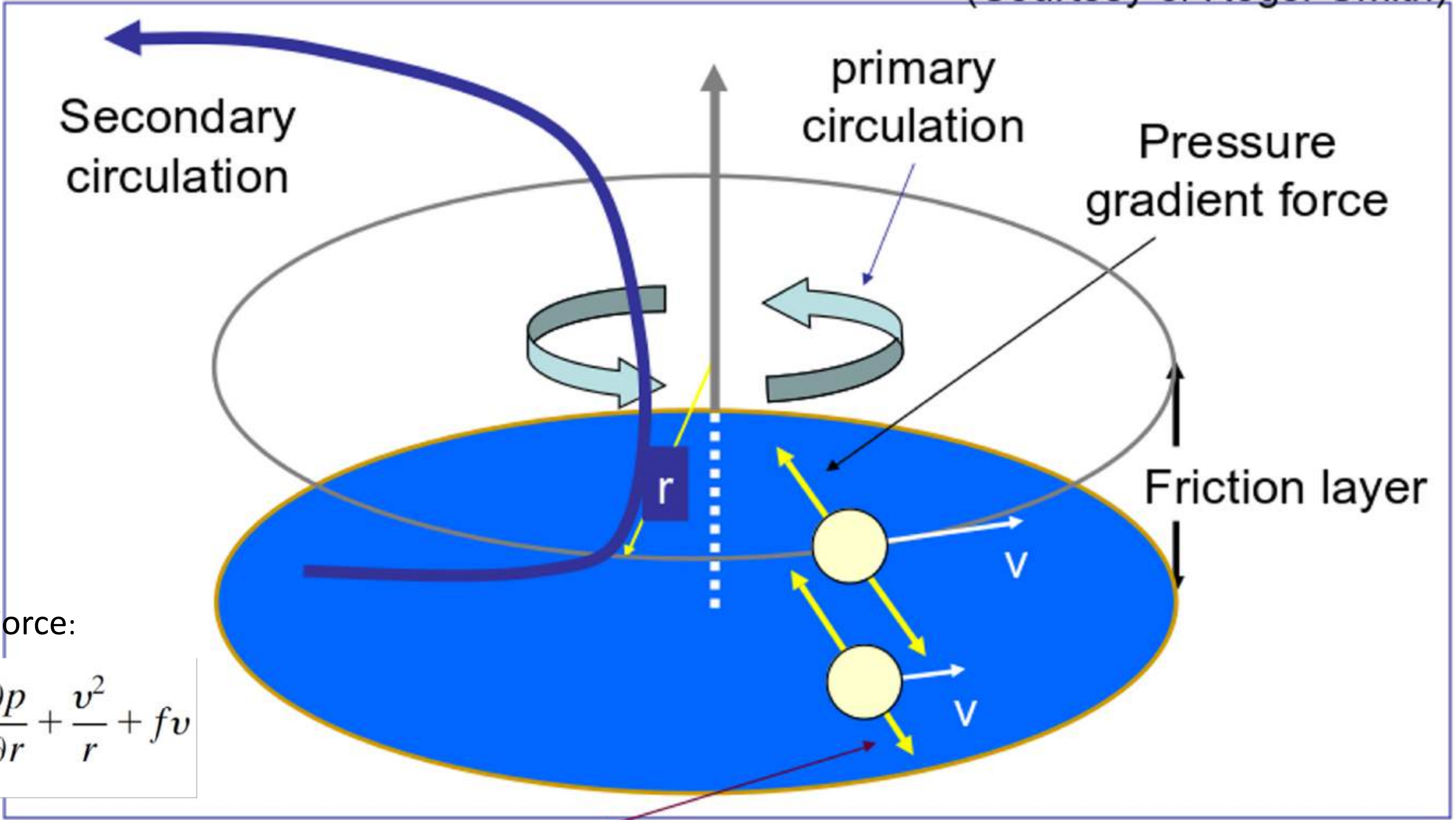
QNSE for tropical cyclone conditions

- Tropical cyclones feature cyclostrophic rotation ($\hat{f}$), and so the total Coriolis parameter is $\tilde{f} = \hat{f} + f$, where $\hat{f} = 2\frac{U_m}{R_m}$ and f is the earth Coriolis parameter
- The cyclostrophic addend provides for the observed dependence of spectral amplitudes on TC intensity
- Inside the radius of maximum wind speed (R_m), the flow is in near solid body rotation; turbulence is homogeneous, thus QNSE expressions apply
- In the outer core region, turbulence is inhomogeneous; $\hat{f} \to 0, \tilde{f} \to f$, the spectra are expected to rebound to their NG counterparts

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

Frictionally-induced secondary circulation

(Courtesy of Roger Smith)



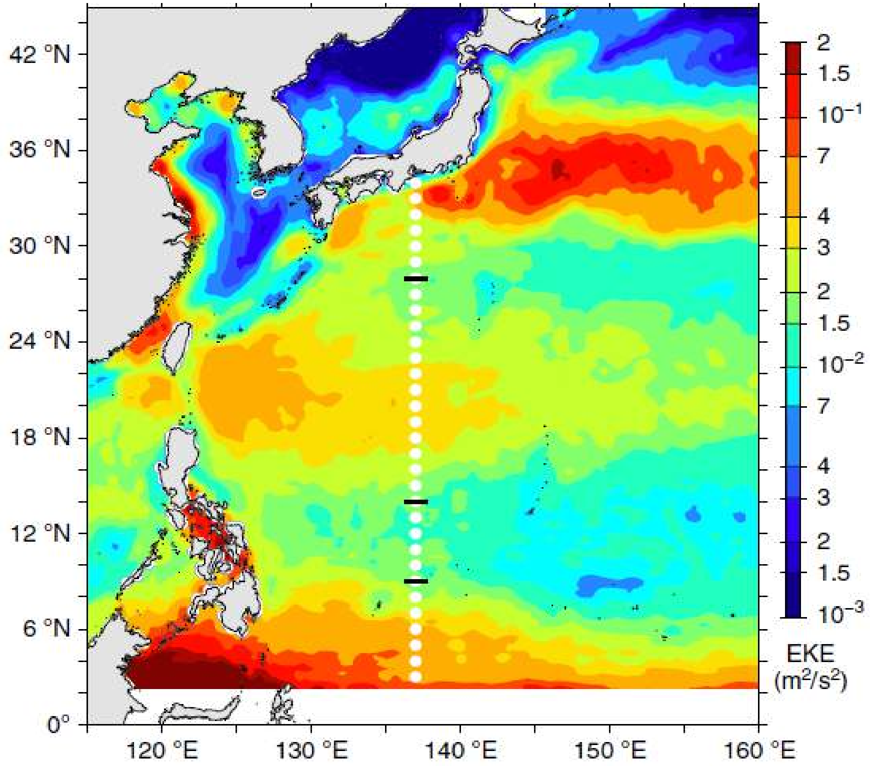
Agradient Force:

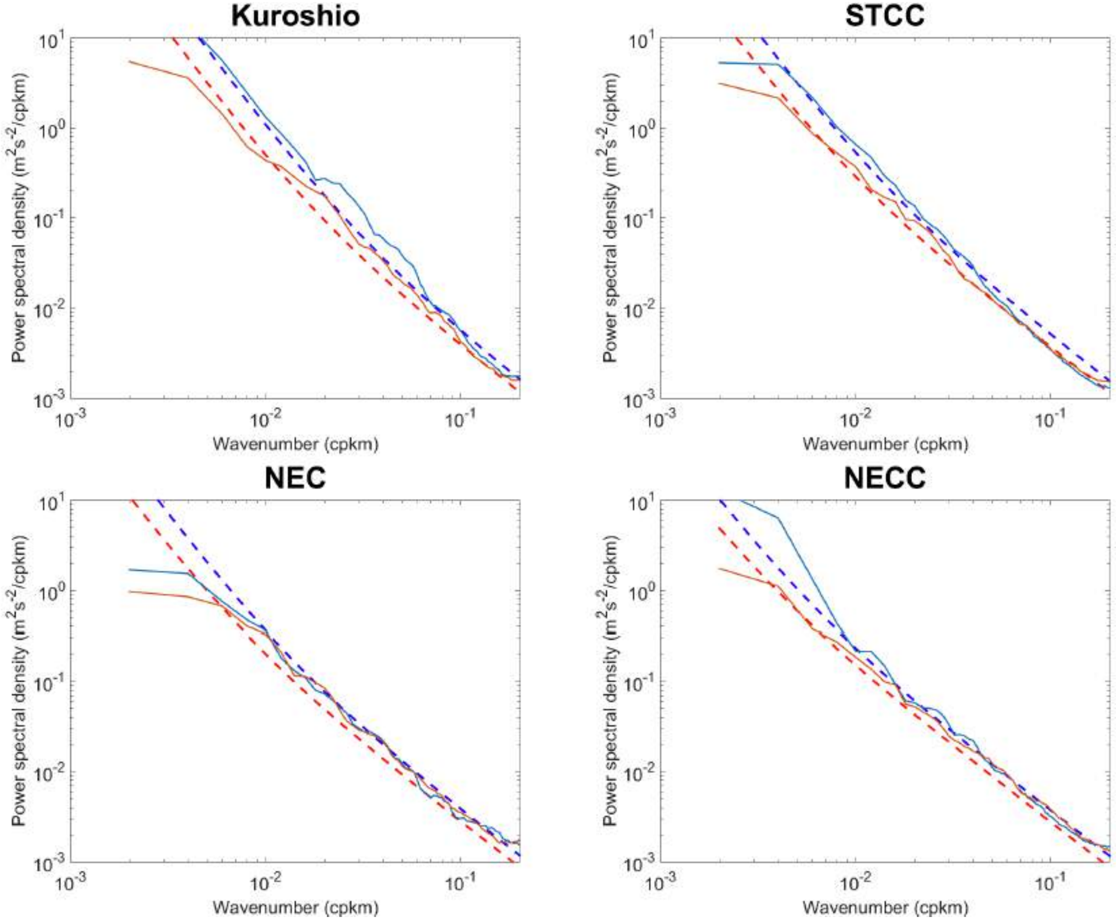
$$\mathrm{AF} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{v^2}{r} + fv$$

Centrifugal force and Coriolis force are reduced by friction

Non-TC observations vs. QNSE

Ship observations of ocean current velocity from Japan to equator (over four regions)

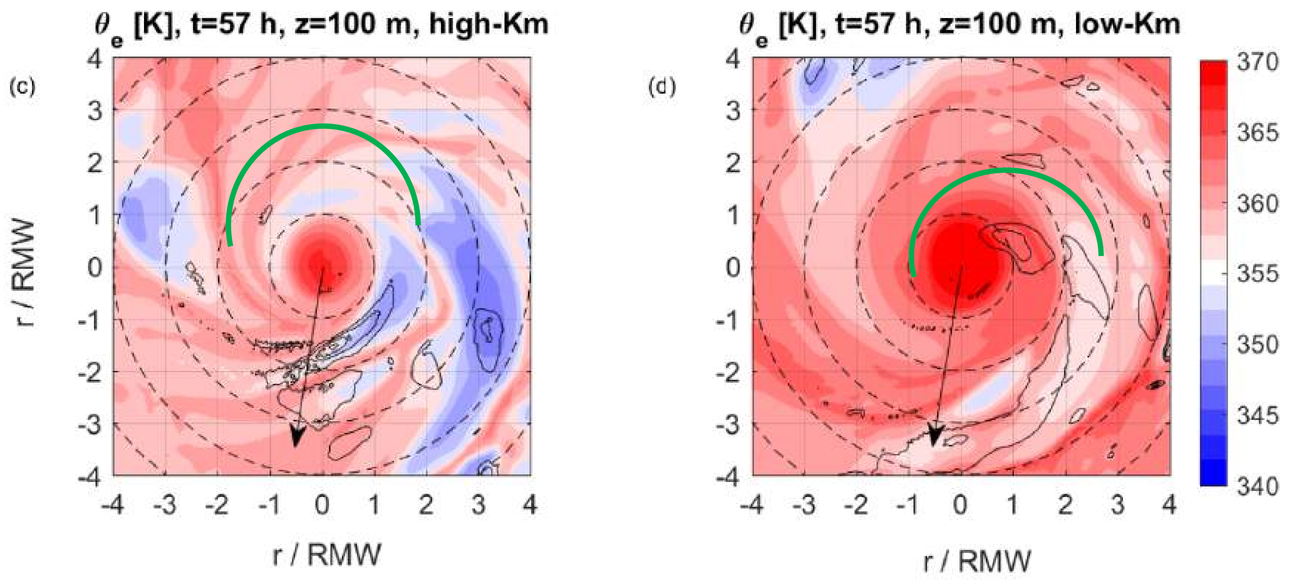




- ➢ The same QNSE expressions (dashed lines) successfully represent the observed (solid lines) longitudinal (red) and transverse (blue) spectra in the Northwest Pacific ocean in different regions where *f* varies
- ➢ Spectral slope can be different for different wavenumbers but the QNSE theory nicely predicted this slope change.

Note that tropospheric observations (e.g., Khatri et al. 2018) also supported the QNSE theory

Can surface enthalpy fluxes recover the θ_e deficit?



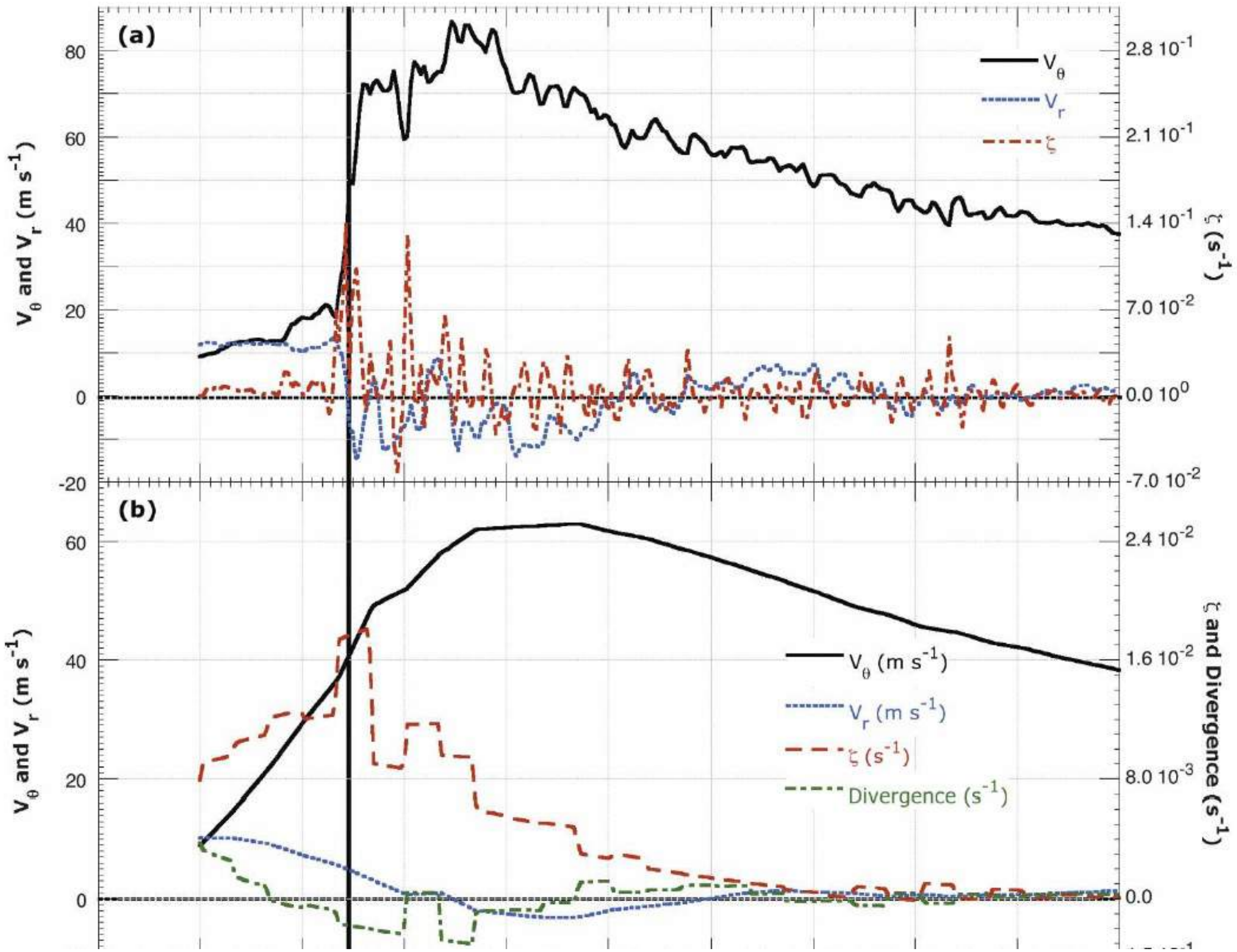
Green curve shows inflow trajectory

HWRF	θ	θ_e	T_{LCL}	F_H	F_q	$d\theta/dt$	dq/dt	$d\theta_e/dt$	$\Delta\theta_e$ (ES)	$\Delta\theta_e$ (OB)
HighKm	301.5	354.5	294.8	19.9	236.1	0.06	0.30	0.95	4.9	8.5
lowKm	301.9	371.0	299.8	38.2	360.6	0.12	0.46	1.53	8.2	6.3

- no
- yes

P3 flight into Hurricane Hugo

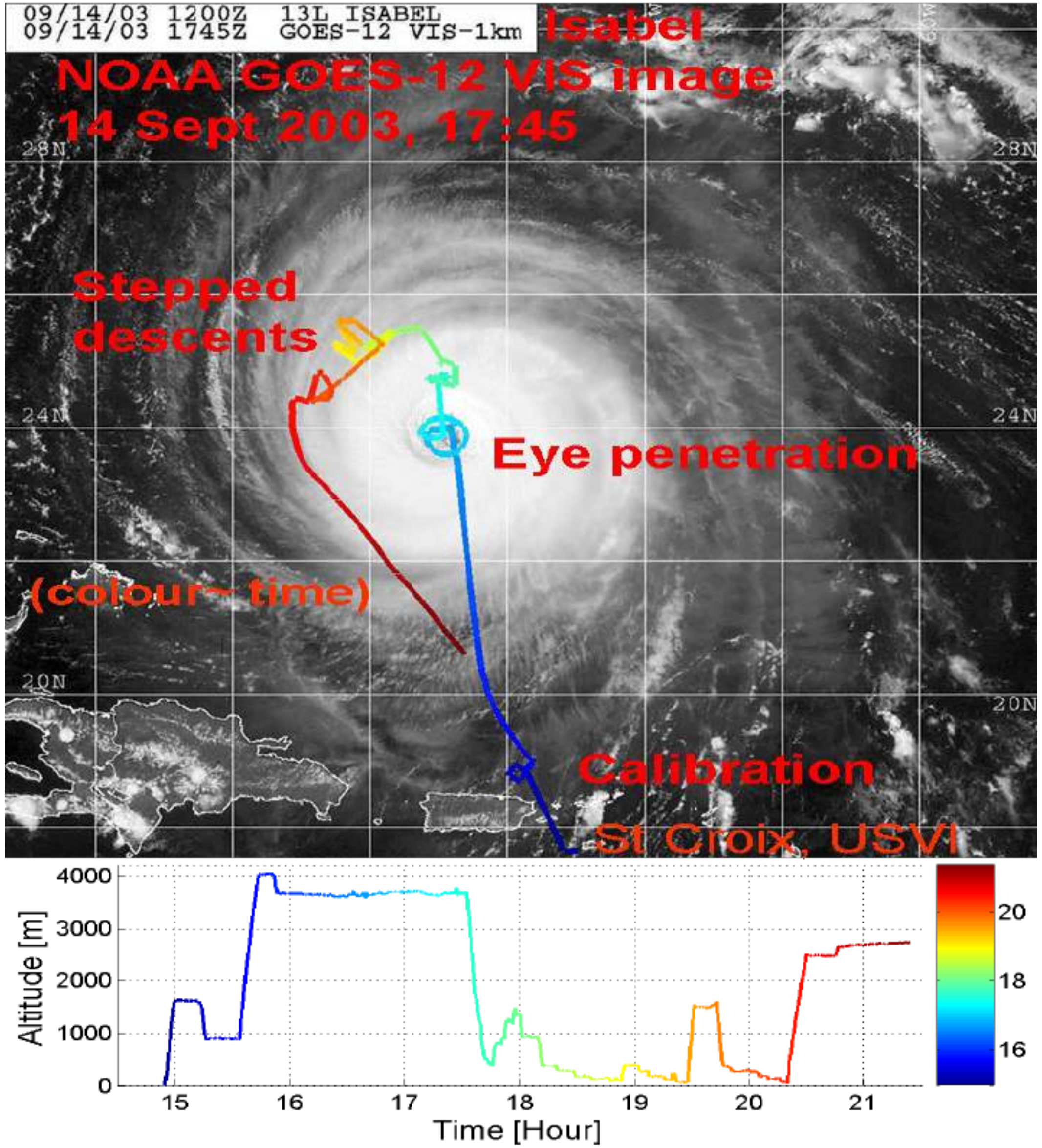
(Marks et al. 2008)



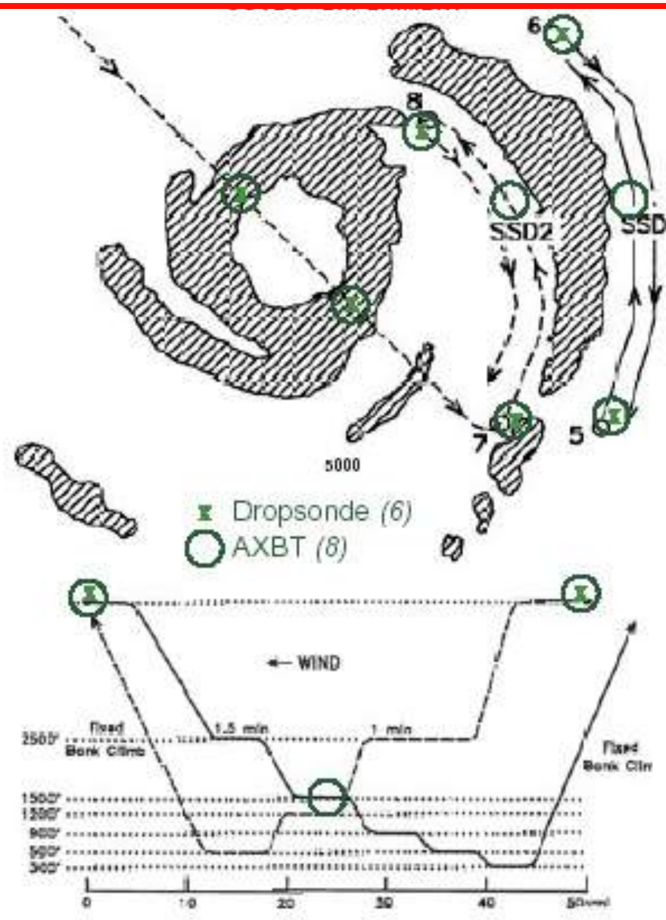
EVM – Eyewall vorticity maximum

On 15 September 1989, during observations for Hurricane Hugo, Hunter NOAA42 flew through an eyewall mesovortex.

The Coupled Boundary Layer Air-sea Transfer Experiment (CBLAST)

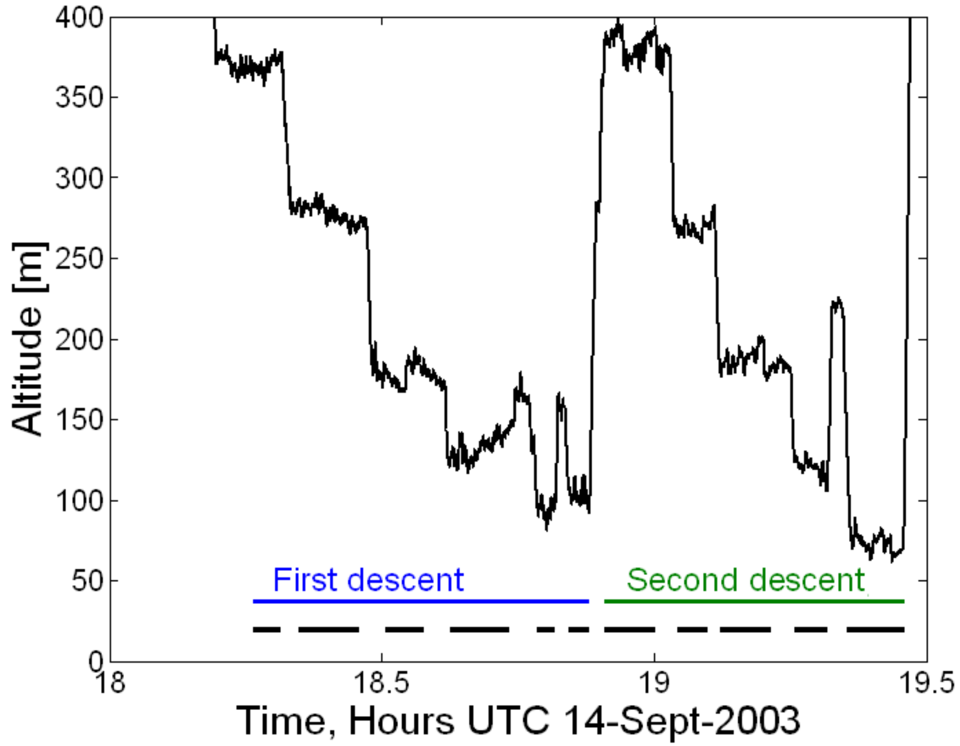


CBLAST STEPPED DESCENTS

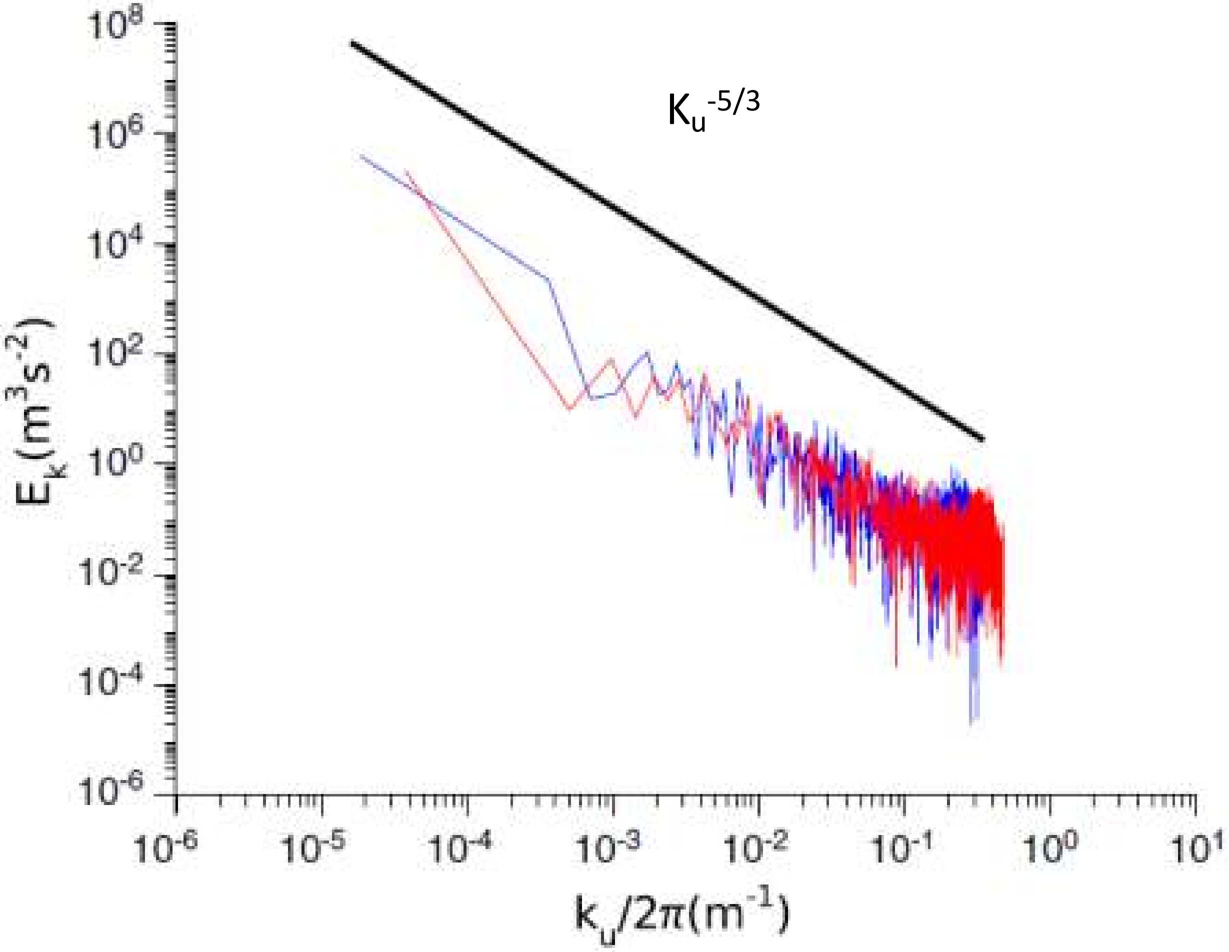


Black lines represent the flux runs

Typical length of a flux run is 24 km



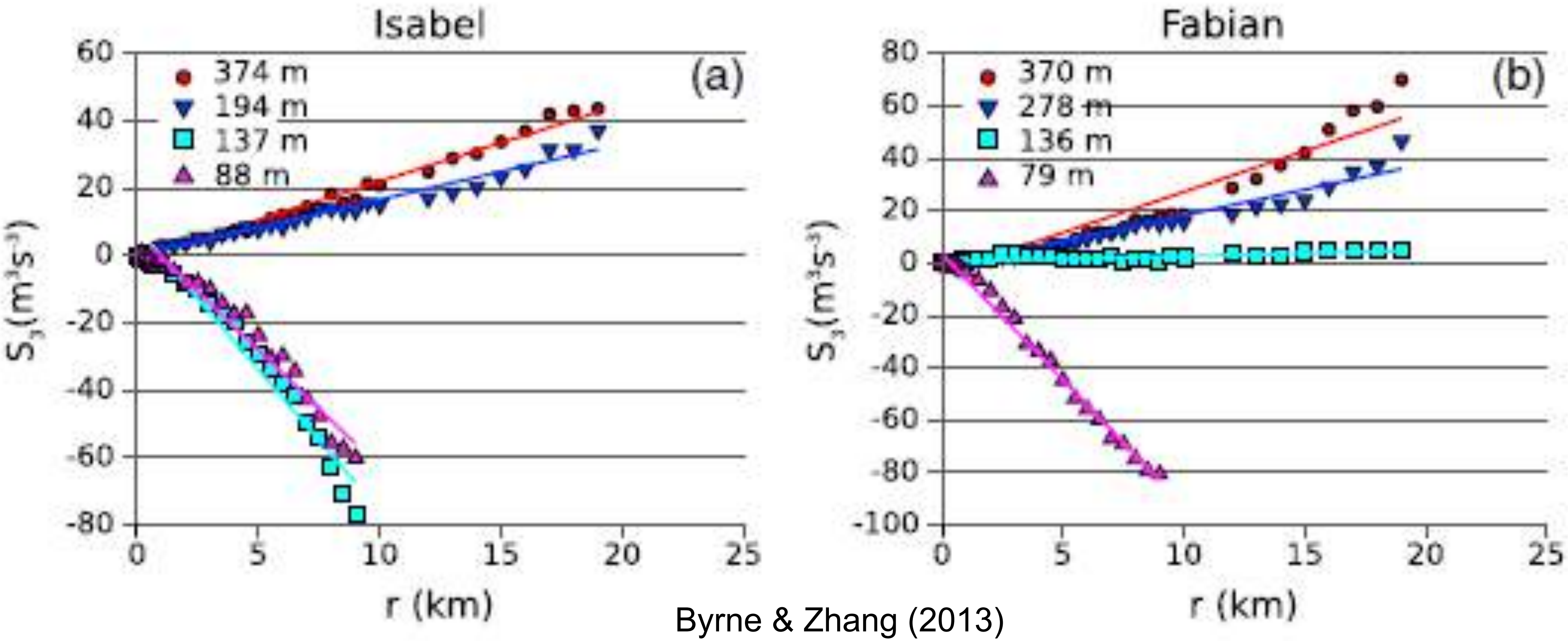
1D Energy Spectra



Wavenumber spectrum of kinetic energy for P3 flight legs at heights of 88m (red) and 194m (blue) in hurricanes. From: Byrne & Zhang (2013), GRL

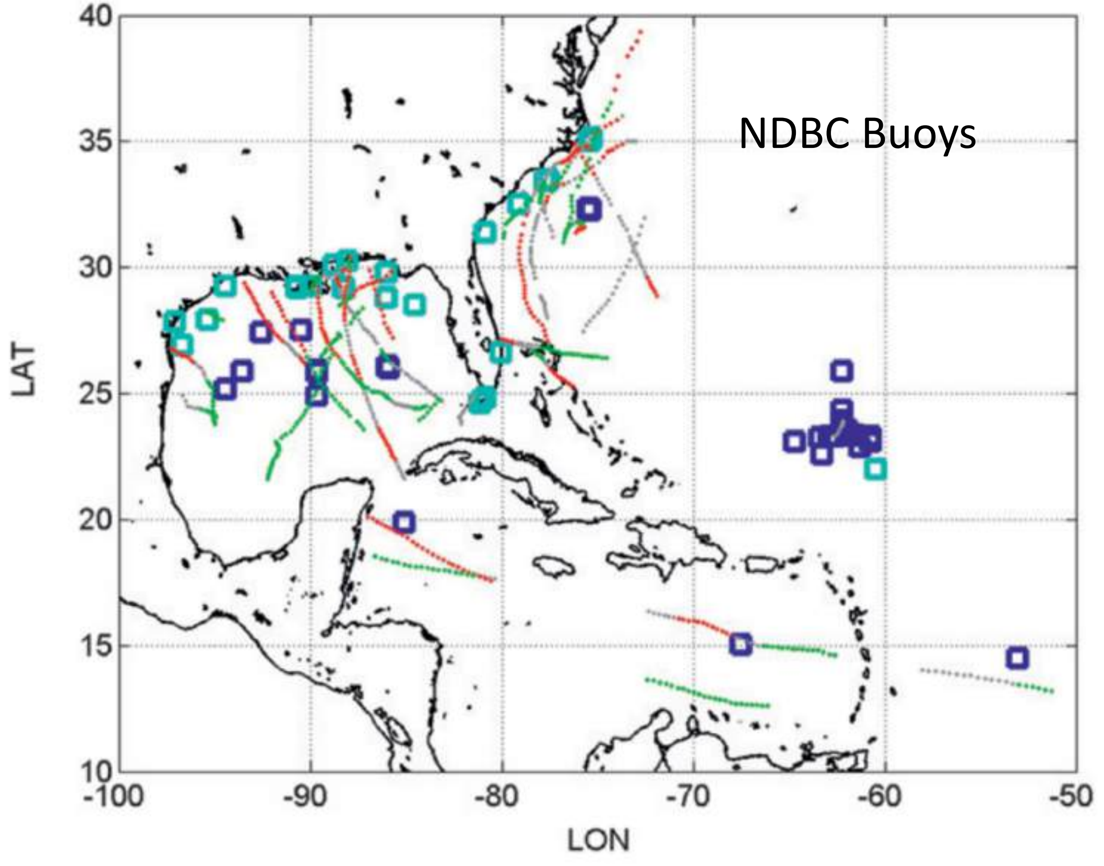
Energy Cascade – 3rd order structure function

- The -5/3 slope in the energy spectra generally points to Kolmogorov 3D turbulence and direct cascade
- If it is 2D turbulence, then the -5/3 slope → inverse cascade



Byrne & Zhang (2013)

Hurricane Intensity change and Air-sea Interaction



Intensifying Hurricanes ≥ 10kt/6hr (TC-INT)

Weakening Hurricanes ≤ -10kt/6hr (TC-FILL)