MSE:
Transforming the Future of Engineering &IT

Air-Sea Interactions at Extreme Wind Speeds

Alexander Babanin

University of Melbourne, Australia

a.babanin@unimelb.edu.au

Contributions of my colleagues and students are acknowledged

@engunimelb

www.facebook.com/engunimelb

Exeter, UK

16 November 2016

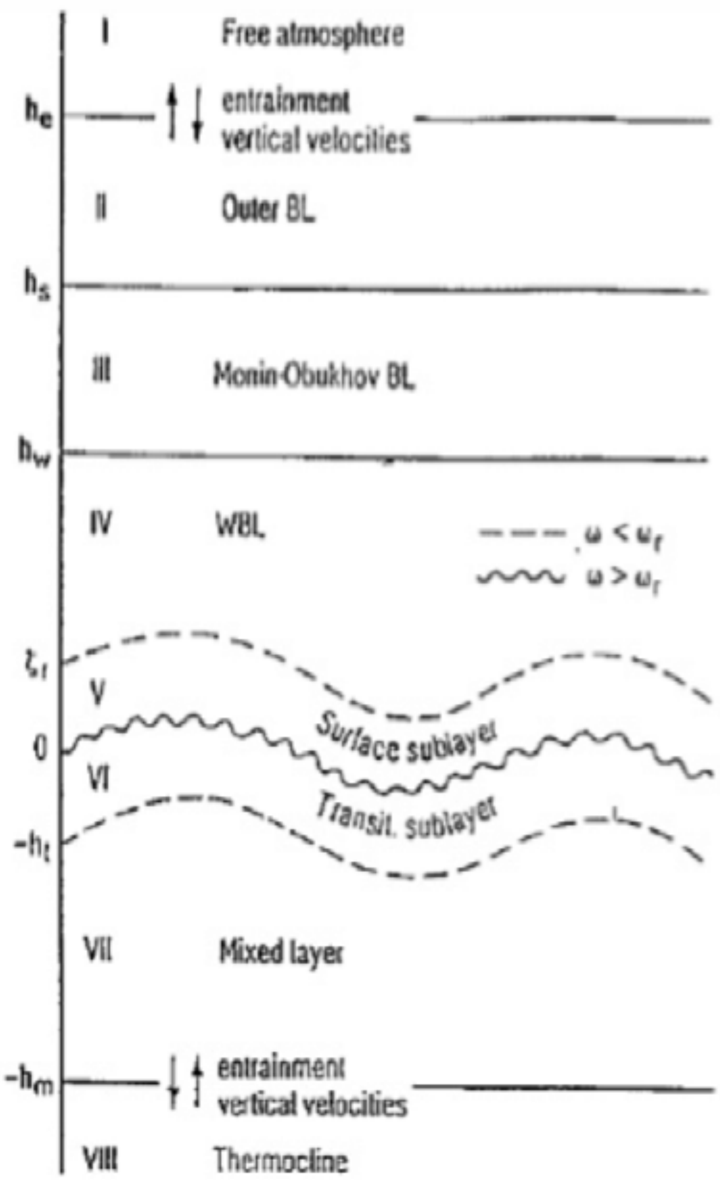
Waves as Atmosphere/Ocean Link

Small- and large-scale air-sea processes are essentially coupled in nature, but not in the models

- Atmospheric boundary layer
  - winds generate waves
  - waves provide surface roughness and change the winds
  - waves evolve, fluxes change
- Upper ocean mixed layer
  - generate currents
  - produce turbulence
  - turbulence: moderate and facilitate mixing
  - changes the circulation, SST

Tradition and future

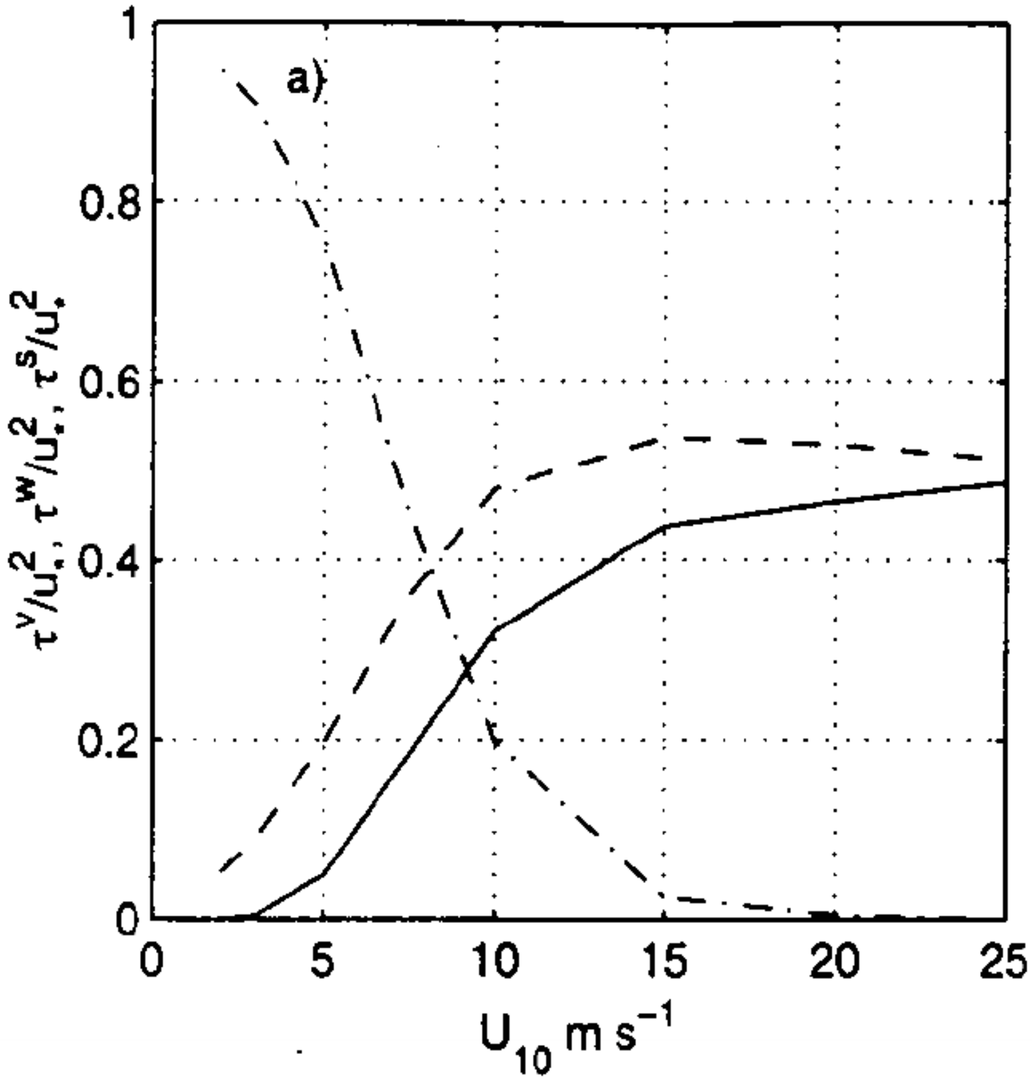
- Small scales and large scales are separated. Models reach saturation in their performance
- They need to be coupled, from turbulence to climate. Understanding exists, computer capacity exists



Chalikov & Belevich, 1993, BLM

Momentum flux

Momentum flux to currents and waves (through slope-coherent pressure and breaking)



Kudryavtsev & Makin, 2011, BLM

Everything changes at extreme conditions

- at wind speeds *U>32m/s,* dynamics of the atmospheric boundary layer, of the ocean wave surface and of the upper ocean layer – all change
- sea drag saturates at U_{10}=*32-33m/s* above the surface (*Powell et al., 2003*)
- at the surface, wave assymmetry saturates at U_{10}*~34m/s.* This indicates change of the wave breaking mechanism to the direct wind forcing (*Leikin et al., 1995*)
- wave breaking probability would no longer be controlled by nonlinear processes
- cross-interface gas fluxes still grow, but at a slow rate if U_{10} *> 35m/s,* additional mechanisms become active below the surface (*McNeil & d'Asaro, 2007*)

Babanin, 2011, Proc. Coasts and Ports

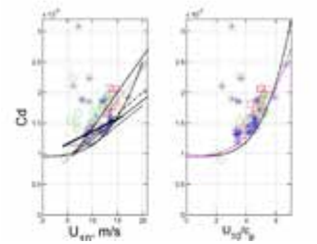
Atmospheric side

- *Wave Boundary Layer (WBL)*
- wind measurements are often done by buoys
- in strong storms, buoys masts are within WBL
- ***how accurate are extrapolations of such buoy wind measurements?***

THE UNIVERSITY OF MELBOURNE

Waves, sea drag, air-sea interactions

- in air-sea interaction and ocean-mixing models, the wind stress is usually parameterised to directly drive the dynamics of the upper ocean
- ~90% of the flux, however, first input into the waves
- air-sea coupling is usually expressed in terms of the drag coefficient C_d (but scatter is big)



$$\tau = \rho_a \overline{u'w'} = \rho_a u_*^2 = \rho_a C_d U_{10}^2 \qquad \textbf{ABL}$$

- the concept relies on existence of the constant flux layer
- coupling with wave models is necessary

$$\overline{u'w'} + \overline{\tilde{u}\tilde{w}} + \overline{p\eta_x} = \tau \qquad \textbf{WBL}$$

- terms due to wave-produced velocity and pressure are absent over flat surface
- they decay rapidly away from the surface, but the sum is constant

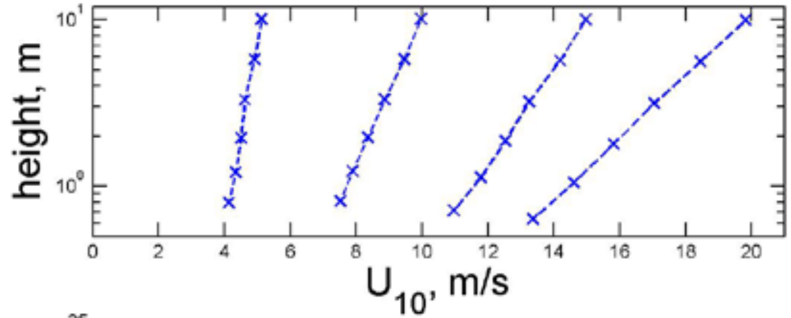
Lake George experiment

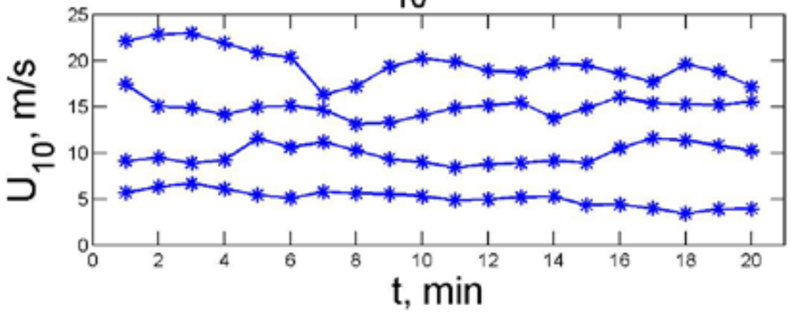
$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

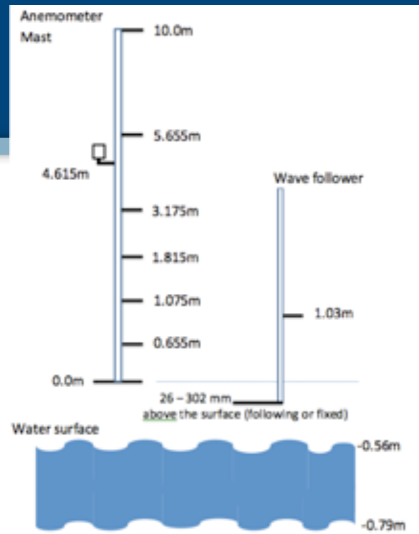
- direct measurements of input and dissipation
- direct measurements of sea drag

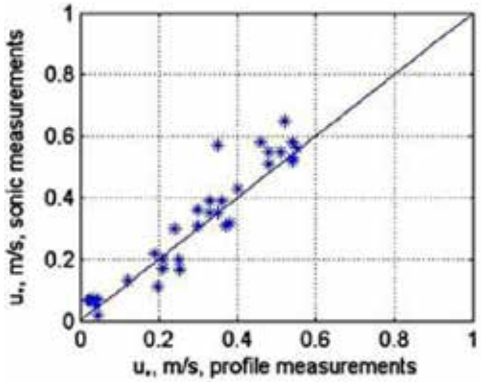
Young, Banner, Donelan, Babanin, McCormic, 2005, JTec

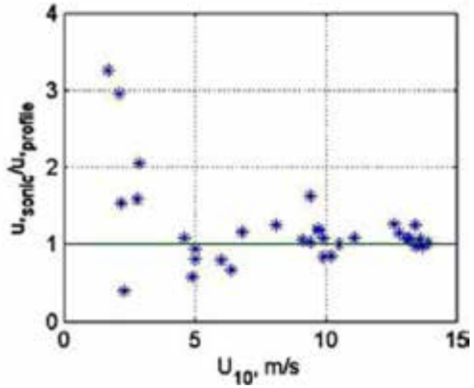
ABL measurements











$$\tau = \rho_a u_*^2 = \rho_a \overline{u'w'} = \rho_a C_d U_{10}^2$$

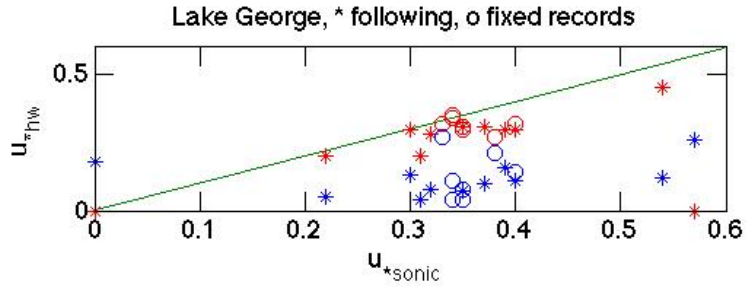
$$U(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0}$$

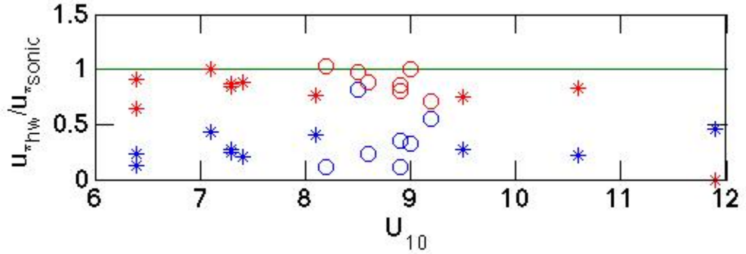
- inter-comparisons were done with Sonic anemometer
- light winds $U_{10} < 4 m/s$ were excluded from analysis

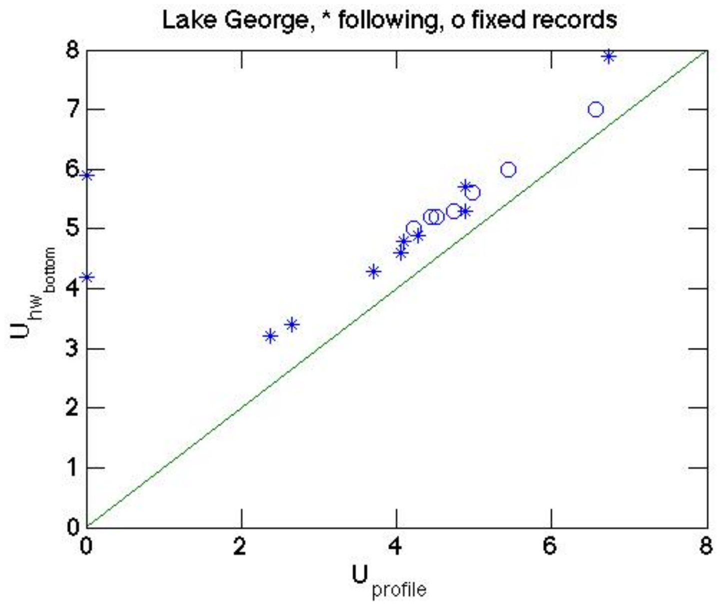
Babanin and Makin, 2008, JGR

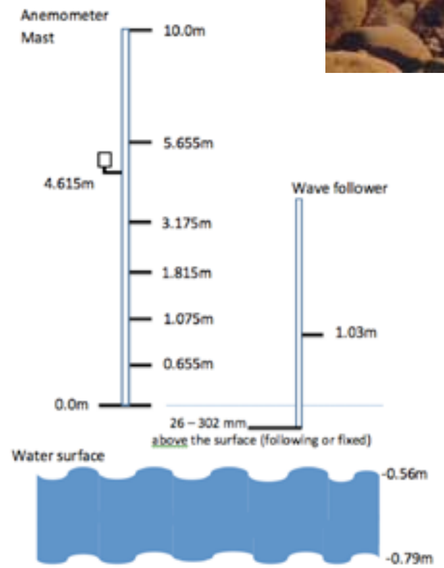
THE UNIVERSITY OF MELBOURNE

WBL measurements, Lake George









$$\overline{u'w'} + \overline{\tilde{u}\tilde{w}} + \overline{p\eta_x} = \tau$$

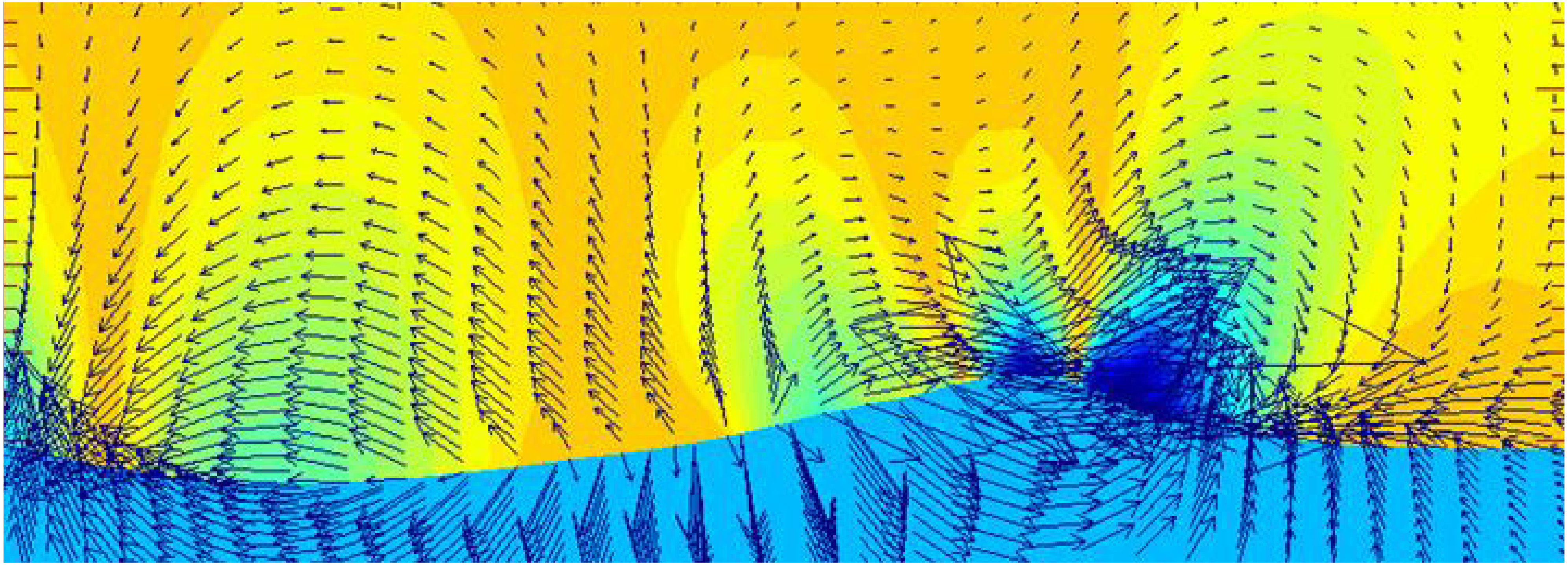
Babanin and McConochie, 2013, OMAE

Example of the 2-D flow structure above waves

A small fragment of the reproduced field is represented

Chalikov & Rainchik (2011)

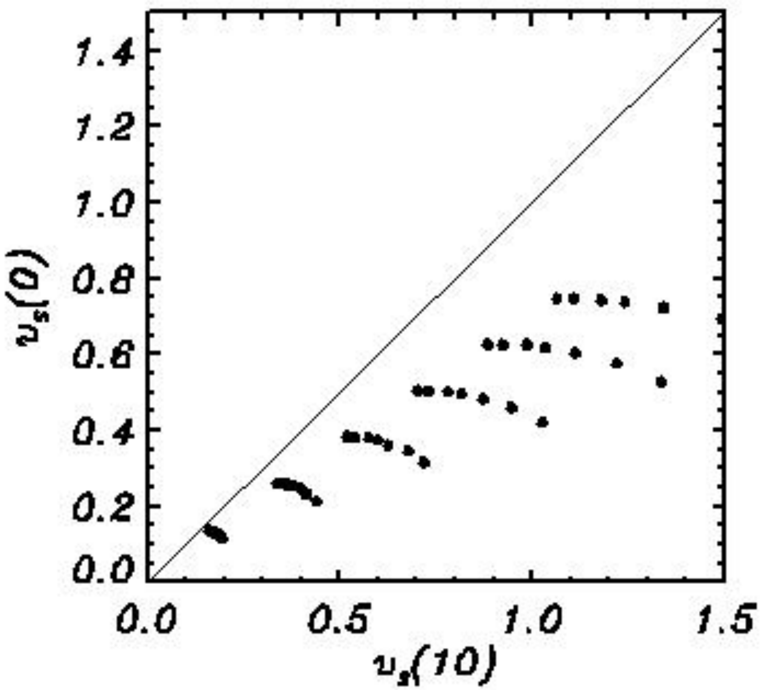
The colors show pressure distribution (solid lines correspond to positive values, dashed lines – to negative values); arrows are vectors of the wave-produced velocity.



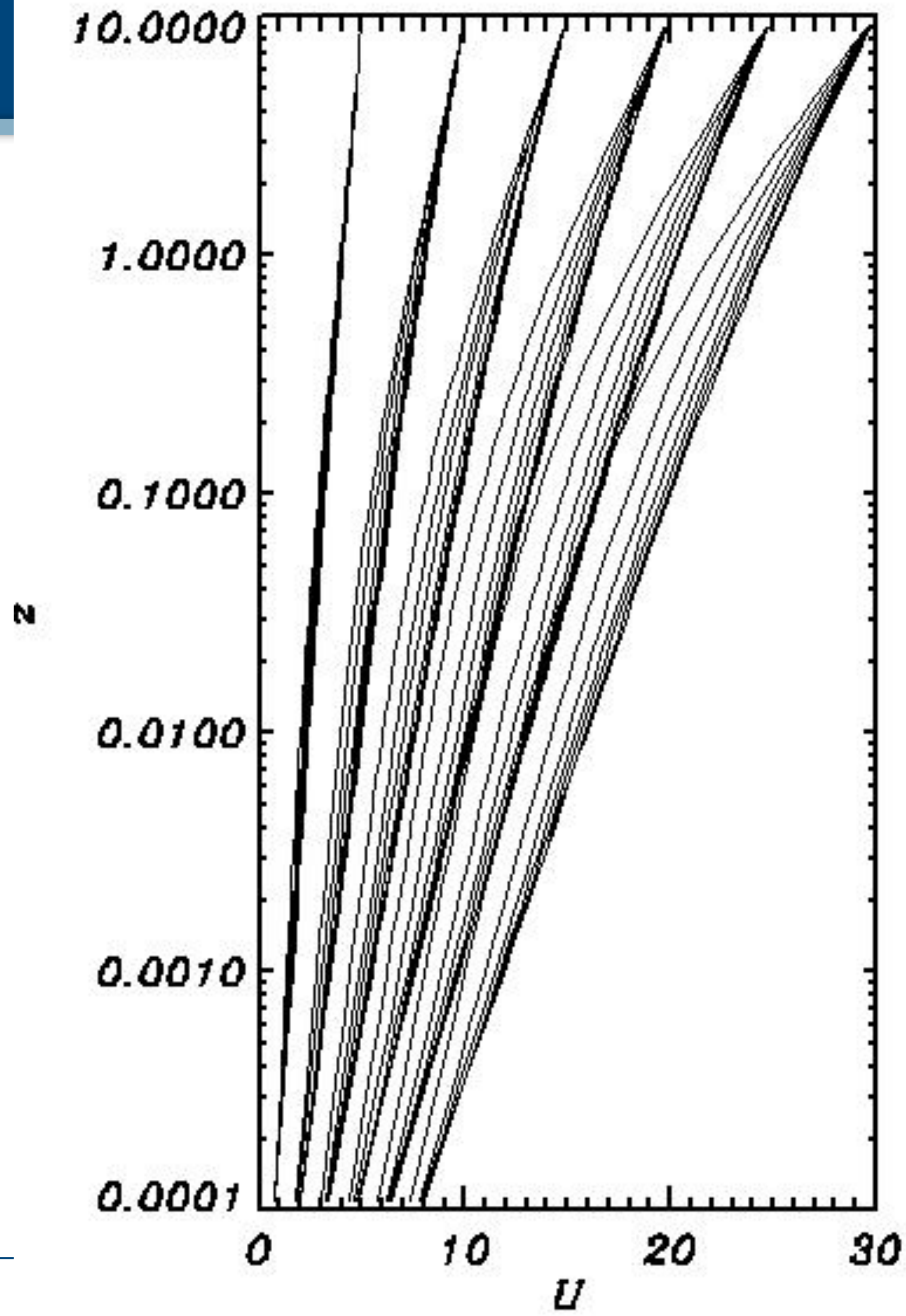
$$\overline{u'w'} + \overline{\tilde{u}\tilde{w}} + \overline{p\eta_x} = \tau$$

$u_{10} = (5,10,15,20,25,30)$ $\quad u_{10}/c_p = (.855,1.,1.25,1.5,2.,3.,5.)$

Friction velocity at the surface and 10m height



Vertical profiles of mean wind speed



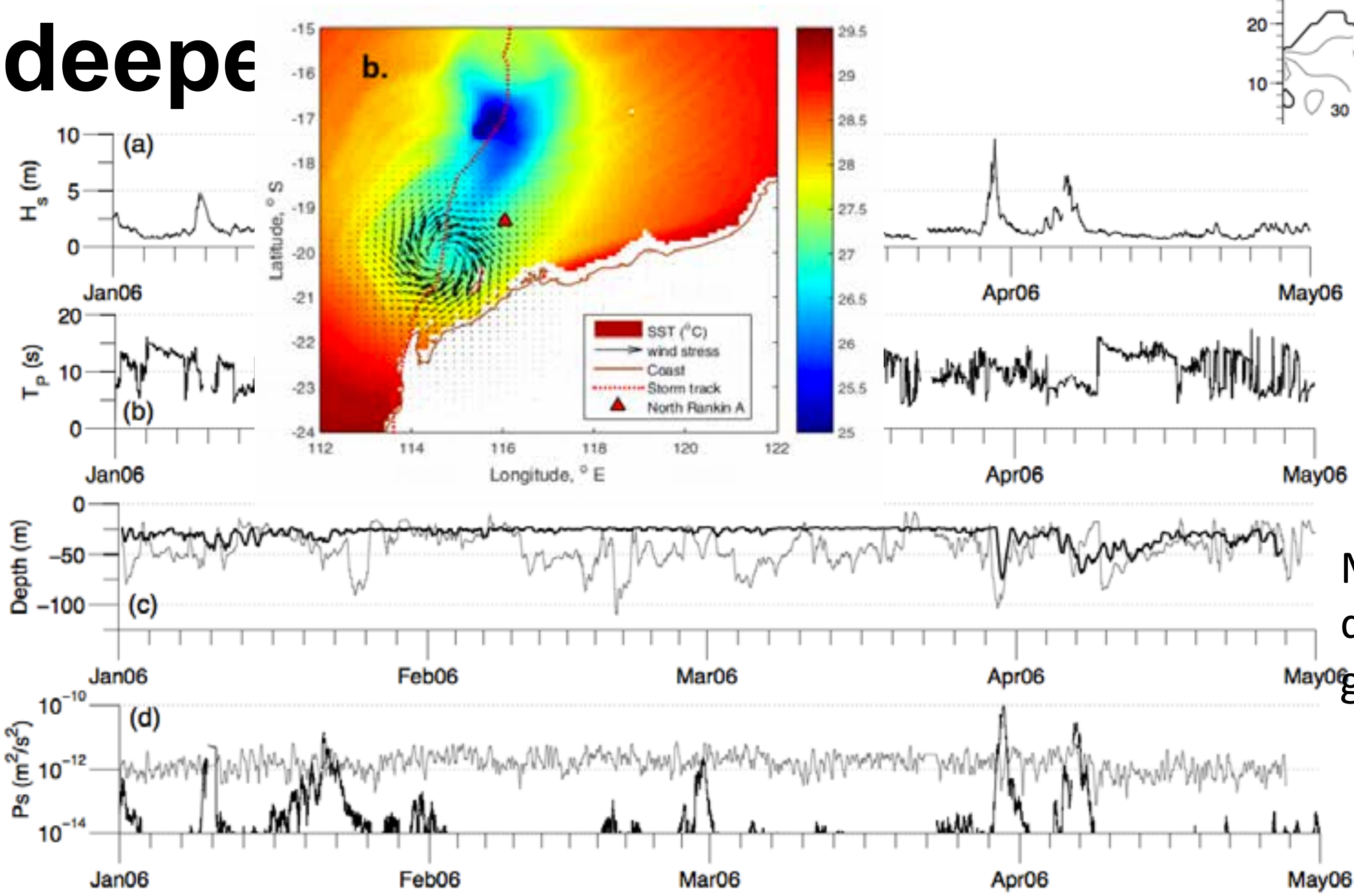
Conclusions (for WBL)

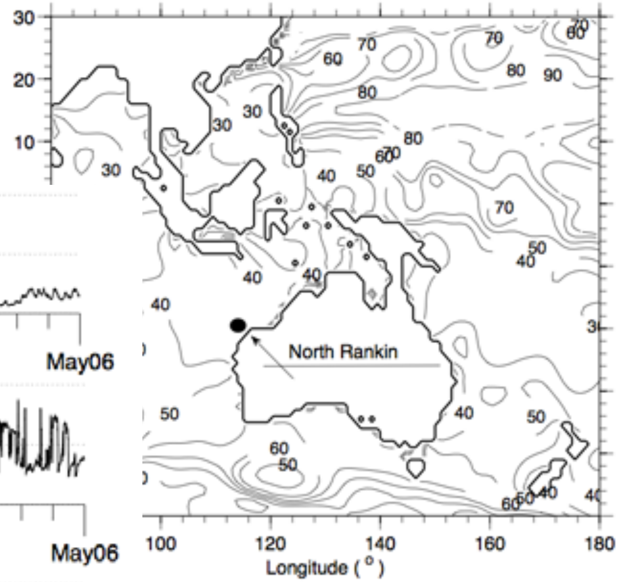
- Wave Boundary Layer is investigated by means of field observations and numerical modelling
- turbulent stress towards the surface is reduced ~7 times
- mean wind speed near the surface is some 5% greater than predictions based on the constant-flux layer profile
- results may have significant implications for extrapolations of buoy measurements in extreme conditions

Water side

- *Wave-induced mixing*
- missing in existing models
- mixes through the thermocline
- can cool the surface and affect intensity of tropical cyclones

Field observations, North Rankin mixed layer deepe



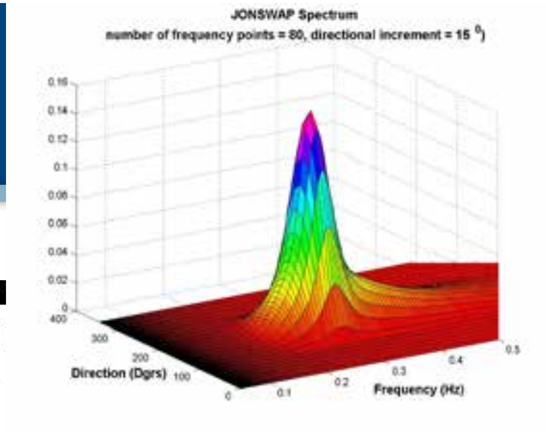


MLD:
dark – wave induced
grey - measured

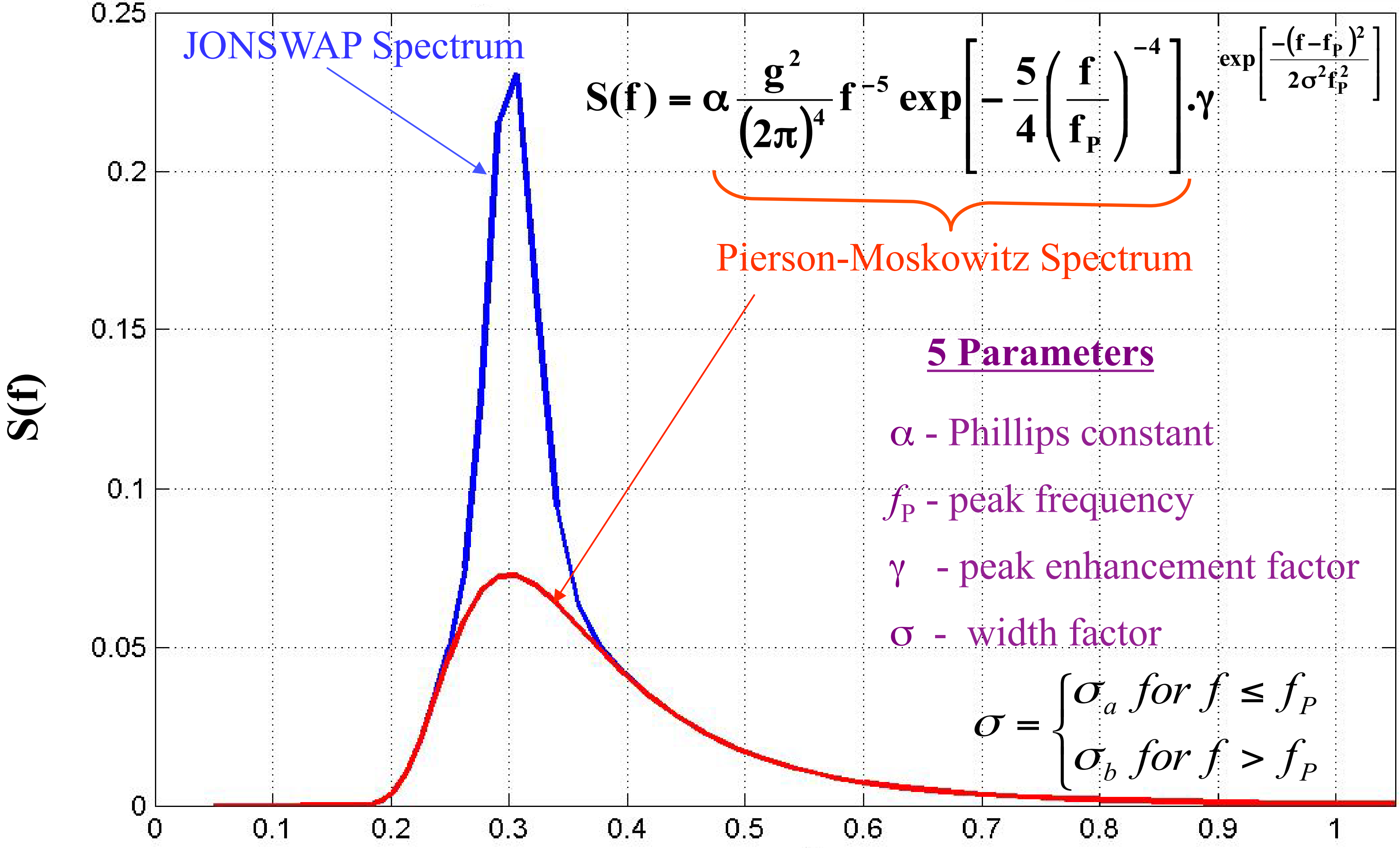
Toffoli et al., JGR, 2012

The waves

JONSWAP SPECTRUM



Energy Spectrum, Source Mode, XNL ı
nfr = 80, f_p = 0.3, ndr = 24, wind =



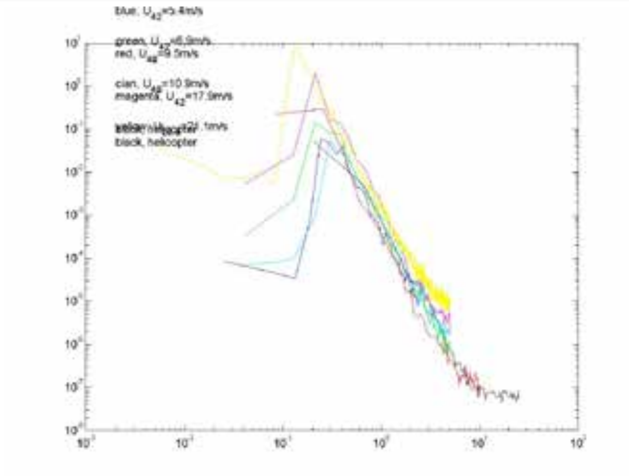
$$S(f) = \underbrace{\alpha \frac{g^2}{(2\pi)^4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_P}\right)^{-4}\right]}_{\text{Pierson-Moskowitz Spectrum}} . \gamma^{\exp\left[\frac{-(f-f_P)^2}{2\sigma^2 f_P^2}\right]}$$

5 Parameters

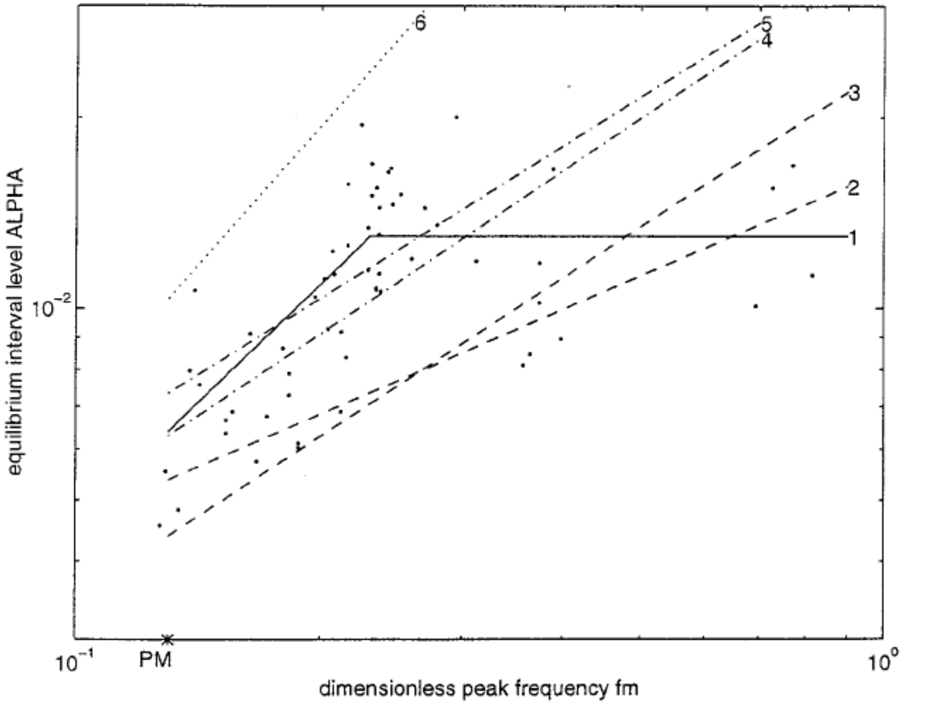
- α - Phillips constant
- f_P - peak frequency
- γ - peak enhancement factor
- σ - width factor

$$\sigma = \begin{cases} \sigma_a \ for\ f \le f_P \\ \sigma_b \ for\ f > f_P \end{cases}$$

Spectral dependences

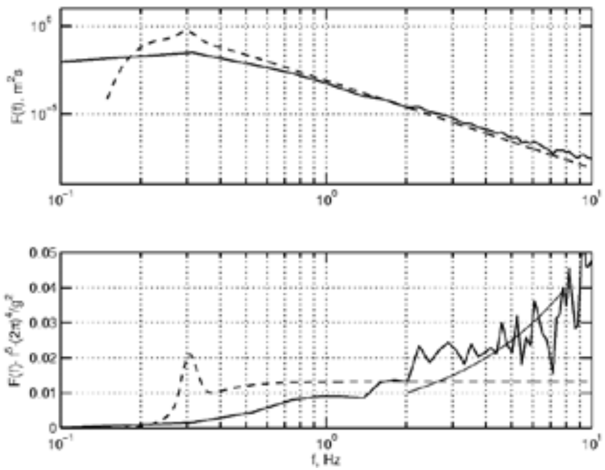


Babanin & Soloviev, 1998, JPO



$$\alpha = \begin{cases} (8.03^{+0.57}_{-0.54})10^{-2}\tilde{f}_m^{1.24\pm0.23} & \text{for} \quad \tilde{f}_m \le 0.23 \\ 13.2 \times 10^{-3} & \text{for} \quad \tilde{f}_m > 0.23. \end{cases}$$

Black Sea, helicopter



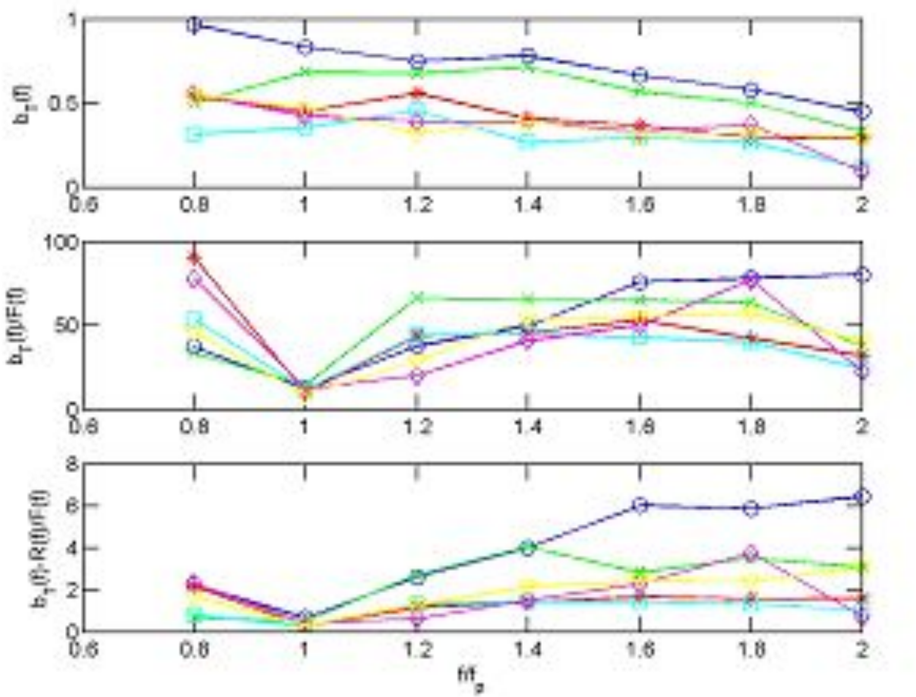
$U^2_{helicopter}/U^2_{Phillips} \gg 16$

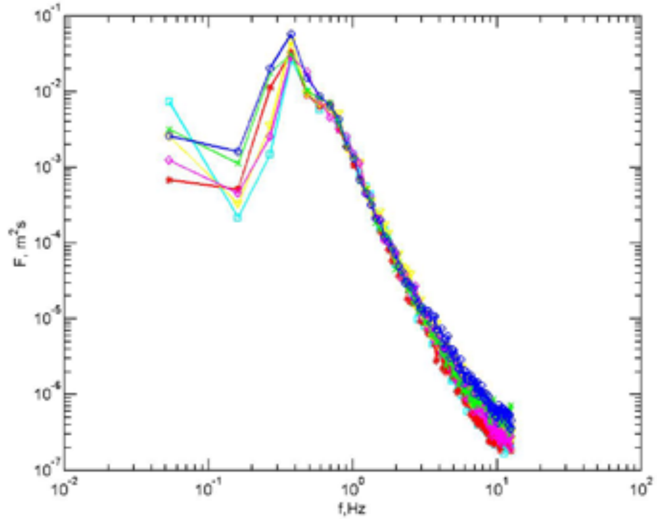
Babanin, 2011

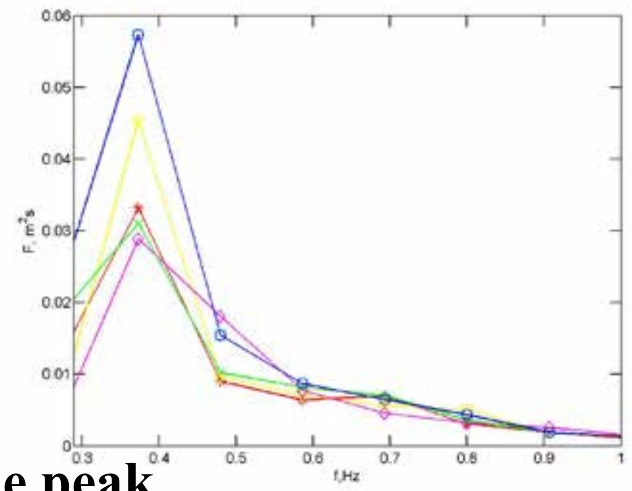
$\alpha_{helicopter}/\alpha_{Phillips}=1.9$

S_{ds} Bubble-detection method

Cumulative effect of wave breaking
Dependence on the wind







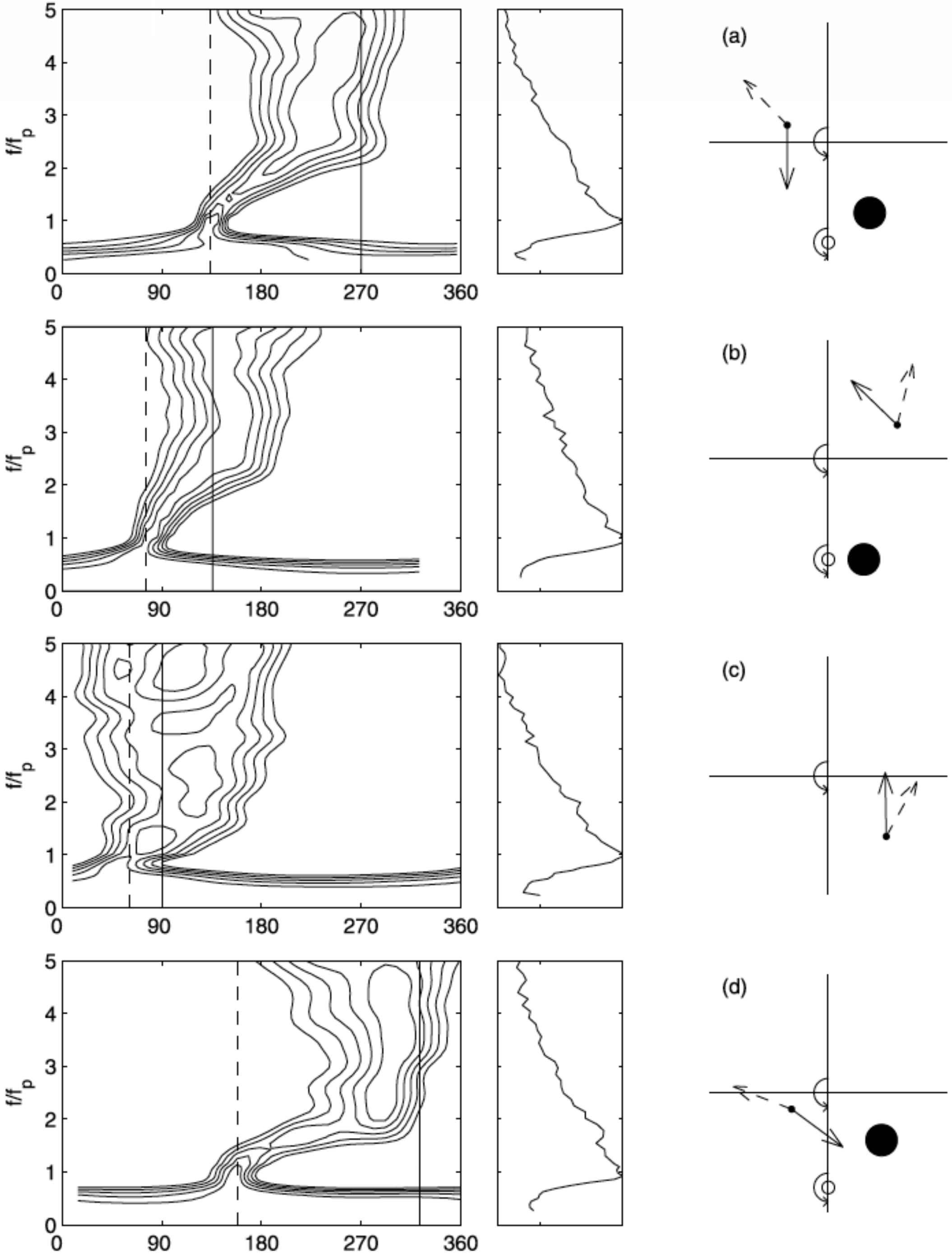
- **two-phase behaviour of spectral dissipation:**

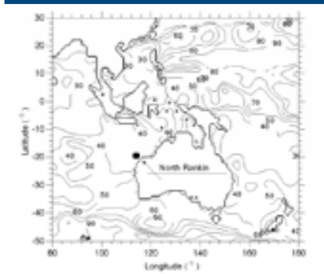
- linear dependence of S_{ds} on the spectrum at the peak

- cumulative effect at smaller scales

- **b_T depends on the wind for $U_{10} > 14$ m/s**

YOUNG: HURRICANE DIRECTIONAL SPECTRA





Young, 2006, JGR

Extreme Events in terms of wind (u10 > 20m/s)

- Self-similarity theory:

$$\tilde{\epsilon} = (2.56^{+2.36}_{-1.23}) \cdot 10^{-5} \tilde{f}_p^{-2.47\pm0.37}$$

– relative growth slower

– overall energy is larger

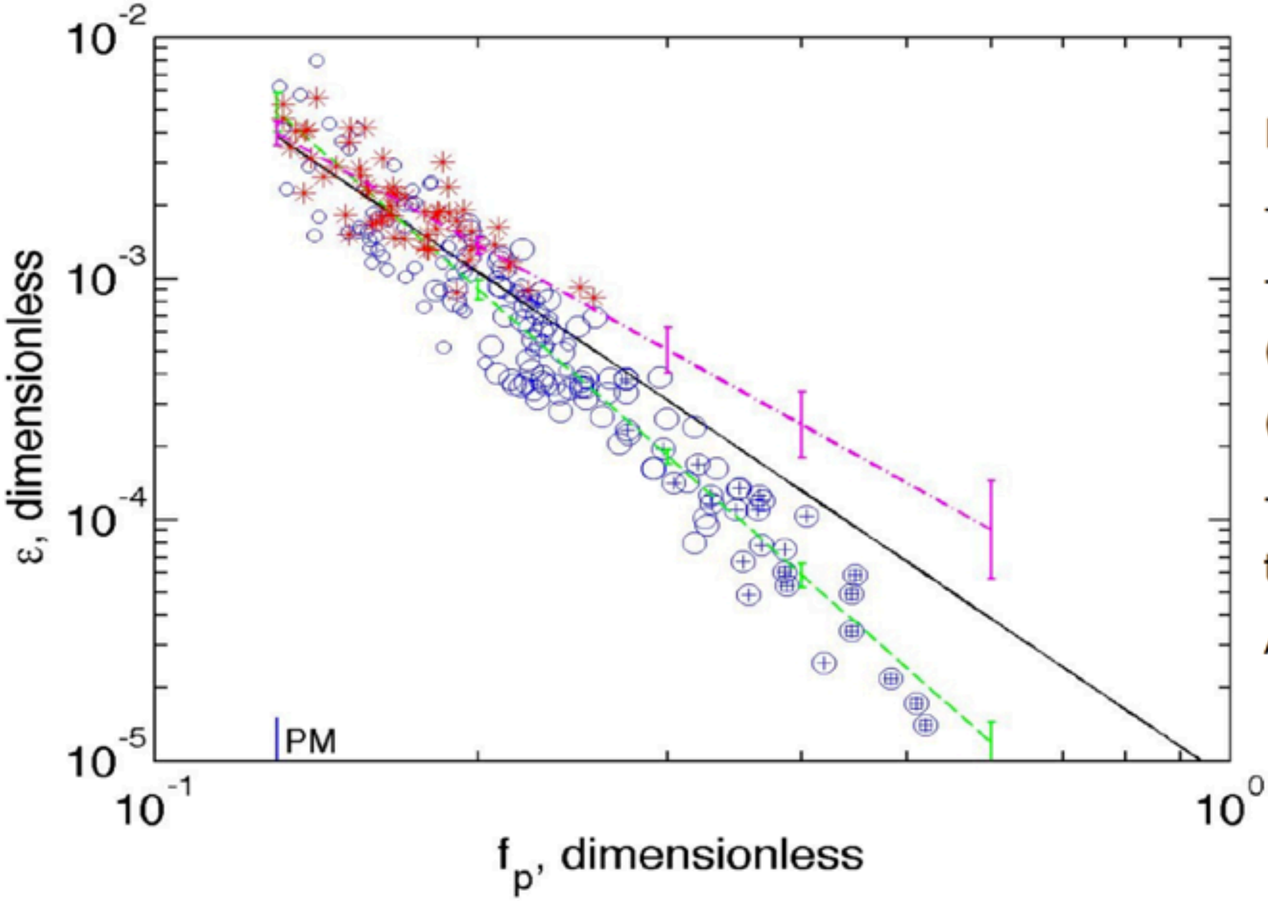


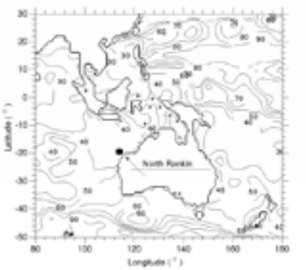
Figure:

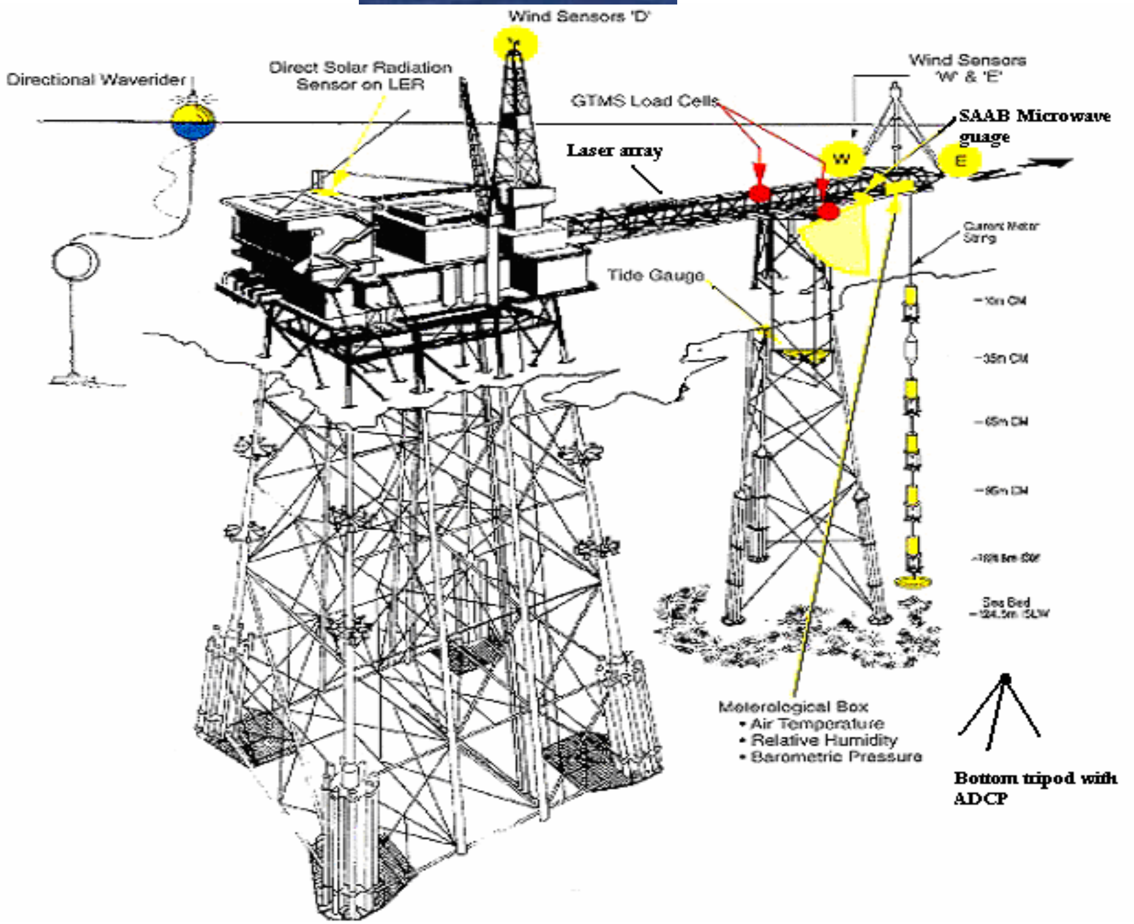
– solid line: typical conditions

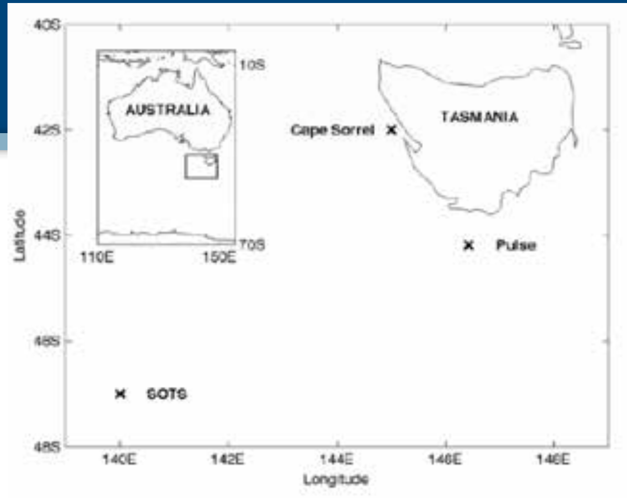
– dash-dotted purple line (asterisks): Southern Ocean (u10>20m/s)

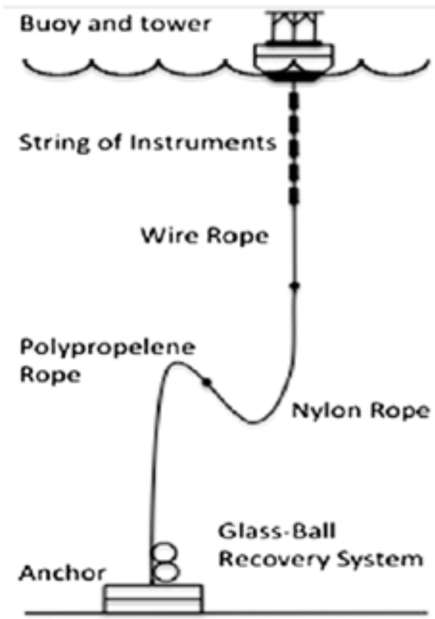
– dash green line (large circles): tropical cyclones (Western Australia)

Facilities









Woodside, North Rankin platform, tropical

Australian Bureau of Meteorology, SOFS station, Southern Ocean

Air-sea interactions at extreme wind forcing

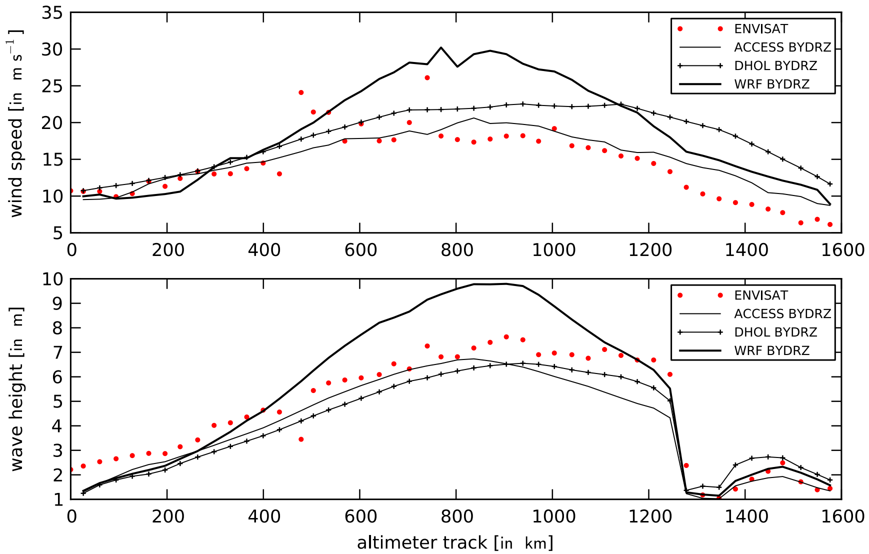
- at wind speeds *$U>32m/s$,* dynamics of the atmospheric boundary layer, of the ocean wave surface and of the upper ocean layer – all change
- sea drag saturates at $U_{10}=32\text{-}33m/s$ above the surface
- cross-interface gas fluxes still grow, but at a slow rate if $U_{10} > 35m/s$, additional mechanisms become active below the surface
- at the surface, wave asymmetry saturates at $U_{10}\sim 34m/s$. This indicates change of the wave breaking mechanism to the direct wind forcing
- wave-induced mixing can substantially cool the surface
- wave spectra exhibit range of specific behaviours
- ***surface/wind relationships are substantially altered***

Spectral hurricane modelling

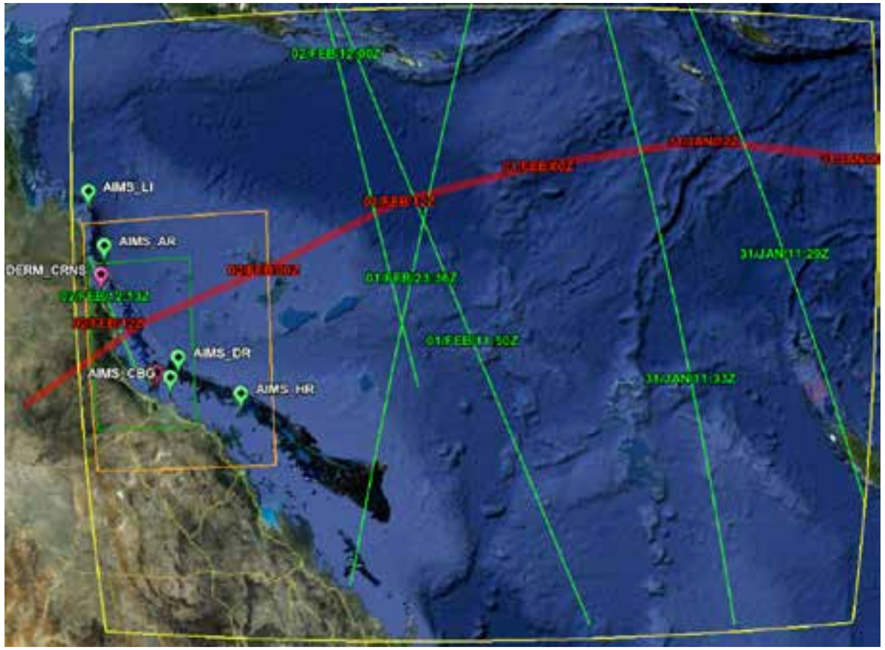
- *Extreme conditions are usually modelled by extrapolation from moderate conditions*
- Physics of air-sea interactions in extreme conditions is different

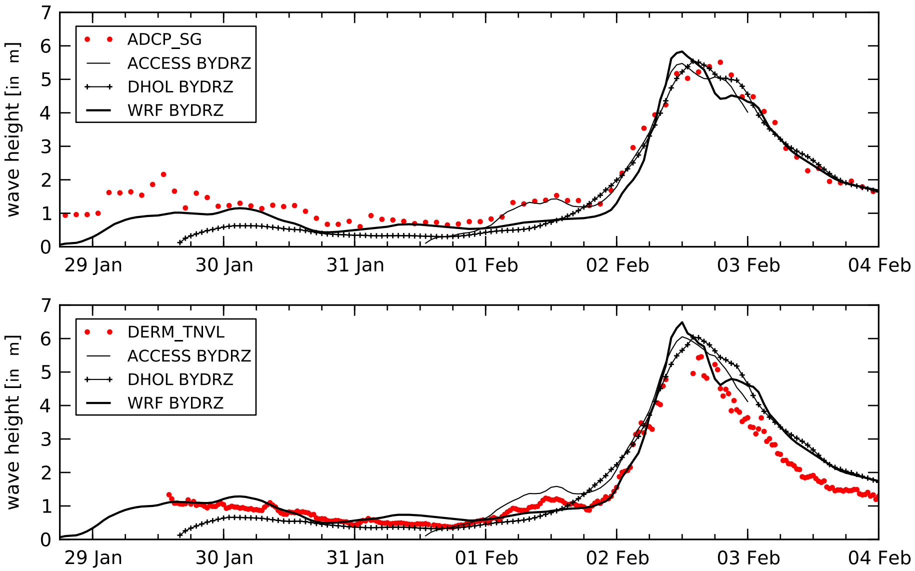
- directional spectra are unknown
- wind fields are a problem
- negative input is a problem
- wind-induced currents are a problem

Cyclone Yasi



Deep water track, winds (top), waves (bottom)





waves next to Townsville (ADCP) and Cape Cleveland (buoy)

Slide by Stefan Zieger

Air-sea interactions at extreme wind forcing

- at wind speeds *$U>32m/s$,* dynamics of the atmospheric boundary layer, of the ocean wave surface and of the upper ocean layer – all change
- sea drag saturates at $U_{10}=32\text{-}33m/s$ above the surface
- cross-interface gas fluxes still grow, but at a slow rate if $U_{10} > 35m/s$, additional mechanisms become active below the surface
- at the surface, wave asymmetry saturates at U_{10}~*34m/s.* This indicates change of the wave breaking mechanism to the direct wind forcing
- wave-induced mixing can substantially cool the surface
- wave spectra exhibit range of specific behaviours
- ***surface/wind relationships are substantially altered***

Drag coefficient

- in every air-sea interaction model
- intends to replace the physics of the boundary layer with a single coefficient, dependent on the wind

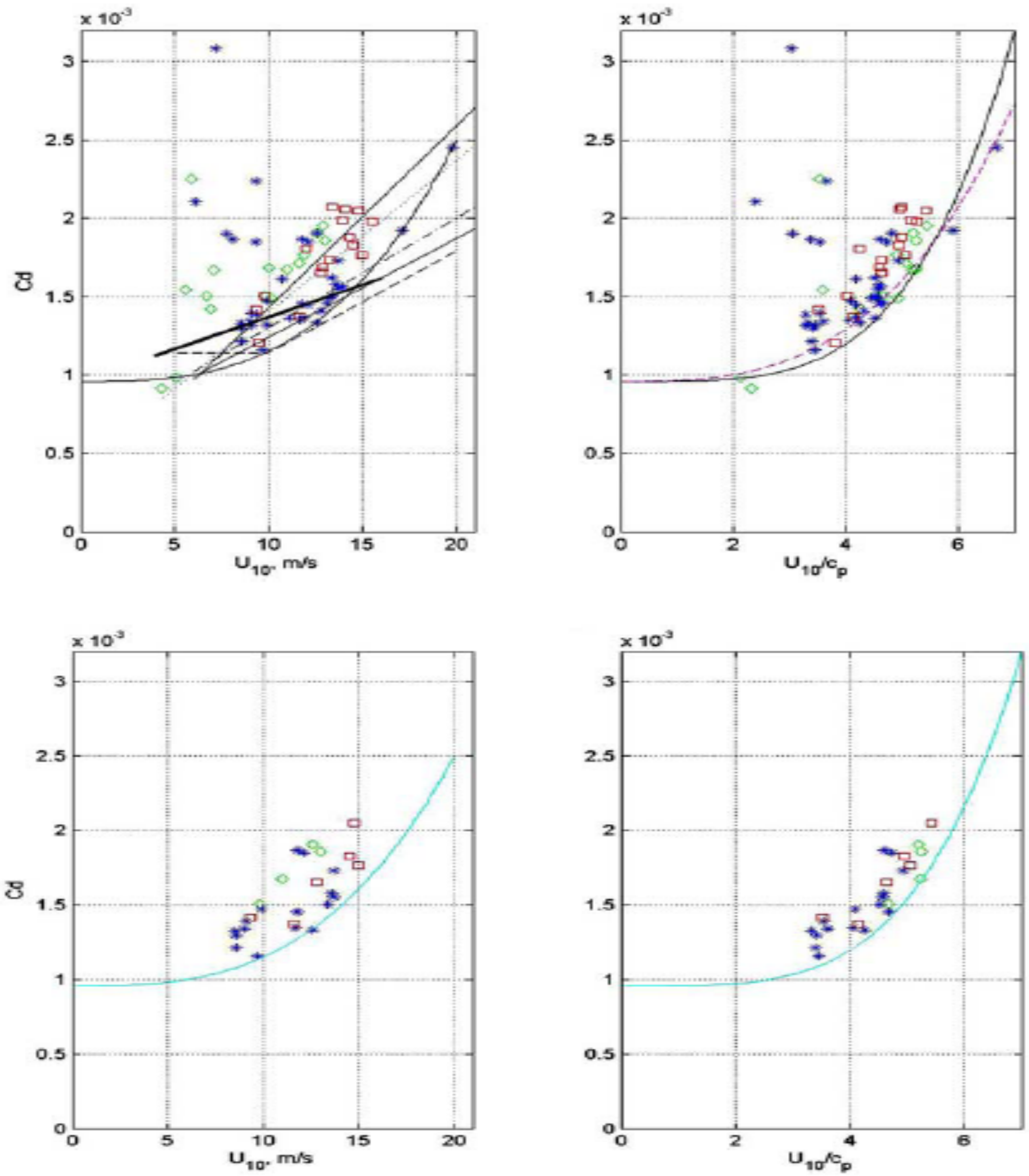
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, C02015, doi:10.1029/2007JC004233, 2008

Effects of wind trend and gustiness on the sea drag: Lake George study

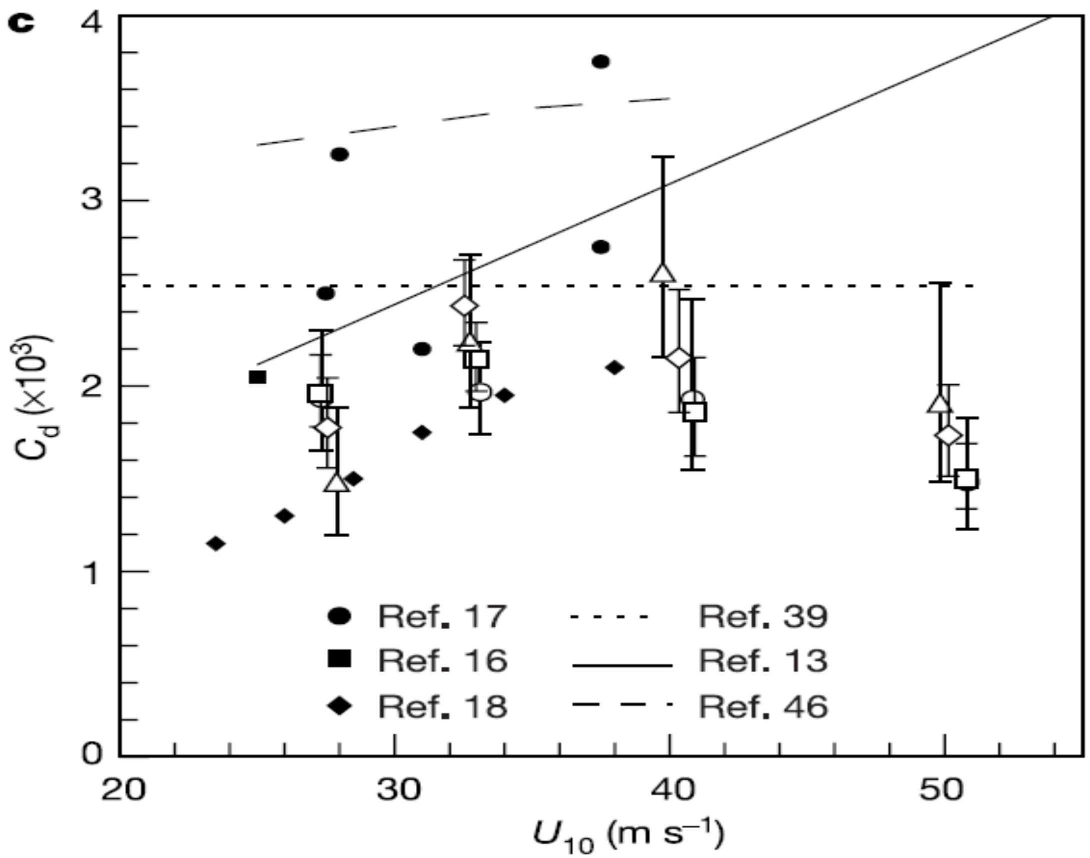
Alexander V. Babanin[1] and Vladimir K. Makin[2]

[10] We believe that a complete list of physical properties and phenomena, whose effect on the sea drag should be investigated and incorporated in the final parameterization to reduce the scatter, includes, among possible others, 1) mean wind speed; 2) sea state dependence; 3) wave steepness; 4) full flow separation for strongly forced wind waves; 5) enhancement of sea drag due to wave breaking; 6) rising and falling winds; 7) gustiness of the wind; 8) temperature stratification in the atmospheric boundary layer; 9) swell; 10) non-linear wind-wave interactions; 11) wave horizontal skewness and vertical asymmetry; 12) variation of the wavy surface properties at wave group and wavelength scales; 13) wave directionality; 14) wave short-crestedness; 15) coupled effects in the air/sea boundary layers. The 16th and separate item would be that due to peculiarities of air-sea interaction at extreme wind-forcing conditions which include an entire set of new features irrelevant at moderate winds as mentioned above. In this list, we do not mention properties and processes which breach validity of the constant-flux-layer approximation, as in such circumstances the notion of the drag coefficient (1) becomes

Gustiness, experiment



Saturation of Sea Drag



Powell, Vickery, Reinhold, 2003, Nature

- Extensive research field since 2003, dozens of papers
- field and laboratory experiments
- theories:

- spray theories, 4 classes

- hydrodynamic theories, 2 classes

- turbulence theory: 2D turbulence suppresses 3D vortexes

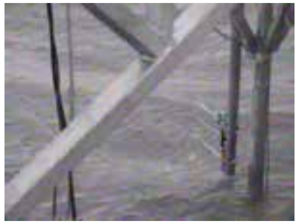
- combination of those

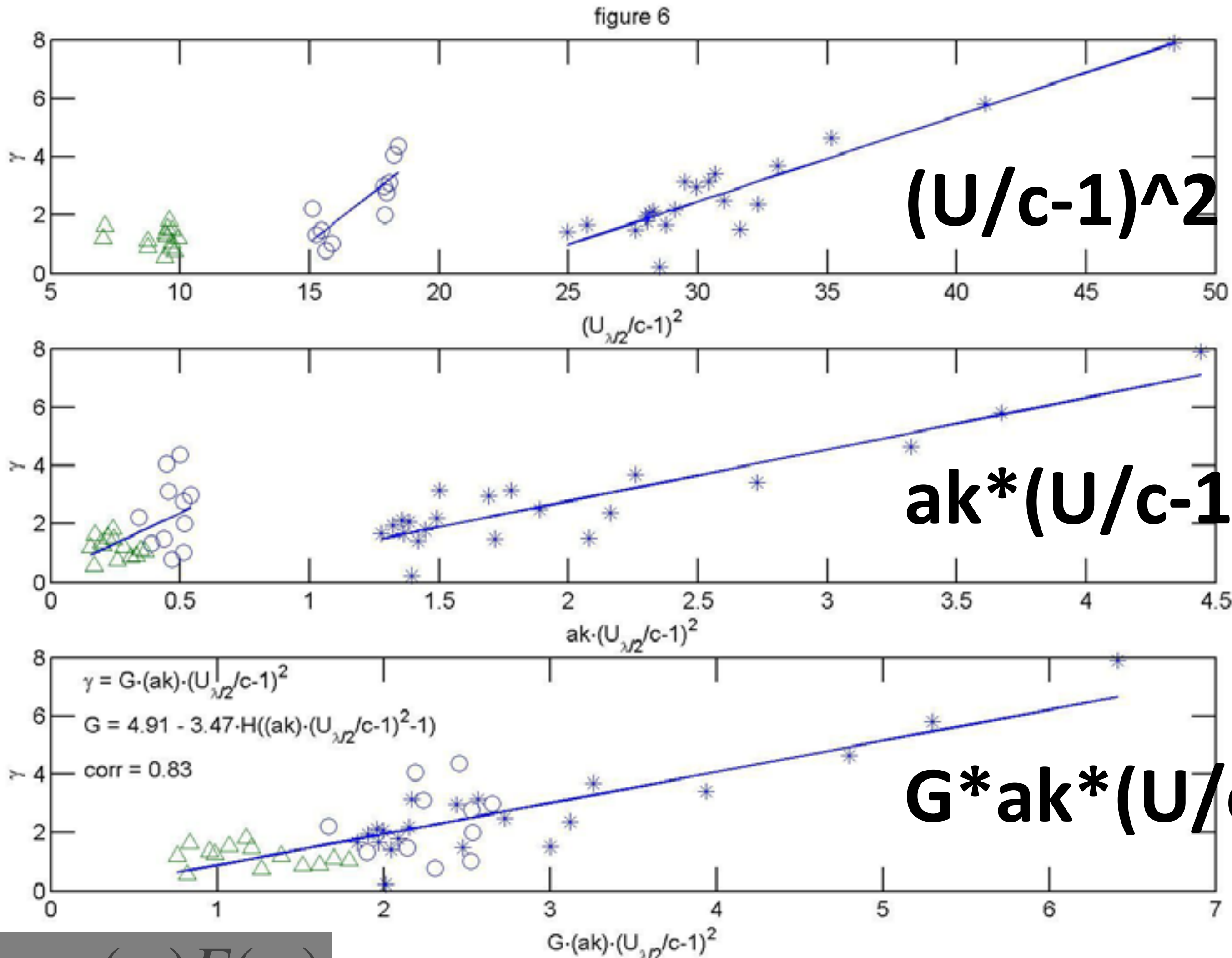
Drag saturates at

U_{10}=32-33m/s

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

Spectrum growth rate γ, LG measurements





(U/c-1)^2

ak*(U/c-1)^2

G*ak*(U/c-1)^2

$$S_{in}(\omega) = \rho_a \omega g \gamma(\omega) E(\omega)$$

Donelan, Babanin, Young, Banner, 2006, JPO

Air-sea interactions at extreme wind forcing

- at wind speeds *$U>32 m/s$,* dynamics of the atmospheric boundary layer, of the ocean wave surface and of the upper ocean layer – all change
- sea drag saturates at $U_{10}=32\text{-}33 m/s$ above the surface
- cross-interface gas fluxes still grow, but at a slow rate if $U_{10} > 35 m/s$, additional mechanisms become active below the surface
- at the surface, wave asymmetry saturates at $U_{10}\sim 34 m/s$. This indicates change of the wave breaking mechanism to the direct wind forcing
- wave-induced mixing can substantially cool the surface
- wave spectra exhibit range of specific behaviours
- ***surface/wind relationships are substantially altered***