U.S.NAVAL RESEARCH LABORATORY

Spectral Properties of Centimeter to Decameter Wavelengths: Microwave Remote Sensing Observations in Mild to Extreme Wind Conditions

Paul A. Hwang
Remote Sensing Division
U. S. Naval Research Laboratory
Washington DC USA

Waves Workshop, Melbourne, Australia, 10-15 November 2019

U.S.NAVAL RESEARCH LABORATORY

Outline

- Measuring cmDm waves in ocean
  - Large wave filtering
  - Doppler frequency shift
  - result

Limited in situ observations, no high wind data

- Microwave remote sensing
  resonance scattering and tilting wavelengths: cmDm

Plenty of field observations in all wind conditions

- Microwave radar and radiometer observations
  - Roughness: scattering element, local incidence angle
    - VV NRCS# => Dominated by Bragg resonance mechanism:

    Radar as surface roughness spectrometer
    Ku, C, and L bands (14, 6, 1.4 GHz)
    [1 cm – 30 cm]: short cmDm

    # Normalized radar cross section

    - L-band LPMSS from GNSSR* (1.4 GHz)
      [>60 cm]: long cmDm

    * Global Navigation Satellite System Reflectometry

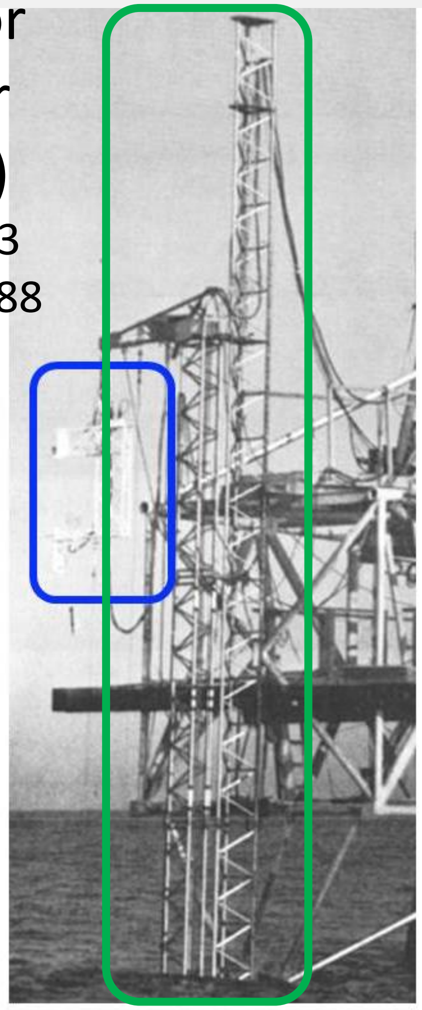
- Spectral slope** and equilibrium spectrum concept

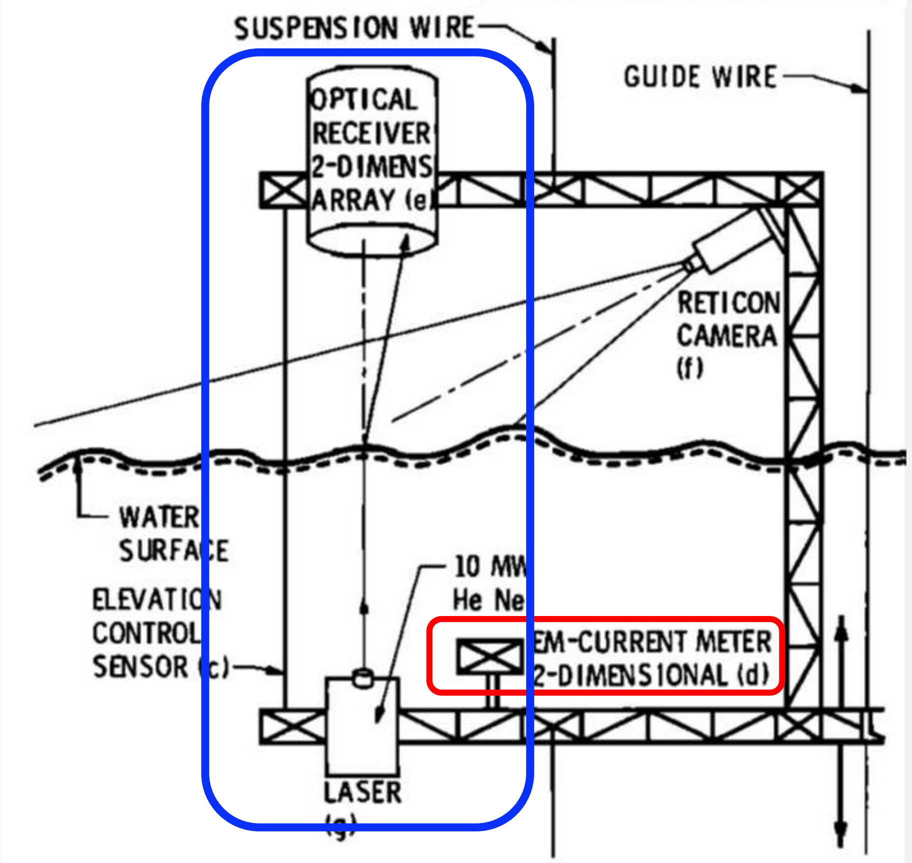
** Not constant

Measuring cmDm waves in ocean

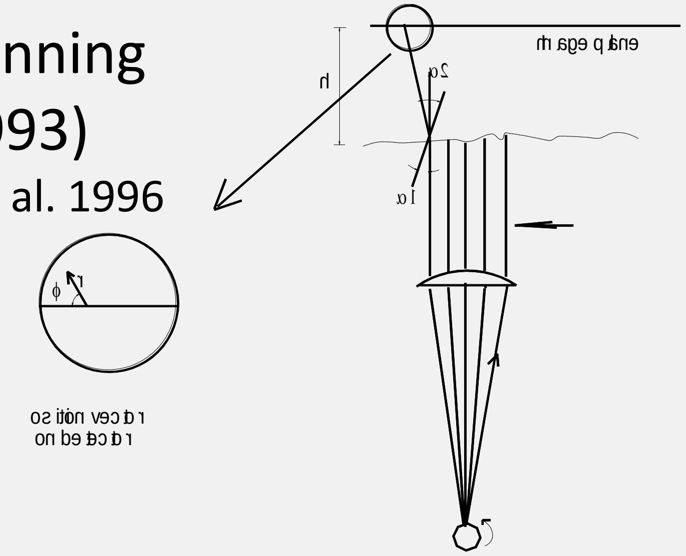
Laser slope sensor on wave follower (~1980 Shemdin)
Tang and Shemdin 1983
Hwang and Shemdin 1988

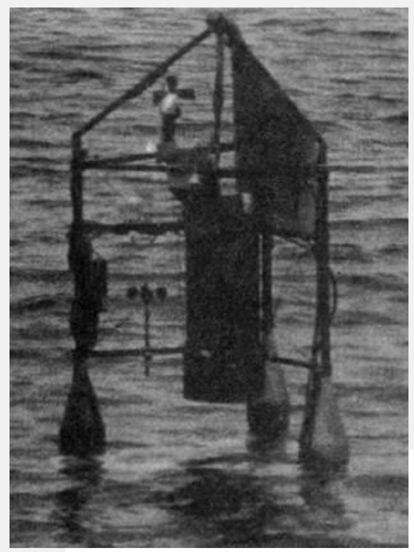
Laser slope gauge for short waves
Wave follower to alleviate large wave issue
Current meter to address Doppler frequency shift



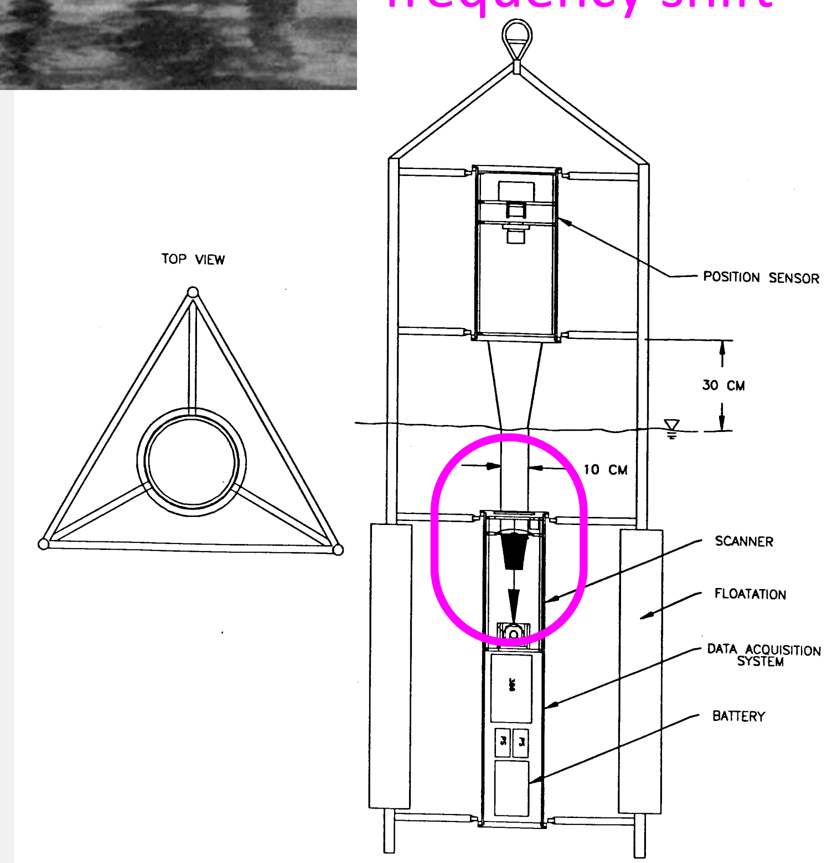


1D scanning (~1993)
Hwang et al. 1996

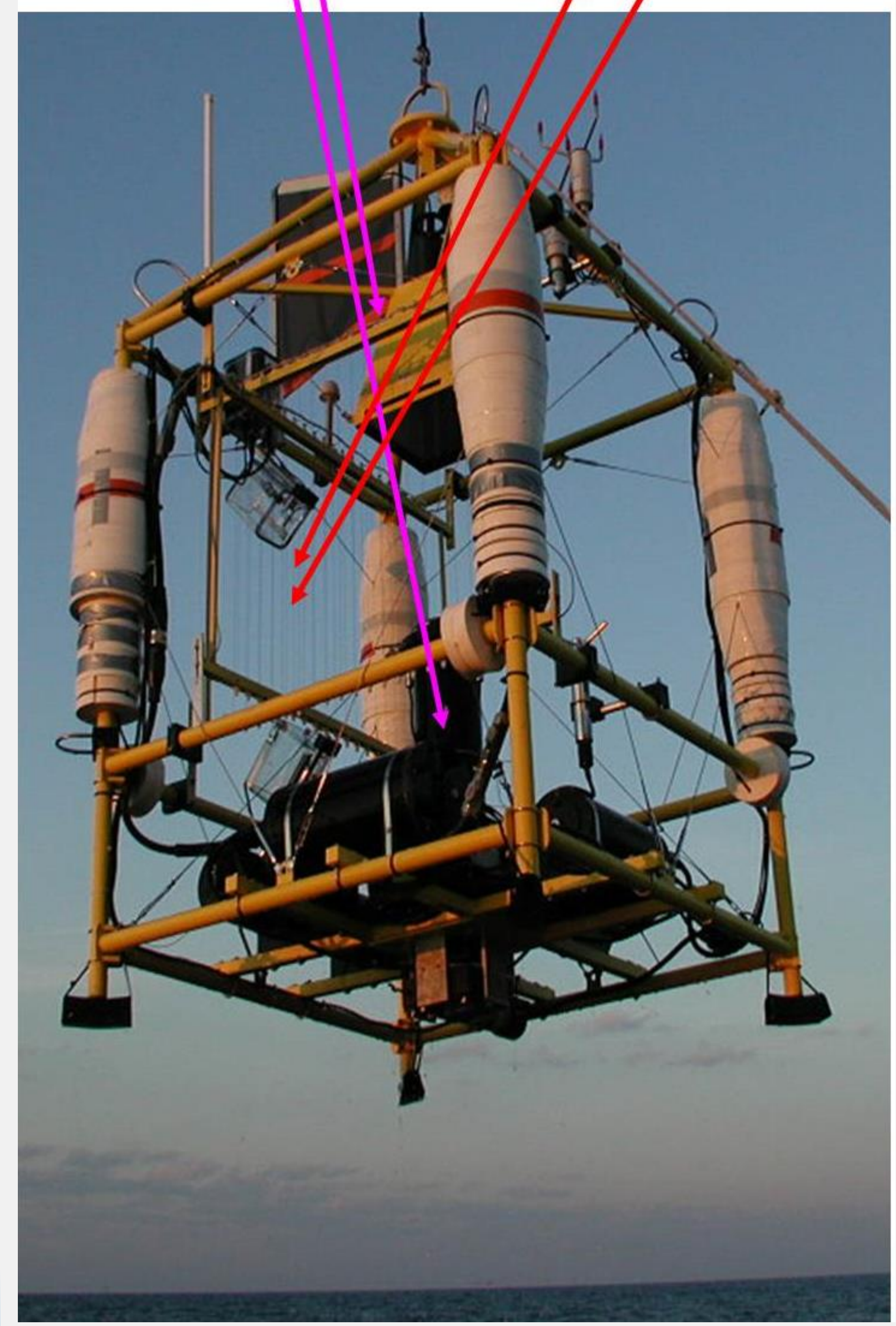




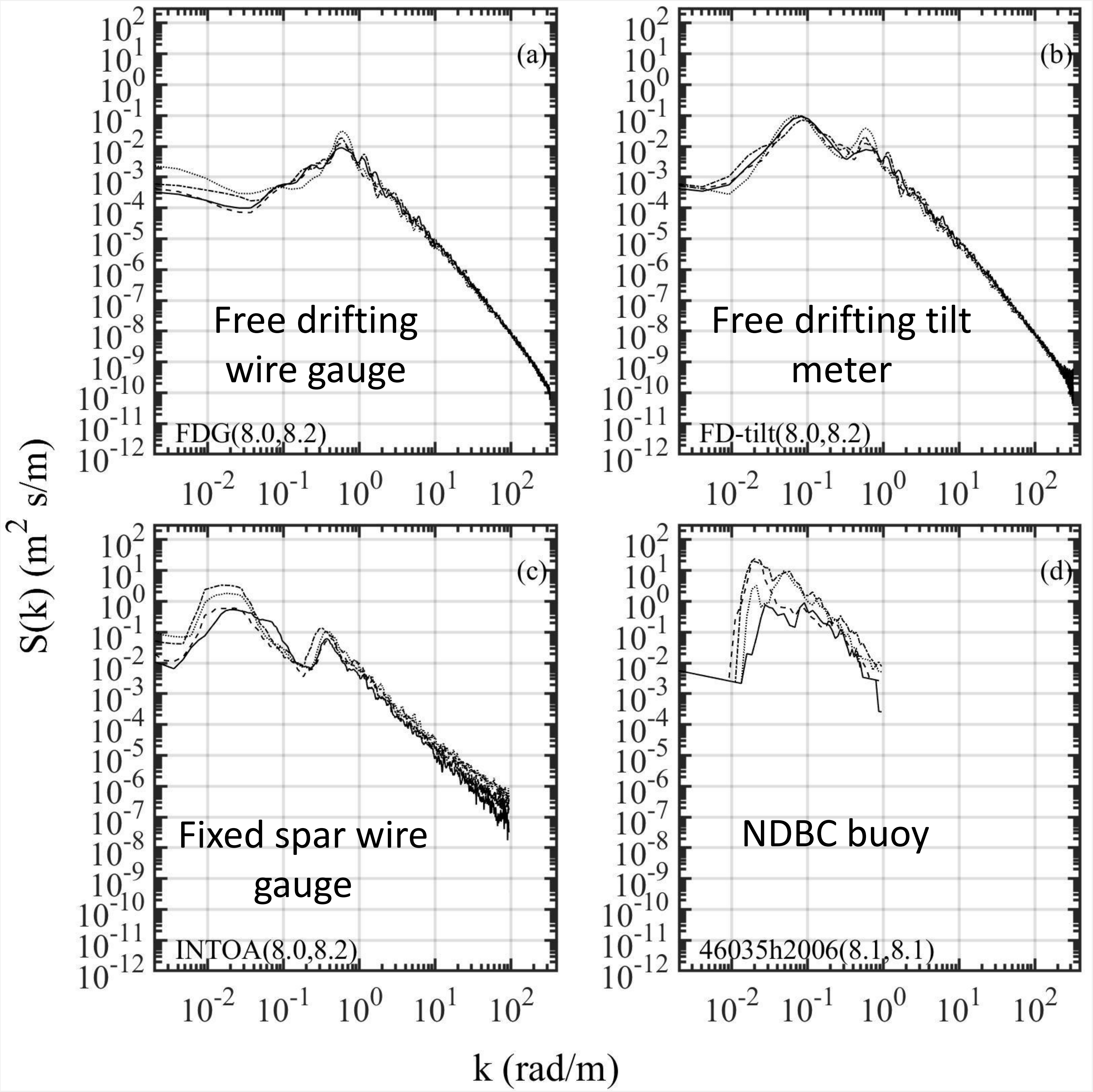
Passive wave following to alleviate large wave issue;
Scanning to alleviate Doppler frequency shift



2D scanning; Wire gauge arrays (~2000)
Hwang and Wang 2004



Measuring cmDm waves in ocean



$$\omega = \omega_0 + \vec{U} \bullet \vec{k}$$

Doppler shift solution: Make $U \rightarrow 0$ (free drifting)

Excellent low-noise wave spectra of free-drifting data [4 randomly selected spectra (min, max)U_{10}]

Parametric function for cmDm wave spectrum

$$B\left(\frac{u_*}{c};k\right)=A(k)\left(\frac{u_*}{c}\right)^{a(k)} \Leftrightarrow B(k,U_{10})$$

$$\omega^2=gk+\tau k^3; \qquad c^2=g/k+\tau k$$

$$B(k)=k^3S(k)=kS_1(k)$$

$B(k)$: 1D dimensionless spectrum

$S(k)$: 1D elevation spectrum

$S_1(k)$: 1D slope spectrum

a represents wind sensitivity and spectral slope

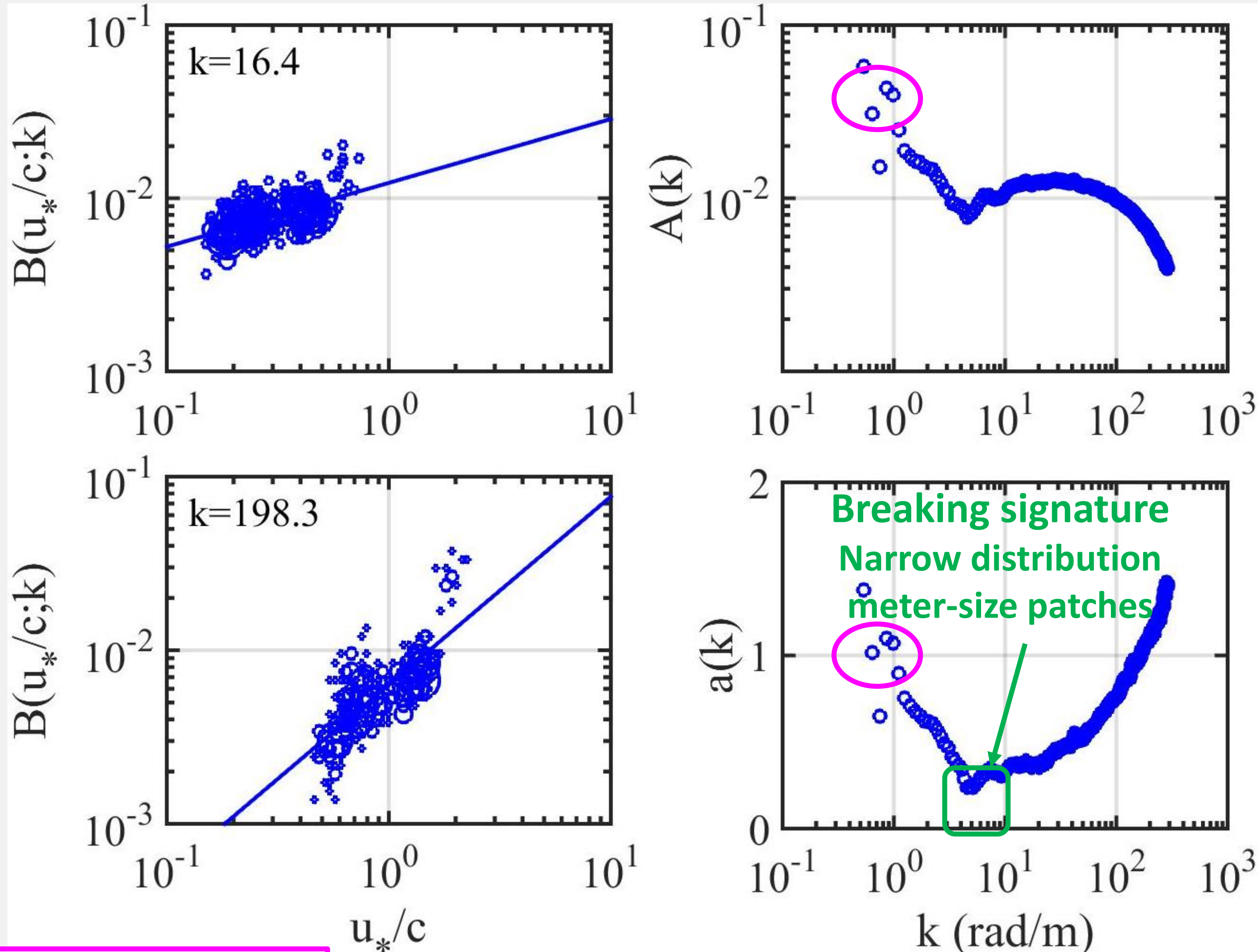
$s_k=3-a/2$ (gravity waves)

$$\left(\frac{u_*}{c}\right)^{a(k)} \sim \quad u_*^{a(k)}\ k^{a/2}$$

$$S_e(k)=bu_*g^{-0.5}k^{-2.5}=b\frac{u_*}{c}k^{-3}; equli.\ spec.$$

Phillips (1985)

$$B_e(k)=b\left(\frac{u_*}{c}\right)=bu_*k^{0.5}/g^{0.5}, \quad b=5.2\times10^{-2}$$



Narrow breaking size distribution in meter scales in observations of radar sea spikes

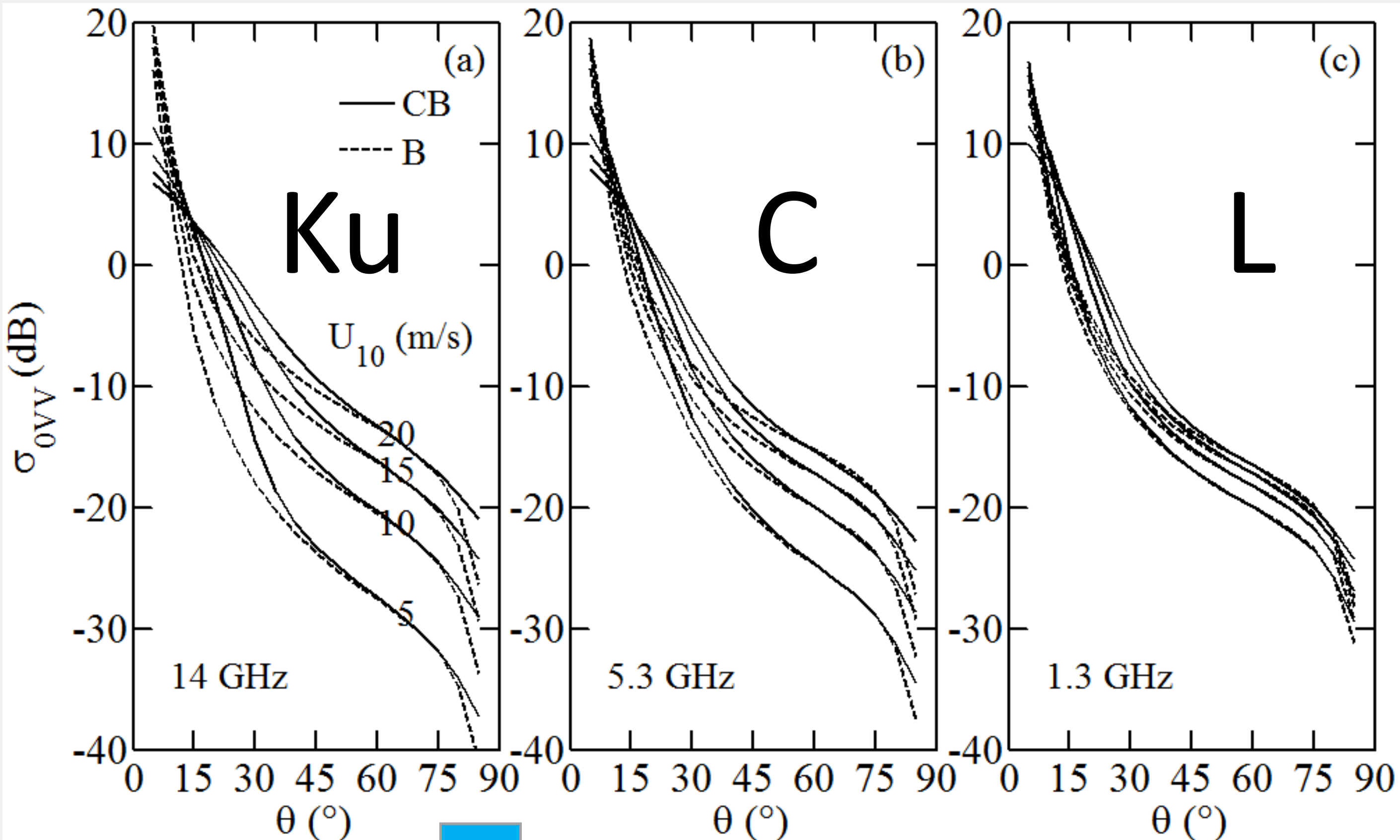
Frazier et al. (1998); Liu et al. (1998); Hwang (2007); Hwang et al. (2008a,b)

- Similarity relation of cmDm waves: $B(k)$ ~ power function of (u_*/c)
- Each cmDm wave component is represented by two numbers: $A(k)$ and $a(k)$

Hwang and Wang (2004); Hwang (2005+)

U.S.NAVAL RESEARCH LABORATORY

Radar Scattering and cmDm Waves



$$\sigma_{0VV}(\theta,\phi_B)=\frac{\pi}{\tan^4\theta}\left|g_{VV}(\theta)\right|^2 B(k_B,\phi_B)$$

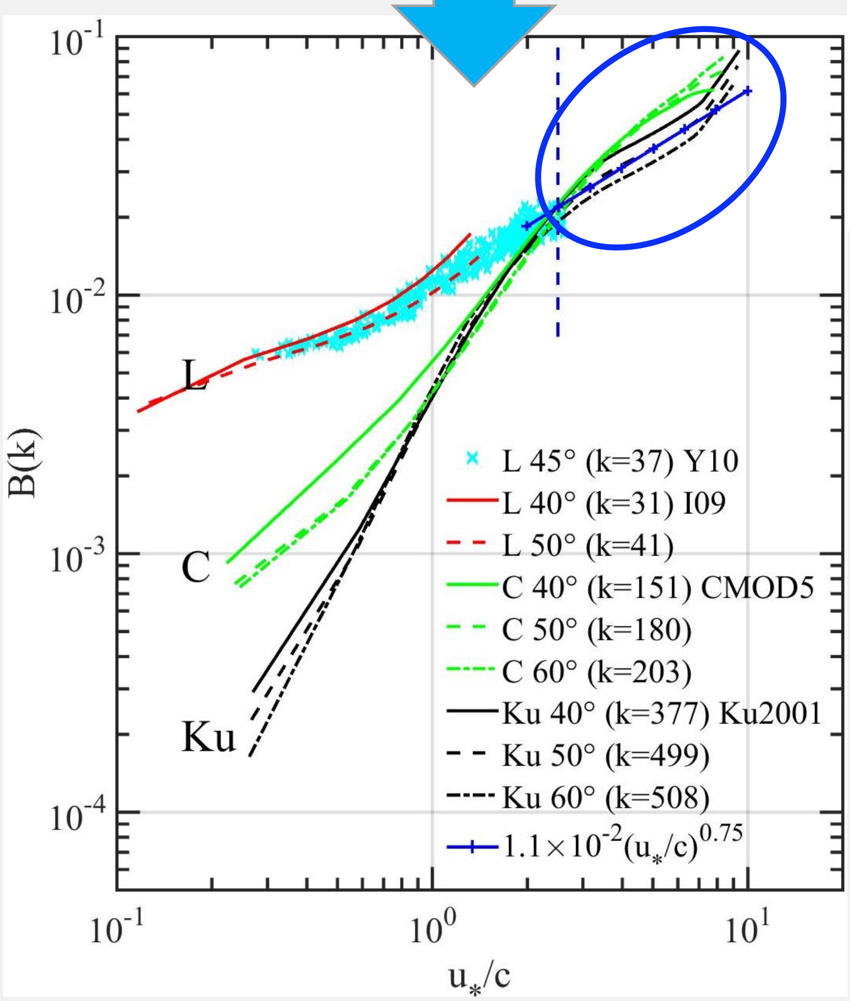
Crombie (1955); Wright (1968); Valenzuela (1978)

$$\theta\in[50\pm10^\circ]\ approx.;\qquad k_B=k_r 2\sin\theta$$

VV NRCS is dominated by Bragg resonance scattering:

Radar is a surface roughness spectrometer

$$B\left(\frac{u_*}{c};k\right)=A(k)\left(\frac{u_*}{c}\right)^{a(k)}$$



Similarity function changes in ~TC wind condition

High wind coverage

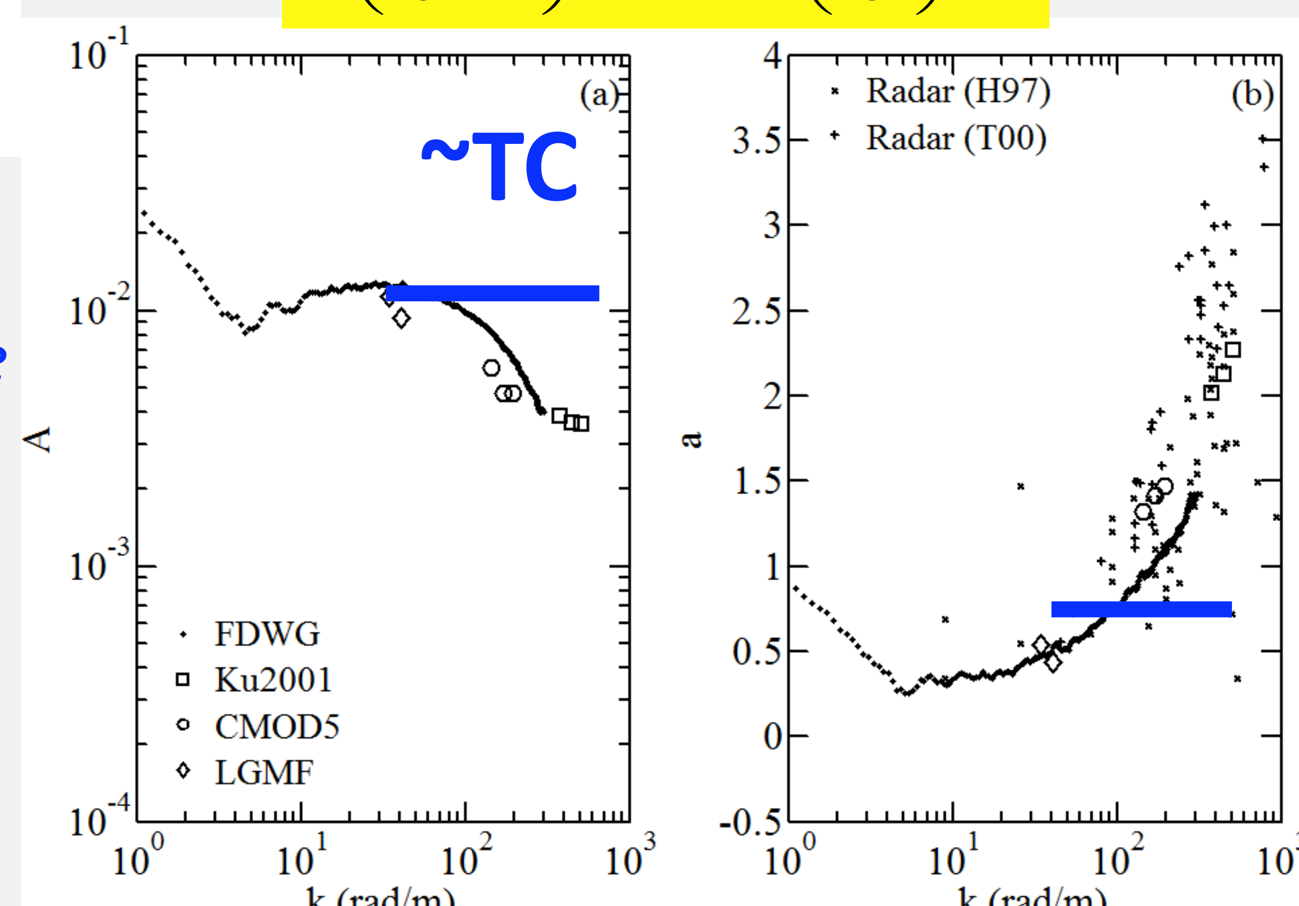
L: → 28 m/s

C: → 60 m/s

Ku: → 70 m/s

(L to Ku band *c* ~0.3 to 0.5 m/s)

Hwang et al. (2013)



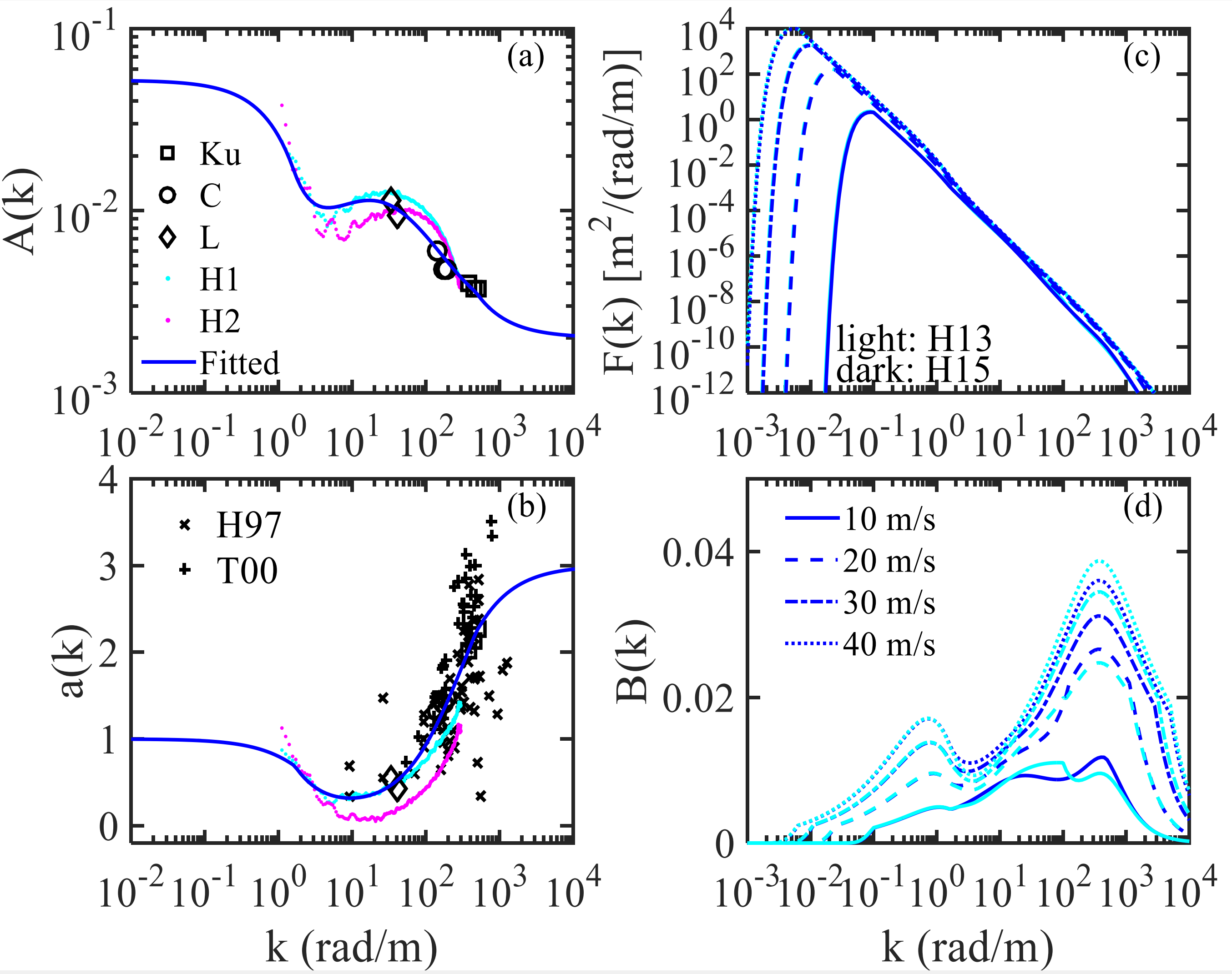
Microwave Radars and Wave Spectrum

(2013, 2015)

VV NRCS Bragg scattering:
Radar is a surface roughness spectrometer

$$\sigma_{0VV}(\theta,\phi_B) = \frac{\pi}{\tan^4\theta}\left|g_{VV}(\theta)\right|^2 B(k_B,\phi_B)$$

$\theta \in [50 \pm 10^\circ]$ *approx.* $k_B = k_r 2\sin\theta$



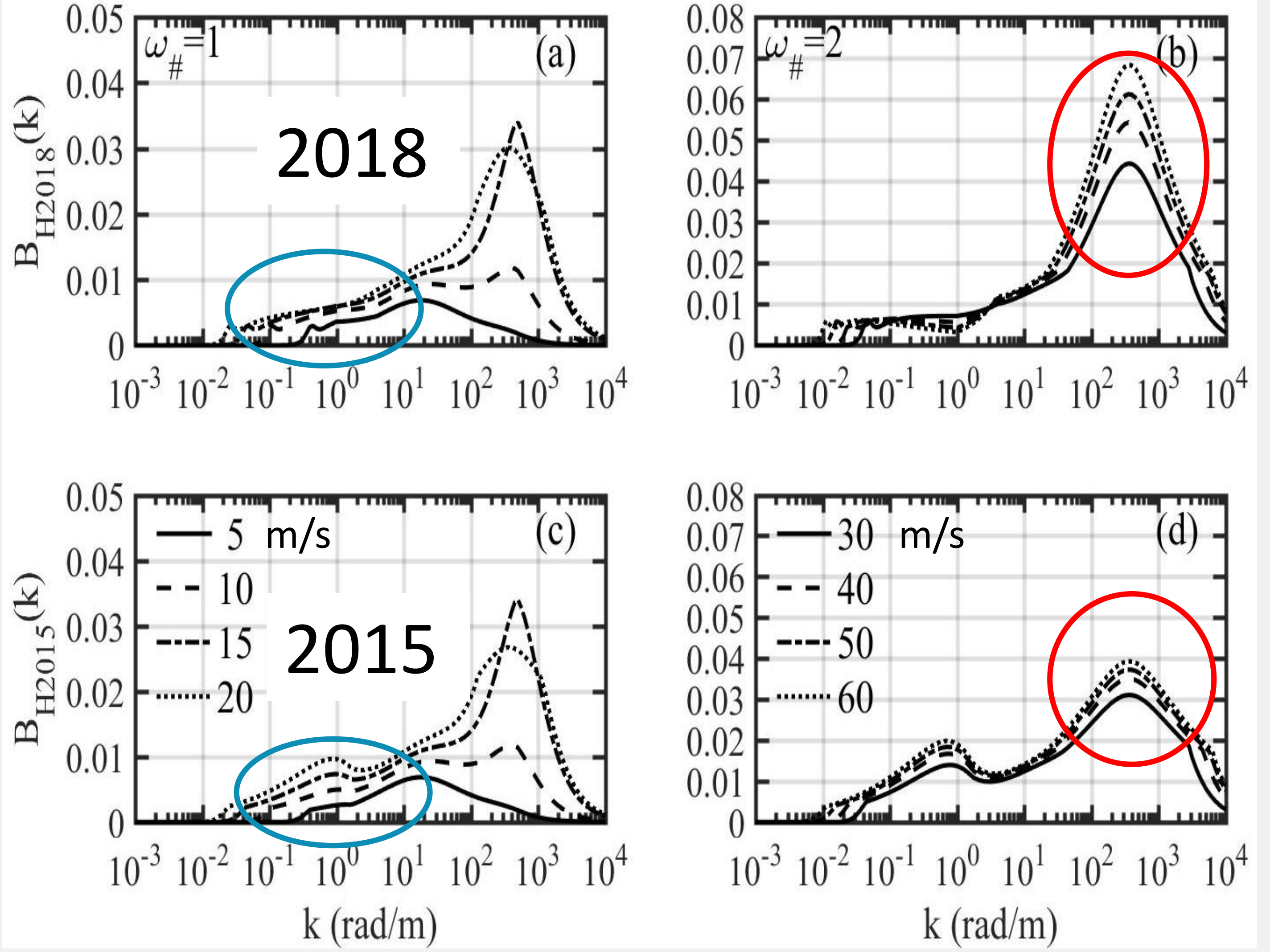
(2018)

(1) GNSSR* LPMSS** and longer cmDm waves

* Global Navigation Satellite System Reflectometry

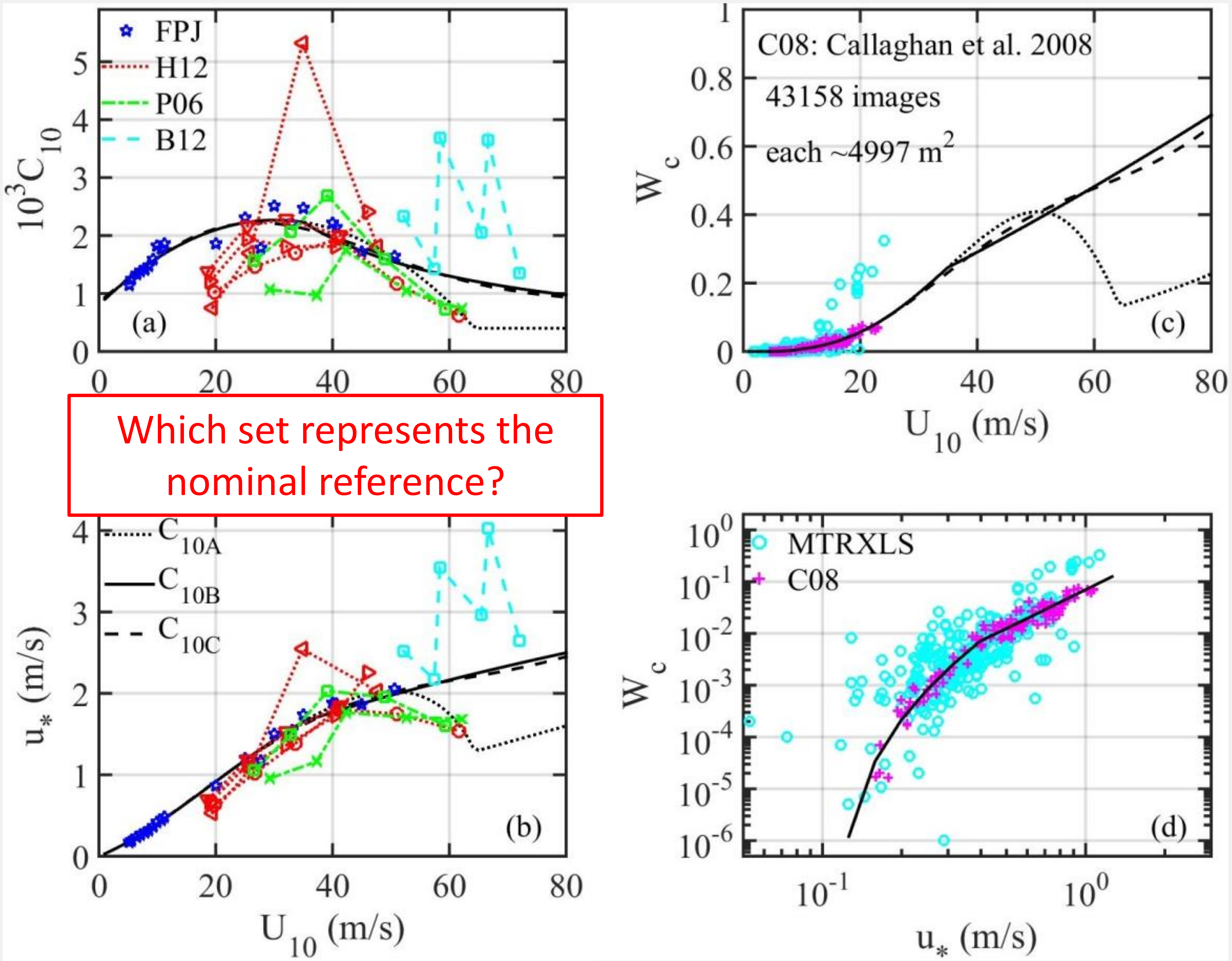
** Lowpass-filtered mean square slope

(2) Revised drag coefficient formula: (u_*/c)
[microwave emission monotonic dependence on wind speed = surface wind stress monotonic dependence on wind speed]



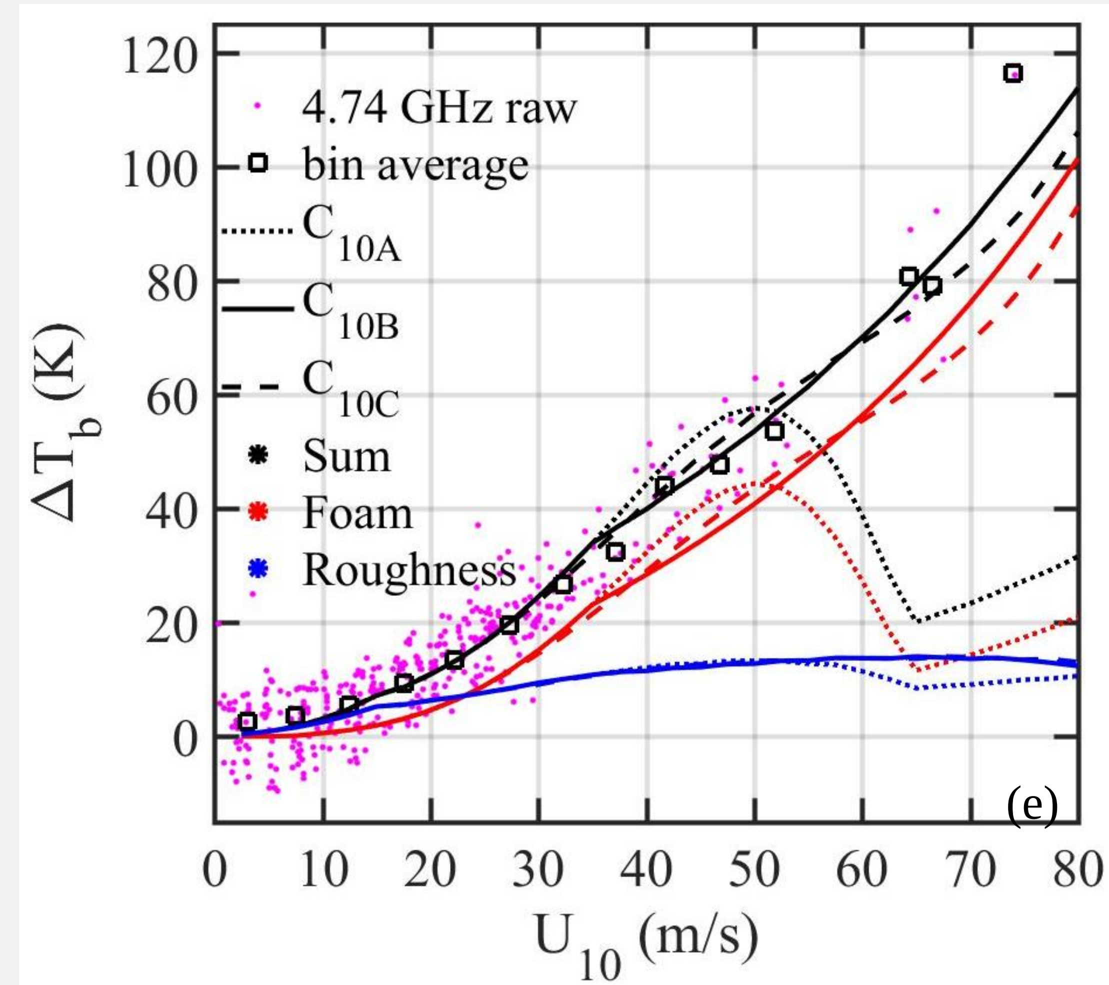
U.S.NAVAL RESEARCH LABORATORY

Revising Drag Coefficient Formula



Which set represents the nominal reference?

SFMR (stepped frequency microwave radiometer) brightness temperature: Hurricane Hunter measurements



FPJ: low to TC winds; P06, H12: more TC dropsonde

B12: angular momentum conservation computation

Felizardo et al 1998; Powell et al. 2003; Jarosz et al. 2007; Powell 2006; Holthuijsen et al. 2012; Bell et al. 2012

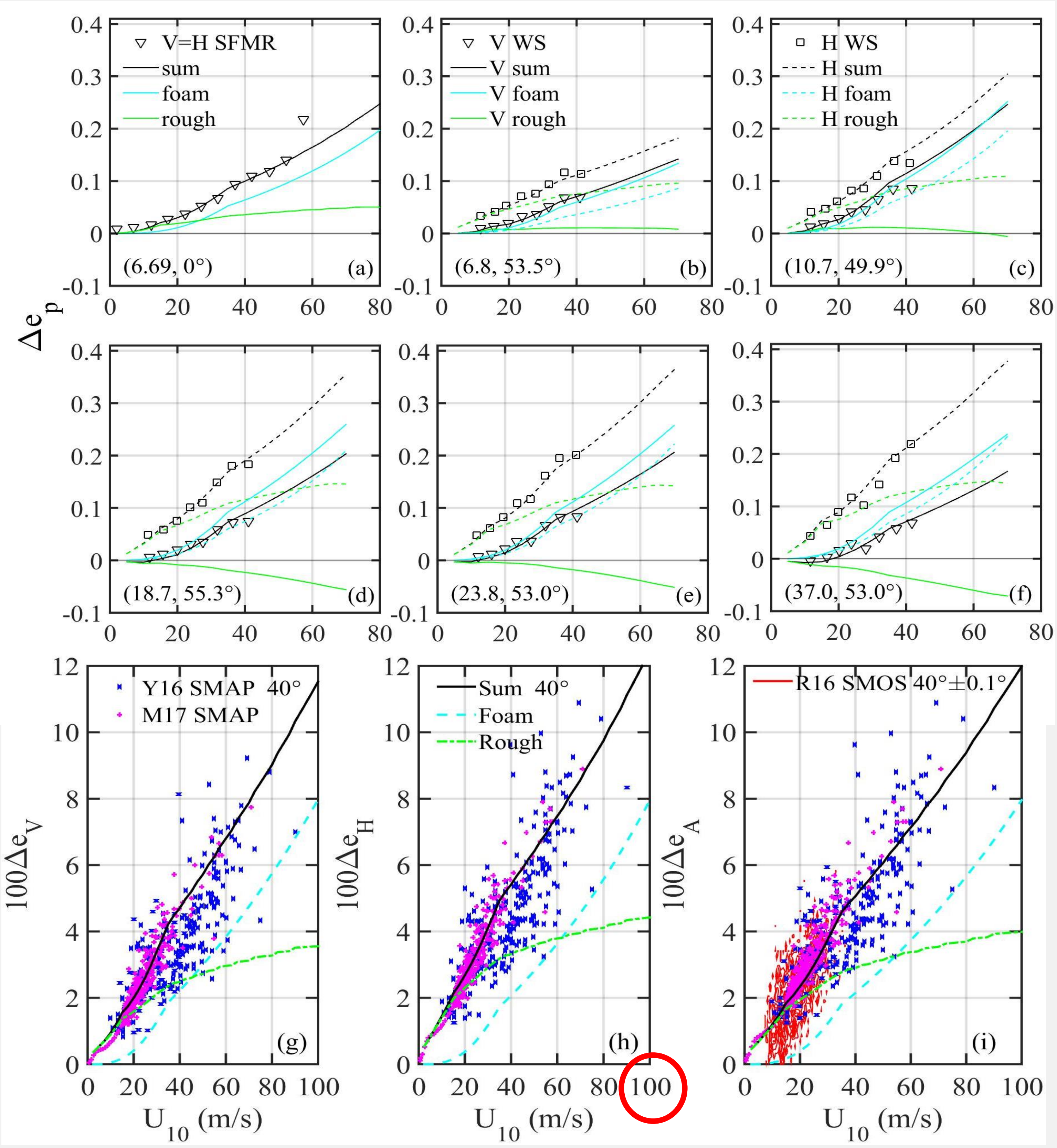
- ΔT_b depends on roughness and whitecaps
- Roughness and whitecaps depend on surface wind stress
- ΔT_b is a good data source for examining C_{10}

$$C_{10} = \begin{cases} 10^{-4}\left(-0.0160U_{10}^2 + 0.967U_{10} + 8.058\right) \\ U_{10} \le 35\text{m/s} \\ \boxed{\begin{matrix} 2.23\times10^{-3}\left(U_{10}/35\right)^{-1} \\ U_{10} > 35\text{m/s} \end{matrix}} \end{cases}$$

Hwang 2018, 2019; Hwang et al. 2019a,b

microwave emission monotonic dependence on wind speed = surface wind stress monotonic dependence on wind speed

Revising the Drag Coefficient with Microwave Radiometer Data



Hwang et al. 2019

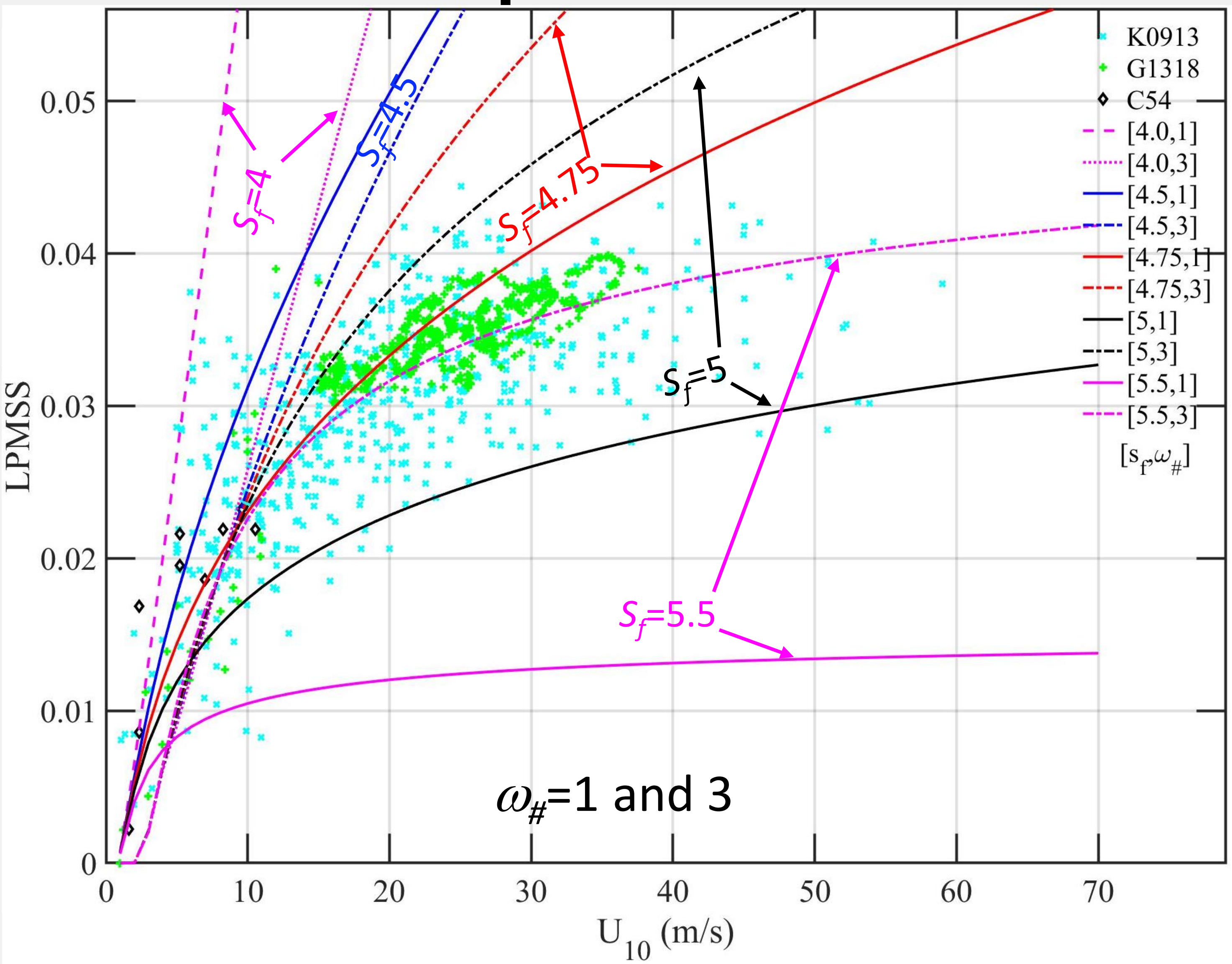
Calculated Δe_V and Δe_H at various microwave frequencies, and comparison with field data.

Top two rows: SFMR and WindSat (4.7 to 37 GHz)
Bottom row (L band 1.41 GHz): SMAP and SMOS

Sum, foam and roughness contributions are given by black, cyan and green curves, solid and dashed lines show vertical and horizontal polarizations, respectively. Numbers in parentheses are frequency (in GHz) and EIA.

U.S.NAVAL RESEARCH LABORATORY

Lowpass-filtered Mean Square Slopes



A general spectrum accepting variable spectral slopes

$$\left(\nabla\eta\right)^2_{LP} = \int_0^{k_{LP}} k^2 S(k)dk$$

$$S(\omega) = \alpha_G g^2 \omega_p^{-5} \varsigma^{-s_f} \exp\left[-\left(\frac{\varsigma}{K}\right)^{-\beta_G}\right]\gamma_G^{\Gamma_G}$$

$$\varsigma = \frac{\omega}{\omega_p}; \Gamma_G = \exp\left[-\frac{(1-\varsigma)^2}{2\sigma_G^2}\right]; K = \left(s_f / \beta_G\right)^{1/\beta_G}$$

$\alpha_G, \gamma_G, \sigma_G$ *functions of* $\omega_\#$ *and* s_f; $\omega_\# = \frac{\omega_p U_{10}}{g}$

Pierson and Moskowitz 1964; Hasselmann et al. 1973, 1976; Donelan et al. 1985; Young 1998; Hwang et al. 2017; Hwang and Fan 2018

(Sun glitter analysis, wavelength λ > 0.3 m)

C54: Cox and Munk 1954

(GPS reflectometry, λ > 0.6 m)

K0913: Katzberg and Dunion 2009; Katzberg et al. 2013

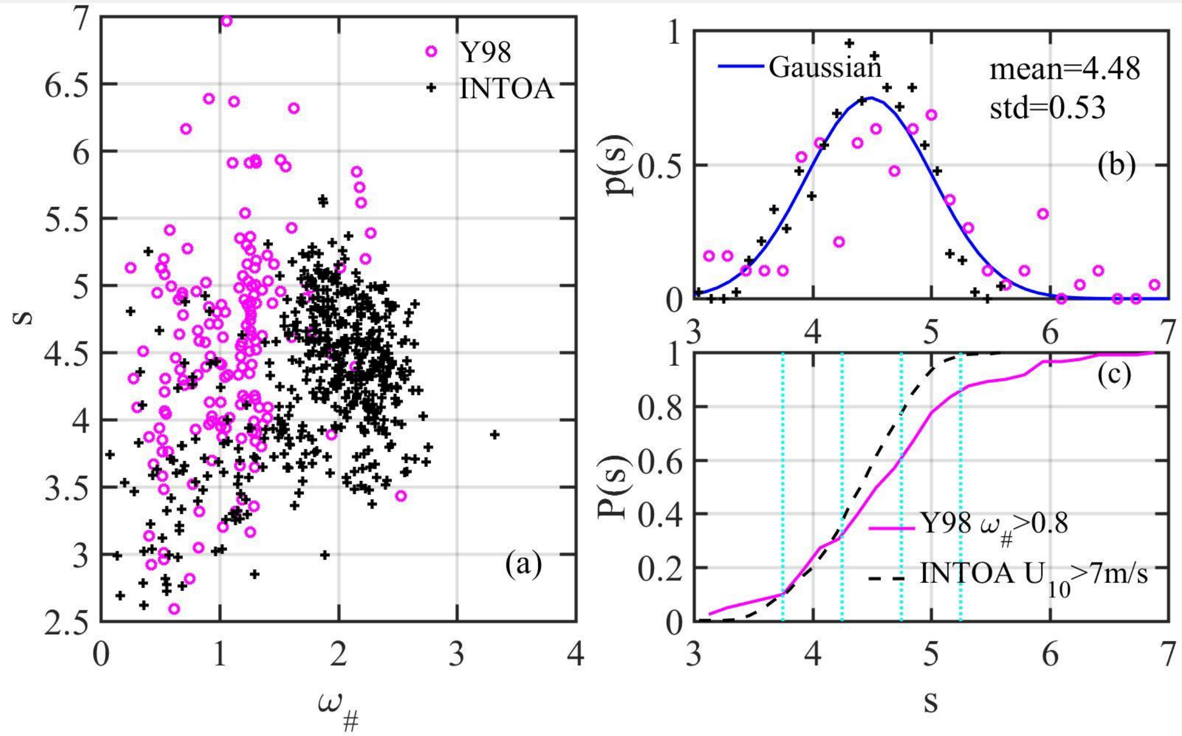
G1318: Gleason 2013; Gleason et al. 2018

U_{10}, $\omega_\#$, and s_f to compute spectrum and LPMSS

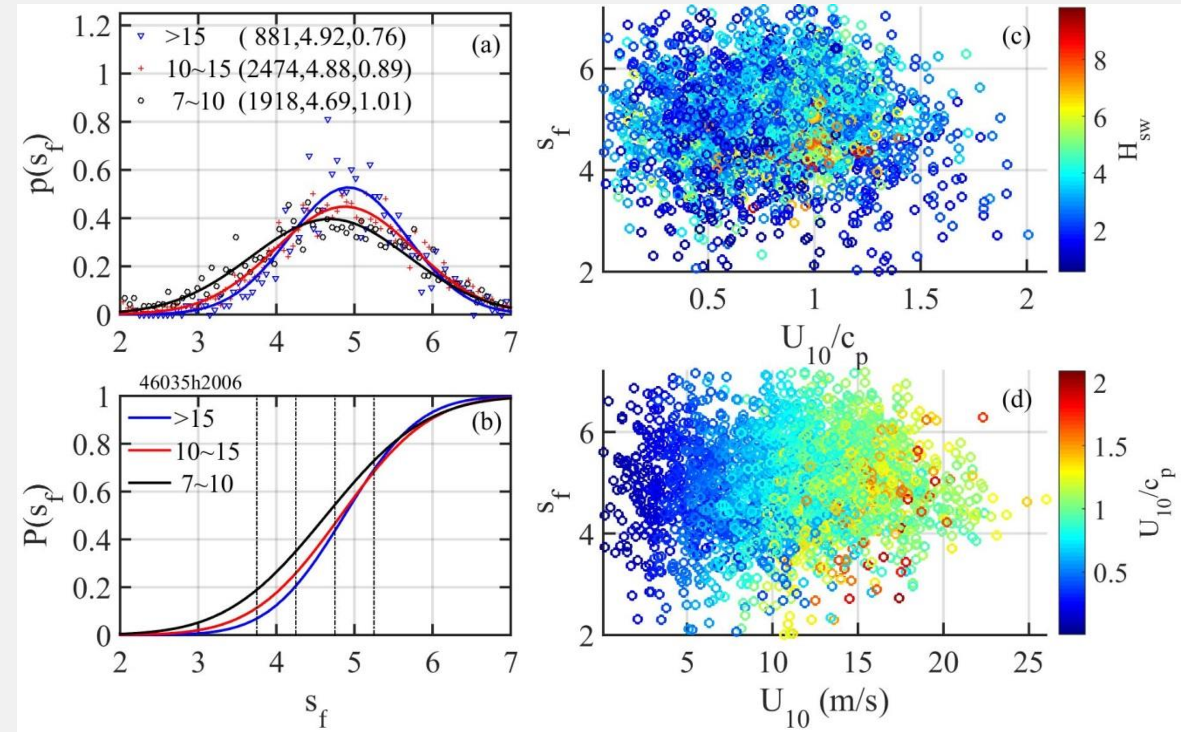
The magnitude of the integrated LPMSS(U_{10}) is critically dependent on the spectra slope s_f and wave age $1/\omega_\#$

U.S. NAVAL RESEARCH LABORATORY

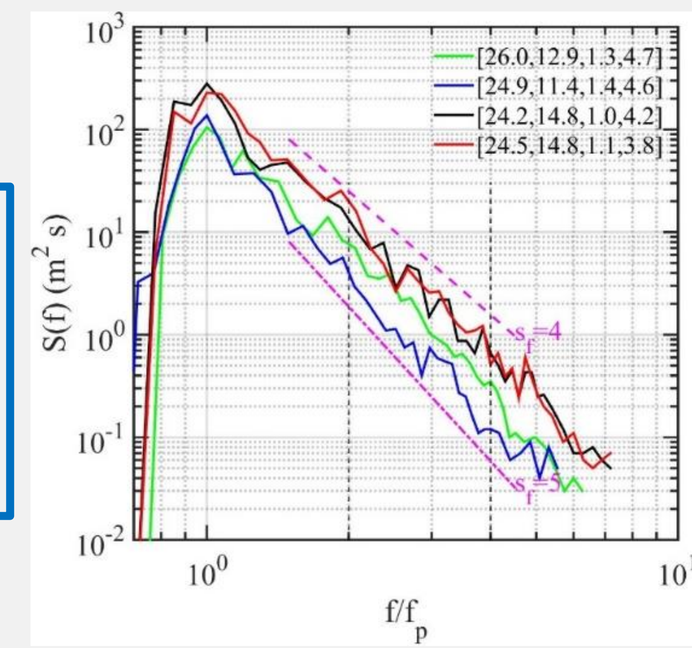
Spectral Slope Observations



Young (1998): Tropical cyclones (buoys)
INTOA (2005): Gulf of Tehuantepec mountain gap wind events (wires 10 Hz sampling) García-Nava et al. (2009); Ocampo-Torres et al. (2011); Hwang et al. (2017)



NDBC buoy 46035 in central Bering Sea (2006)



-4 or -5 or -4 transitioning to -5 spectral slopes is not majority of observations

Slope modified by Doppler frequency shift?

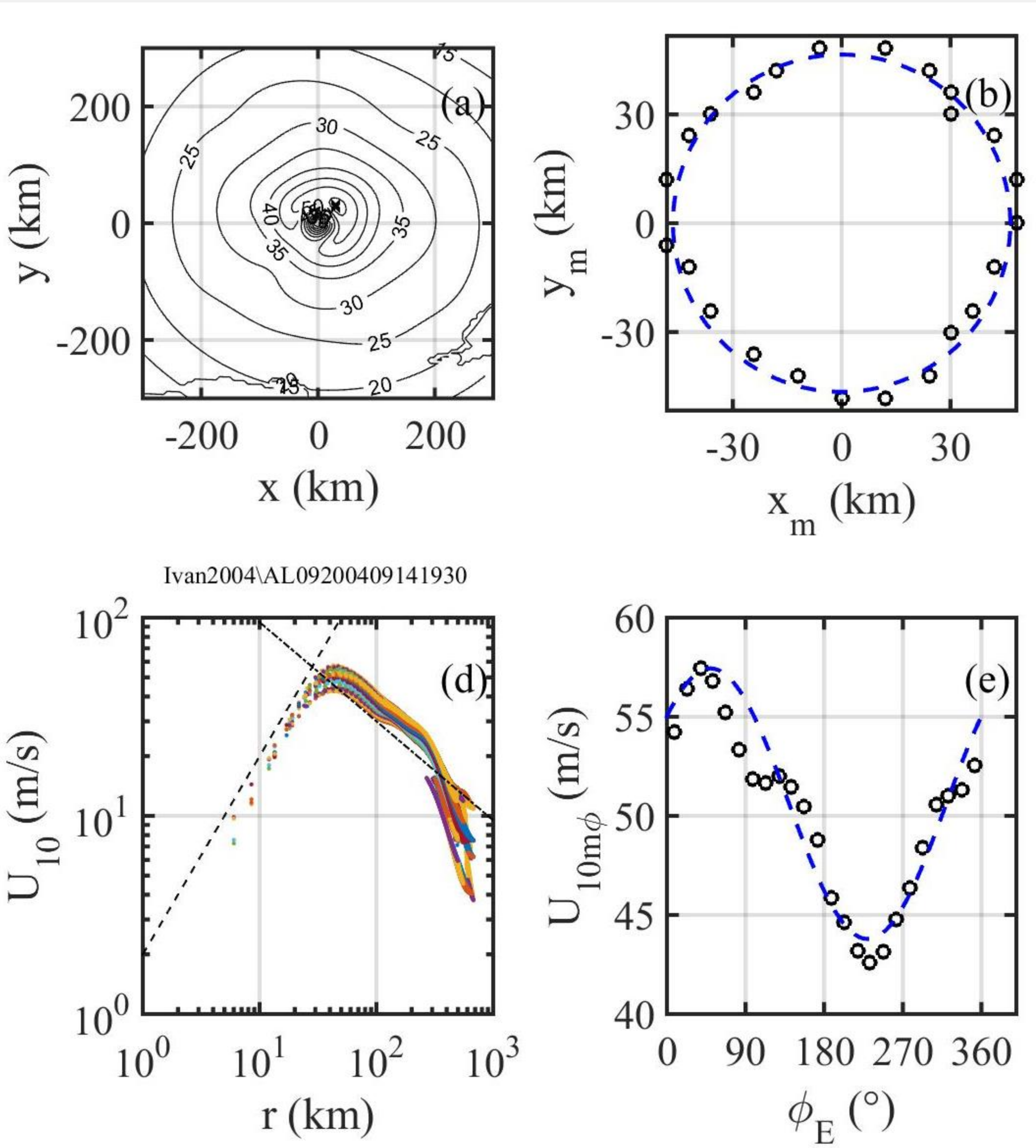
No, waves (2~4)ω_p do not get pushed around easily (Hwang et al. 2017)

Direct 2D wavenumber spectra?

… airborne 3D surface topography (scanning lidar) also show variable spectral slopes [s_k: 2.17±0.09 ~ 2.40±0.04] (Hwang et al. 2000)

Similarity Relationship of Hurricane Wind and Wave Fields

(Tropical cyclones as calibration targets)



U_{10}, $\omega_{\#}$, and s_f to compute spectrum and LPMSS

HWIND analysis for developing the parametric model of hurricane wind fields: (a) the contour map of U_{10}, (b) the coordinates of the maximum wind locations (x_m, y_m) at various azimuth angles, ..., **(d) the radial variation of wind speed**, the slopes of the superimposed power-law line segments are 1 and -0.5, **(e) the azimuthal variation of $U_{10m\phi}$** and ...

Sinusoidal variation is the dominant feature of normalized wind field. Parameters: [U_{10m}, r_m, a_{1U}, ϕ_m]

$$\frac{U_{10}(r,\phi)}{U_{10m\phi}} = \begin{cases} r_*, & r_* \le 1 \\ r_*^{-0.5}, & 1 < r_* \end{cases} \qquad \frac{U_{10m\phi}}{U_{10m}} = 1 - a_{1U}\left[1 - \cos(\phi - \phi_m)\right]$$

Based on Holland (1980), Holland et al. (2010) modified Rankine vortex model, introducing asymmetry factor a_{1U} and ϕ_m

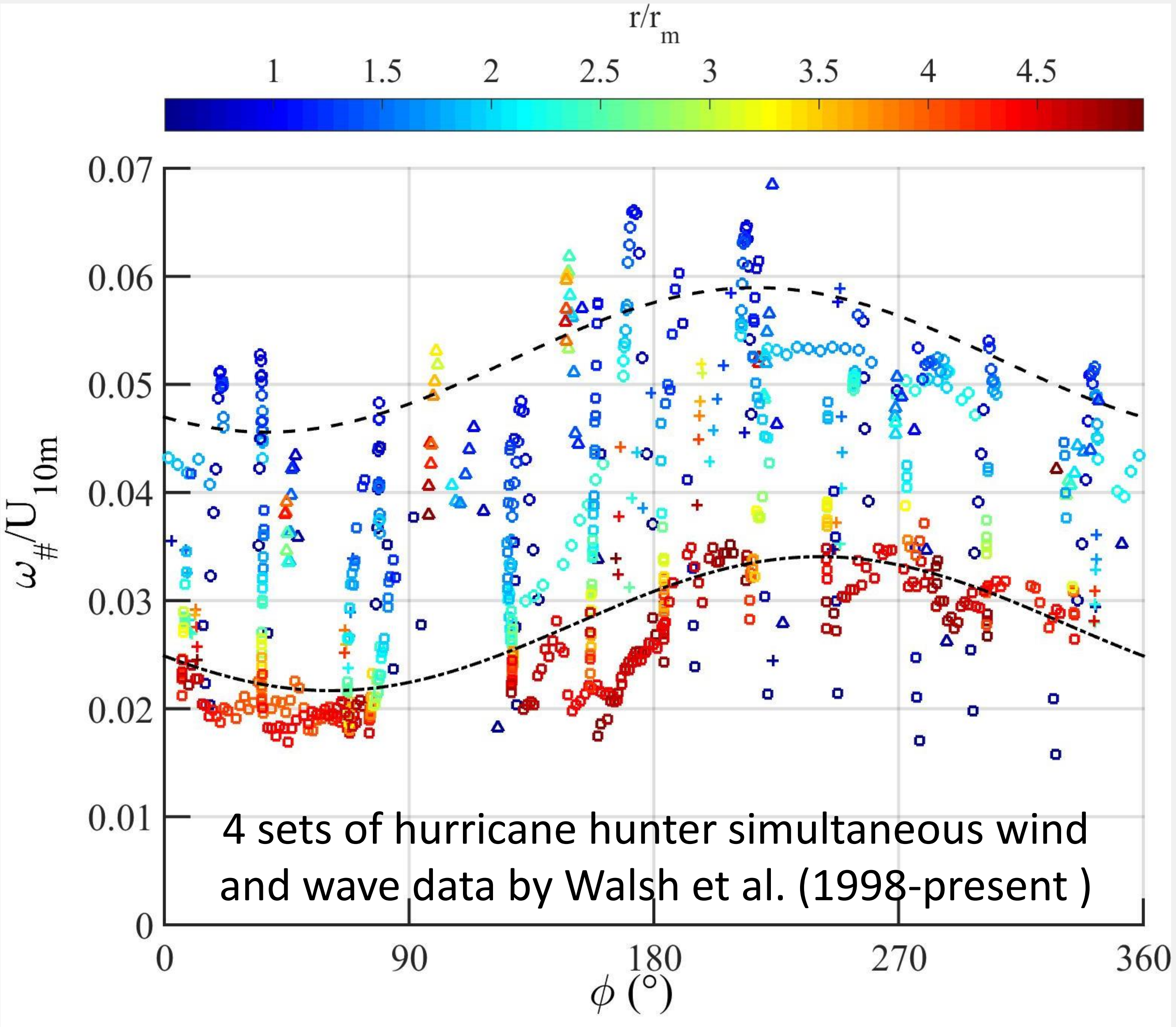
Hwang and Fan (2018)

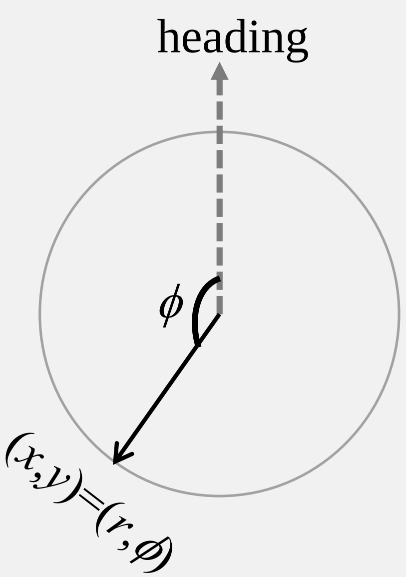
Similarity Relationship of Hurricane Wind and Wave Fields

Fetch- and Duration-Limited Nature

(Young 1988, 1996; Hwang et al. 2016+)

(Tropical cyclones as calibration targets)





U_{10}, $\omega_{\#}$, and s_f to compute spectrum and LPMSS

Azimuthal and radial variations of $\omega_{\#}$.
The normalization factors are U_{10m} and r_m for $\omega_{\#}$ and r, respectively.

Sinusoidal variation is the dominant feature of normalized wave age

$$\omega_* = a_0(r_*) + a_1(r_*)\cos\left[\phi + \delta(r_*)\right]$$

Hwang and Fan (2018)

U.S.NAVAL RESEARCH LABORATORY

Tropical cyclones as calibration targets

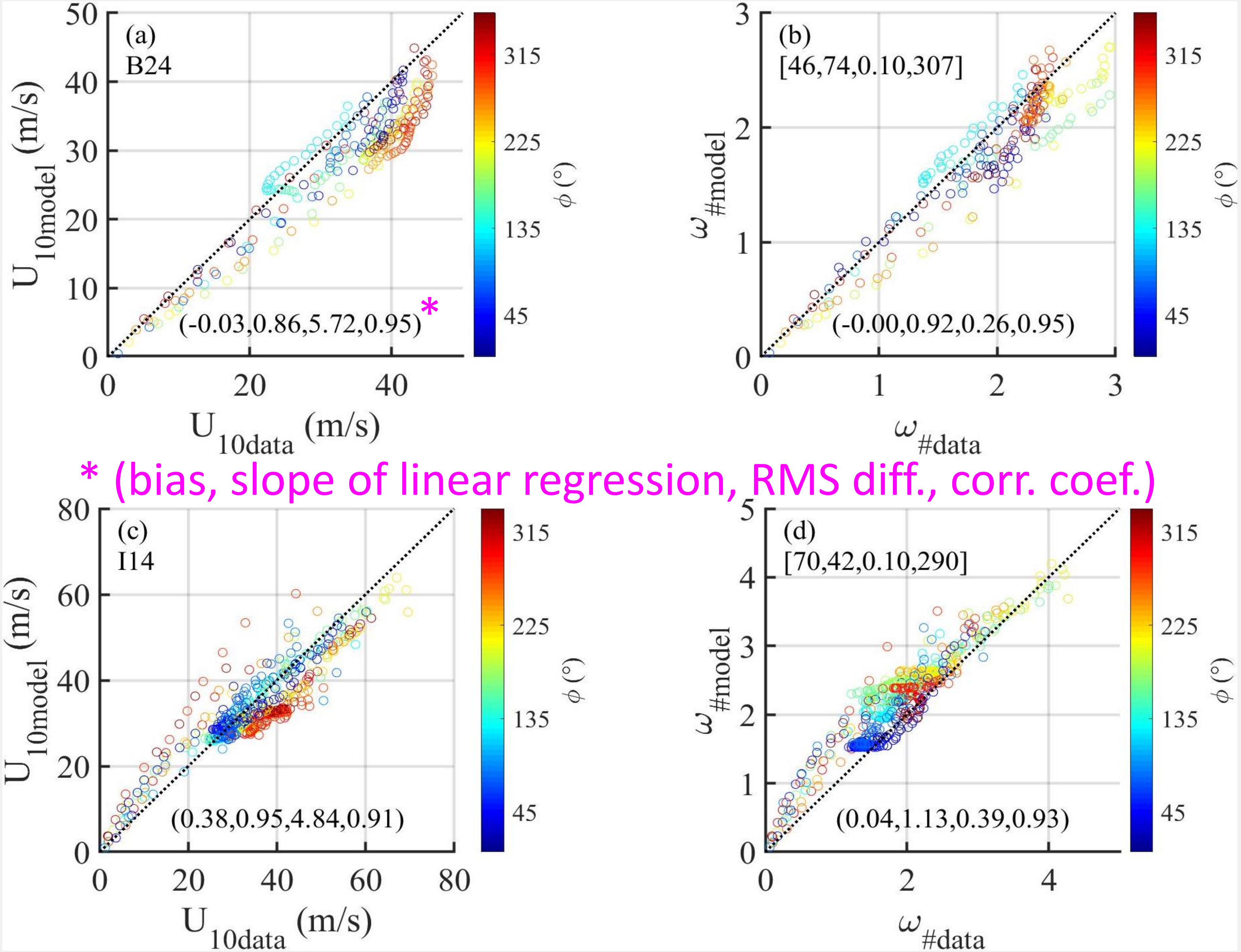
Wind and wave-age fields inside hurricanes

Bonnie 1998

Hurricane hunter reconnaissance and research missions

(Wright et al. 2001
Walsh et al. 2002
Fan et al. 2009
Hwang and Fan 2017)

Ivan 2004



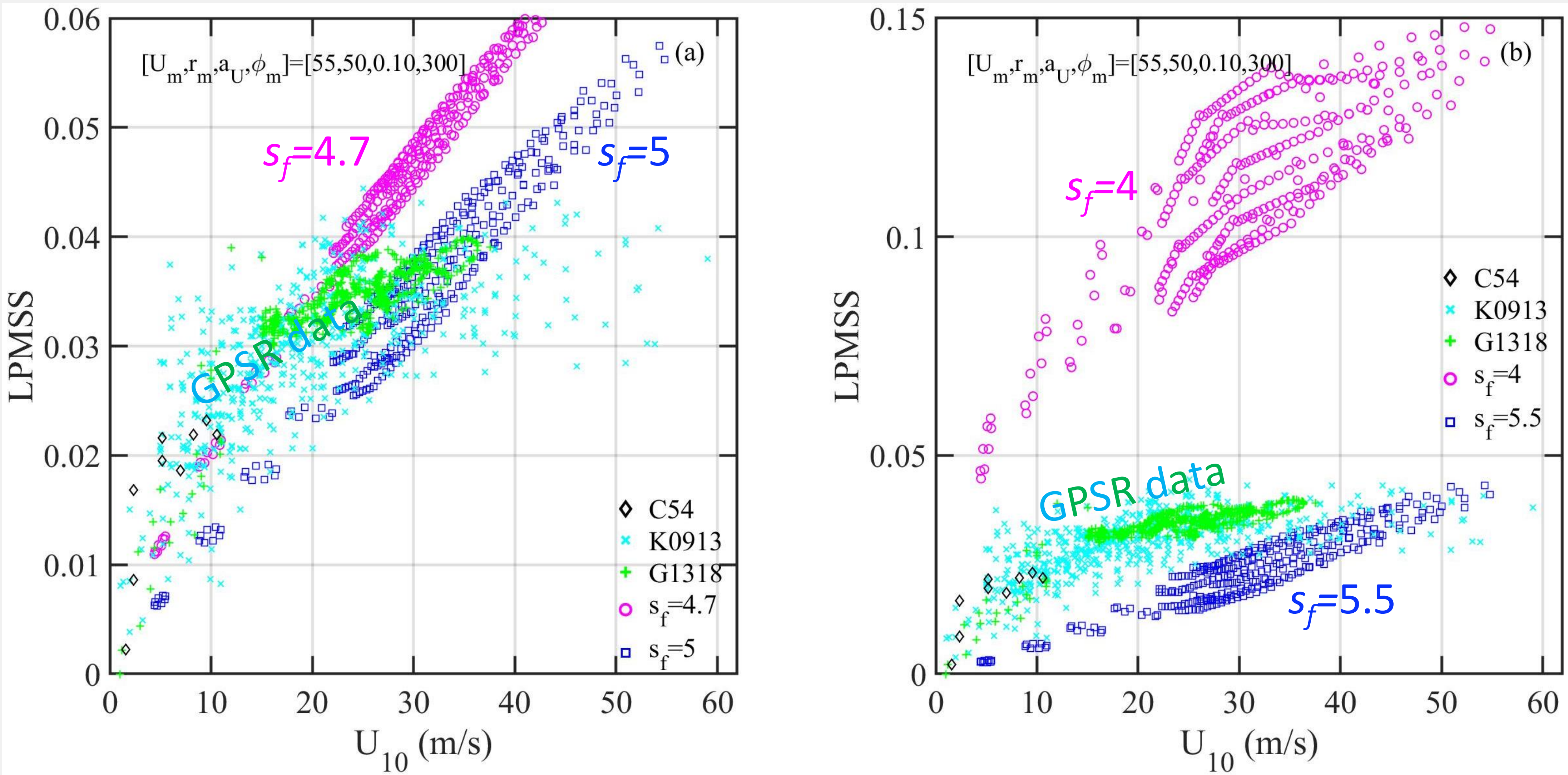
Knowing U_{10} and $\omega_{\#}$ the wave spectrum can be calculated at any position inside a hurricane given a small number of hurricane parameters: [U_{10m}, r_m, ϕ_m, a_{1U}]

LPMSS to Evaluate Long cmDm Waves

What is and what is not?

… constant spectral slope?

U_{10}, $\omega_{\#}$, and s_f to compute spectrum and LPMSS:
s_f is the remaining unknown



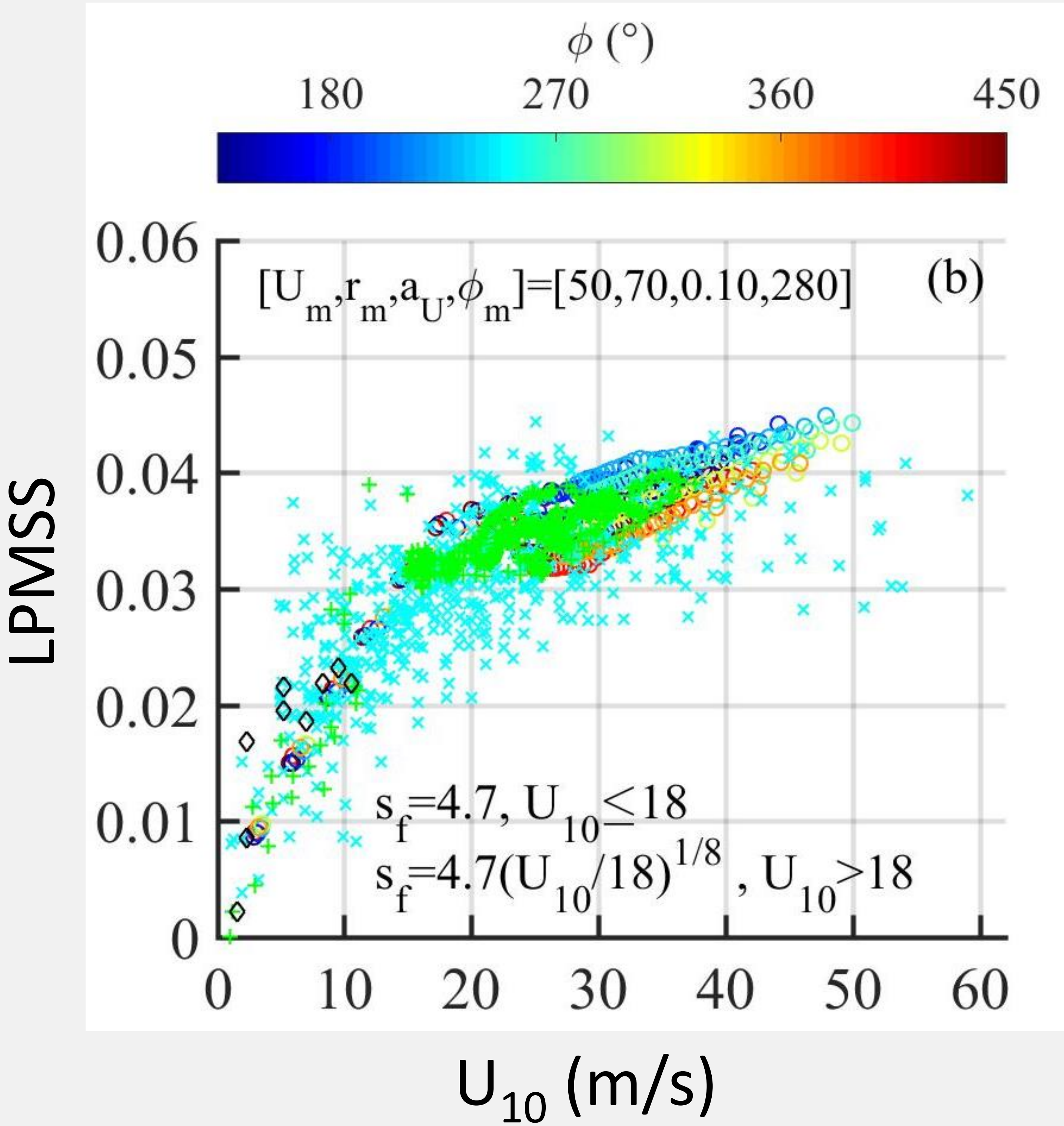
Magenta and blue: LPMSS integrated from spectrum (wavelengths longer than 0.6 m)

Cyan and green: GNSSR (wavelengths longer than 0.6 m)

Black: Sun glitter analysis (wavelengths longer than 0.3 m)

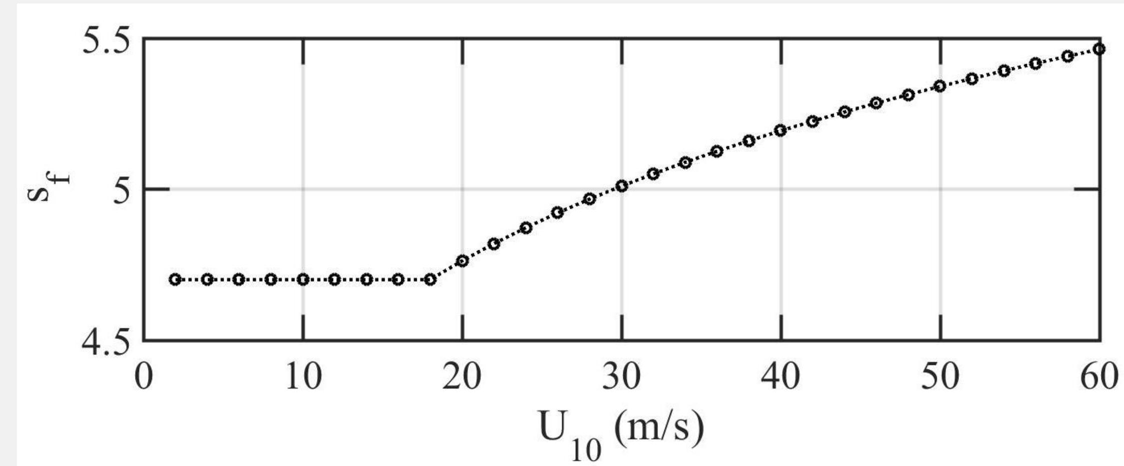
Spectral slope of long cmDm waves is NOT a constant, or a constant transitioning to another constant

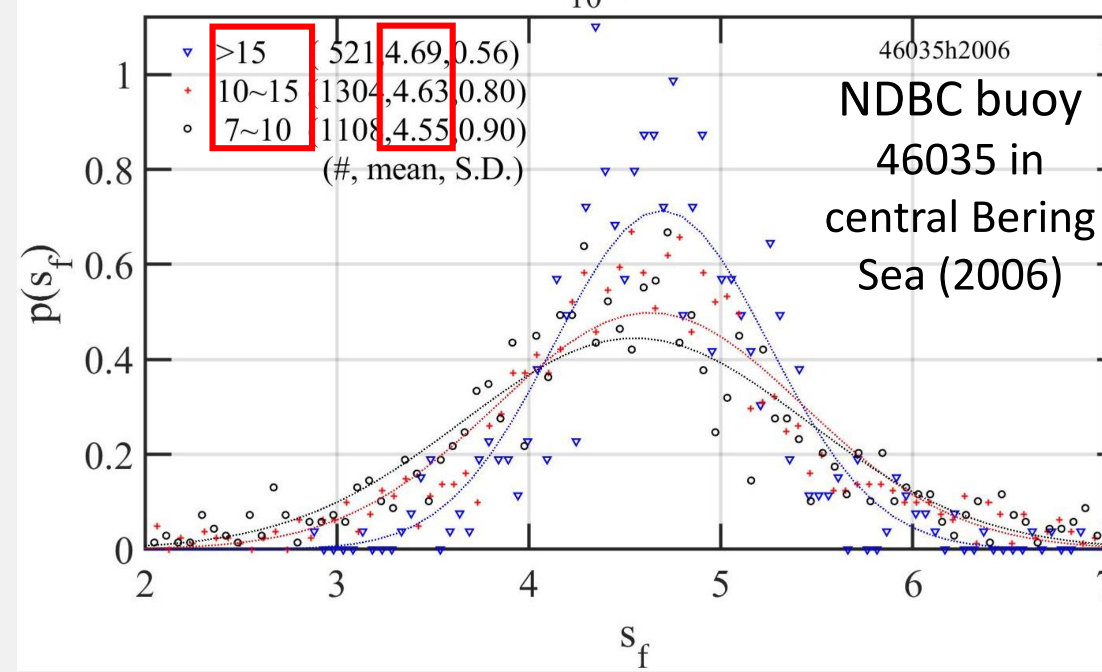
LPMSS to Evaluate Long cmDm Waves



What is and what is not?

U_{10}, $\omega_{\#}$, and s_f to compute spectrum and LPMSS:
s_f is the remaining unknown

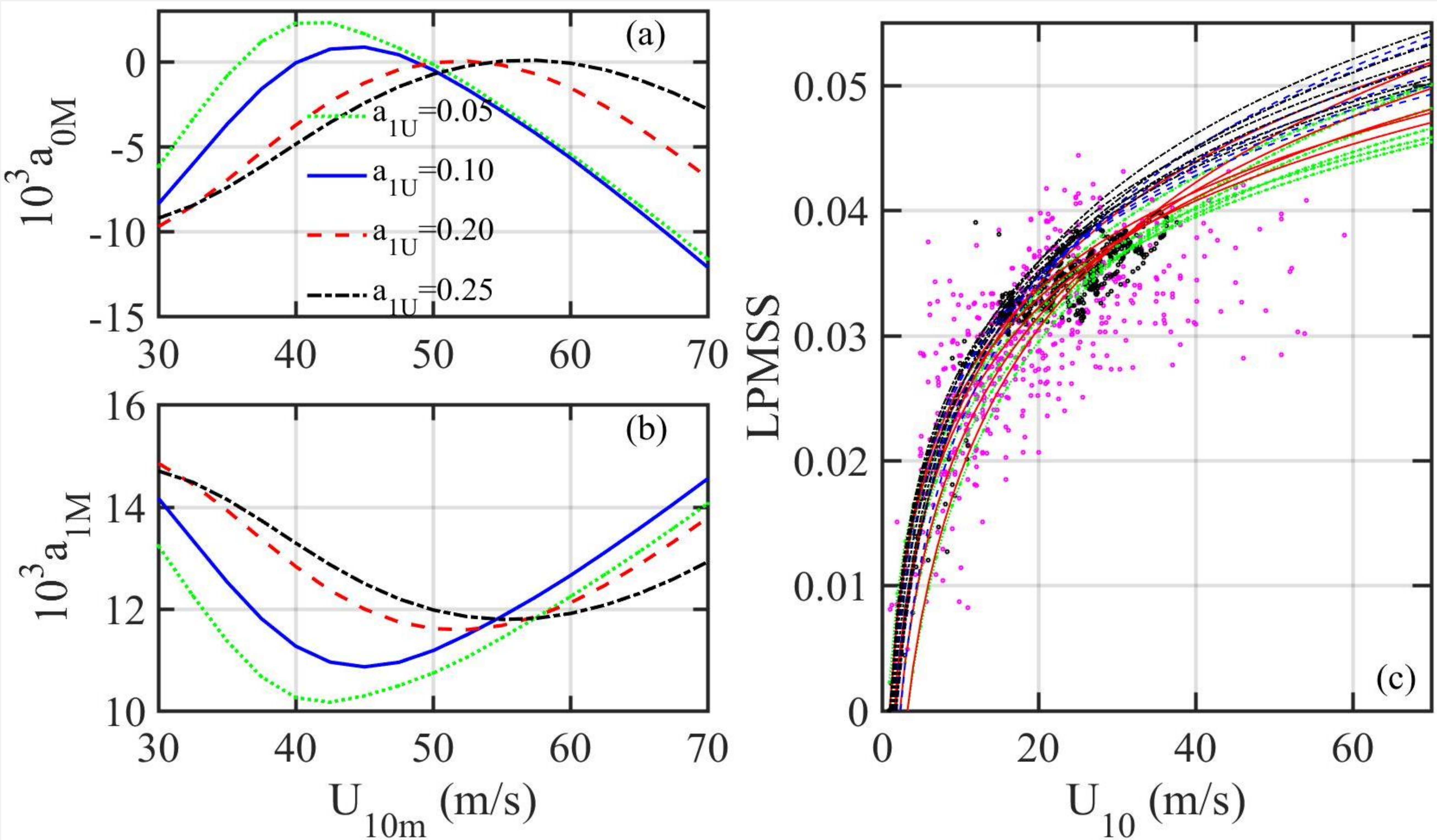




Computation with variable spectral slopes; wind speed is a good index of [*average*] spectral slope variation

Hwang and Fan 2018

Varying the TC parameters to generate U_{10} and $\omega_{\#}$ fields



$$LPMSS = a_{0M} + a_{1M} \ln\left(U_{10}\right)$$

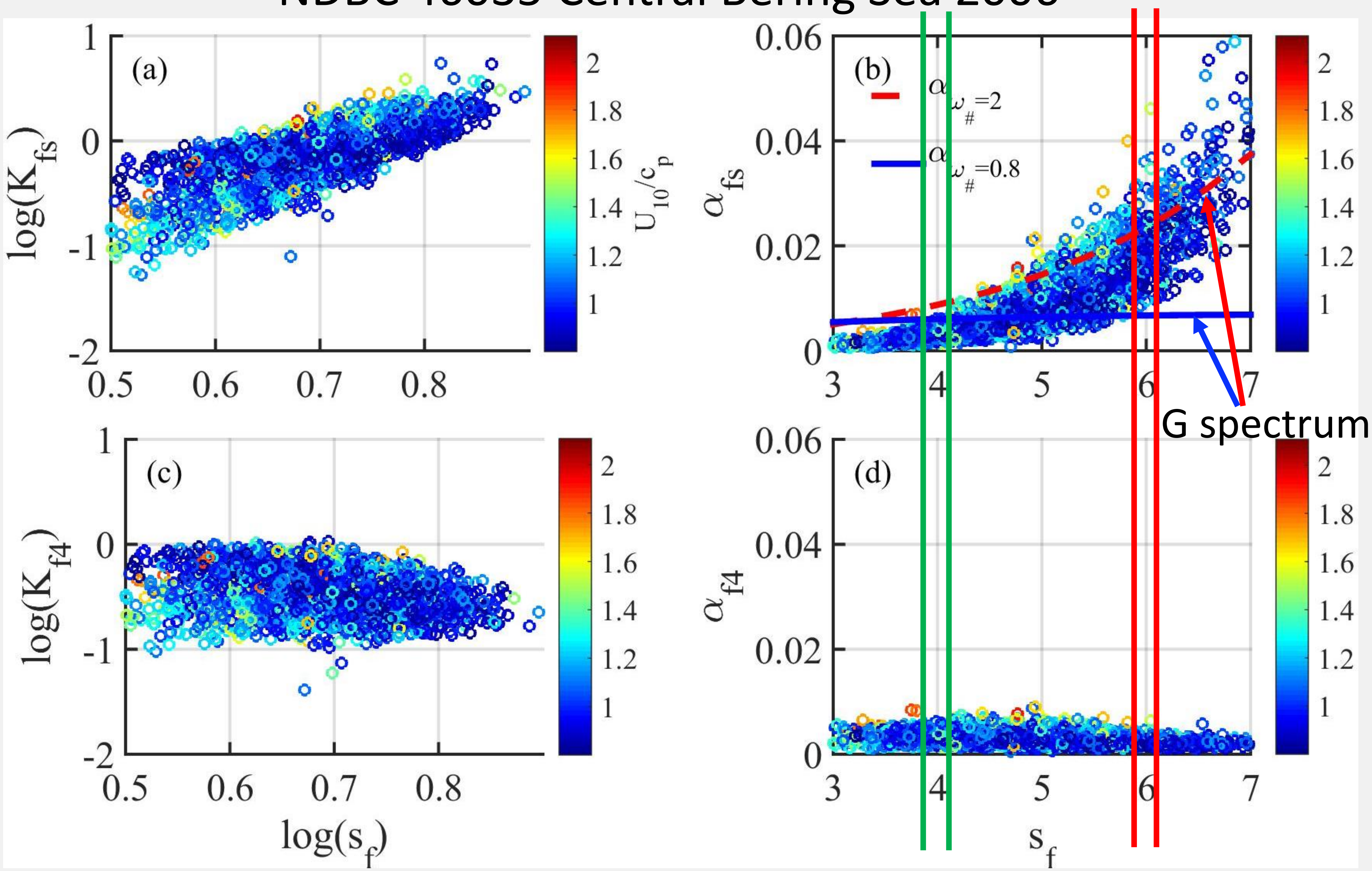
Spectral Slope and Spectral Coefficient

With observed spectral slope

$$S(\omega) = K_f \omega^{-s_f}$$

Assuming constant spectral slope: distorts spectral properties

NDBC 46035 Central Bering Sea 2006



$$S(\omega) = K_f \omega^{-s_f}$$

$$S(k) = K_k k^{-s_k}$$

$$S(\omega) = \alpha_f g^2 \omega_p^{s_f - 5} \omega^{-s_f}$$

$$S(k) = \alpha_k k_p^{s_k - 3} k^{-s_k}$$

$$S(\omega) = \left[\alpha_f g^{s_f - 3} \omega_\#^{s_f - 5}\right] U_{10}^X \omega^{-s_f} = K_f \omega^{-s_f}$$

$X = 5 - s_f$

Dependence on s_f becomes dependence (or lack of dependence) on U_{10}/c_p or u_*/c_p

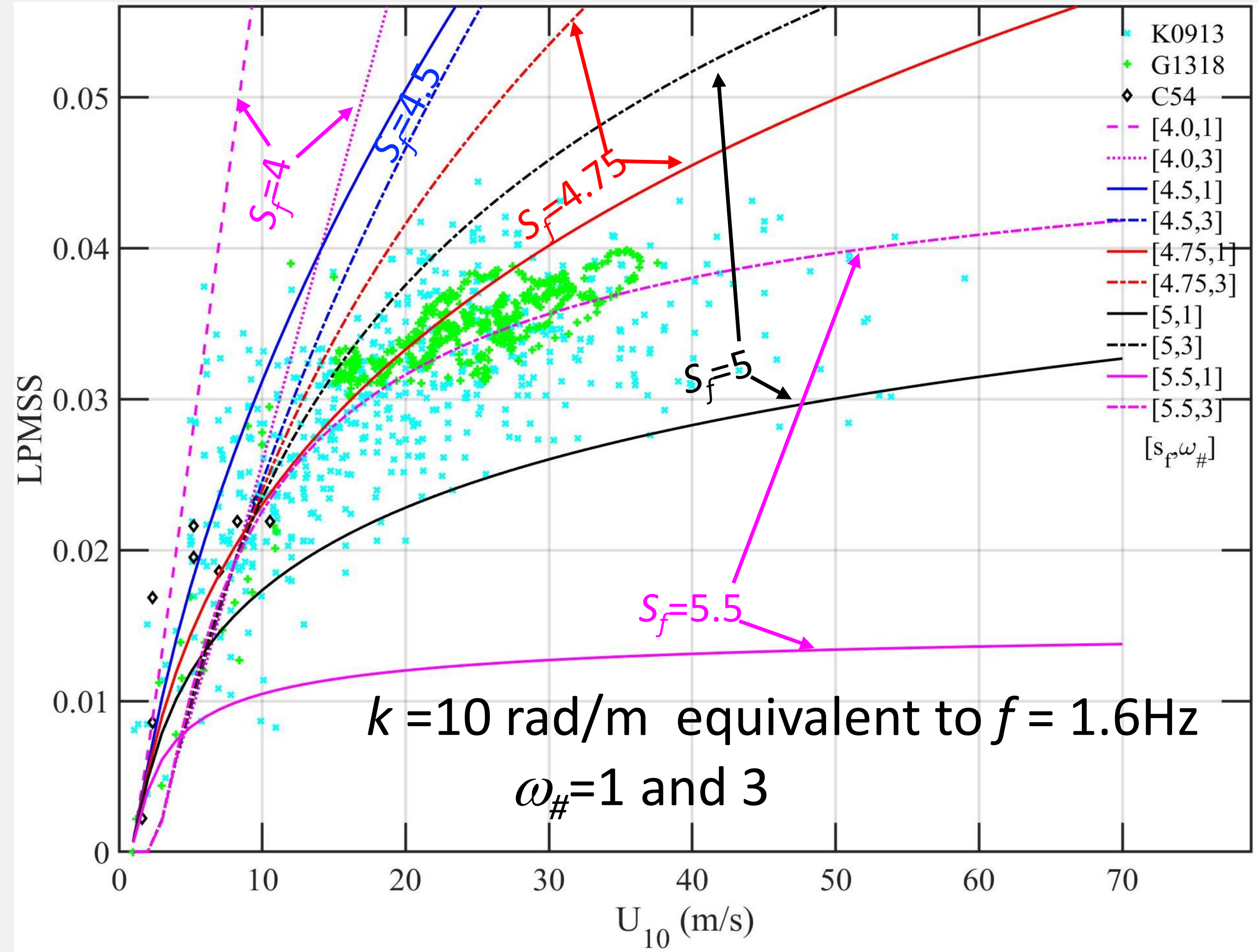
Conclusions

- Measuring cmDm waves in ocean
  - Microwave remote sensing
  - Air-sea exchanges

  Limited in situ observations, especially in high wind

- Microwave radar and radiometer observations
  - Roughness: scattering element, local incidence angle
    - VV NRCS => Bragg dominance: short cmDm
    - L-band LPMSS from GNSSR: long cmDm

  Plenty of field observations in all wind conditions



- ***Equilibrium spectrum concept***
  - ***Constant spectral slope(s) is not supported by observations (minority population)***
  - ***Assuming constant spectral slope(s) distorts wave spectral properties***