Revised estimates of ocean surface drag in strong winds

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+
The SUSTAIN Lab

UNIVERSITY OF MIAMI
ROSENSTIEL
SCHOOL of MARINE &
ATMOSPHERIC SCIENCE

A COMPASS Seminar
September 11, 2019

Measuring and parameterizing air-sea drag to improve hurricane prediction

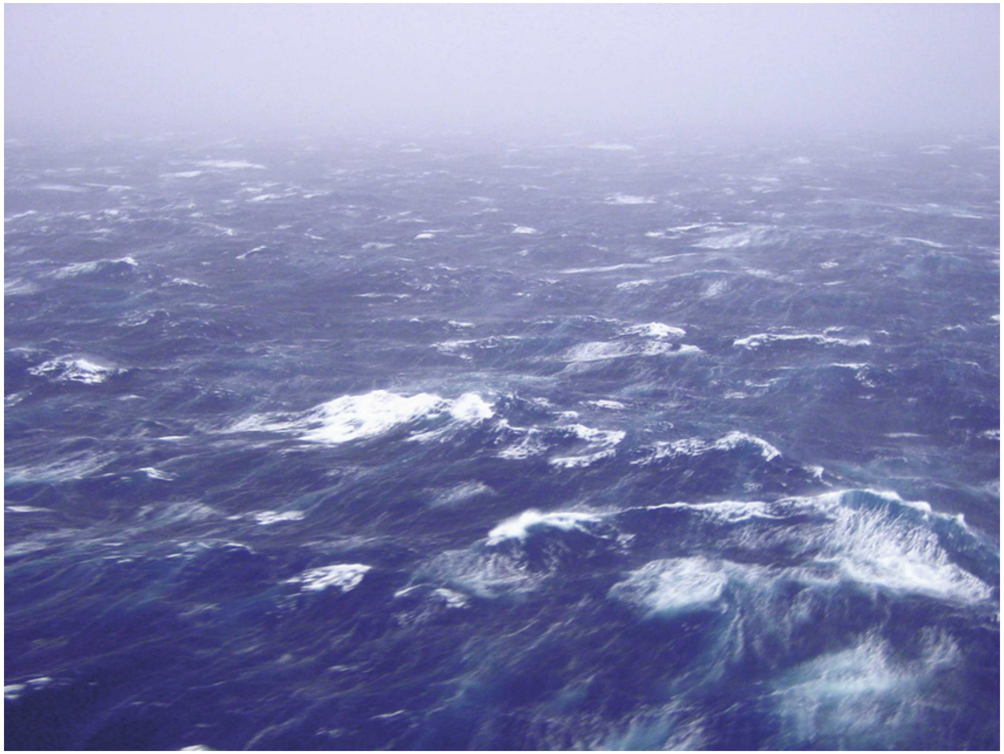
Can we measure air-sea drag in hurricane winds?

What physical processes govern the drag?

Can we better resolve it in models to improve hurricane wind structure and intensity prediction?

Air-sea surface drag

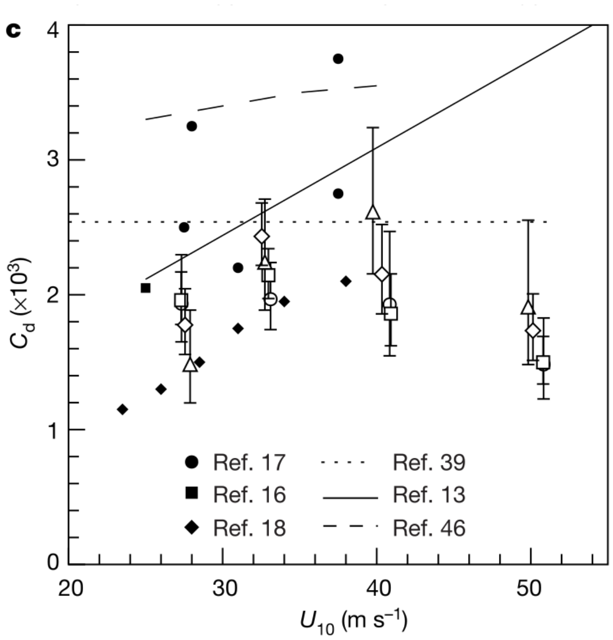
- Vertical flux of momentum between atmosphere and ocean
- Largely wave dependent
- Difficult to measure in extreme weather such as hurricanes
- Essential piece of weather and ocean prediction models



Hurricane Isabel (2003),
photo from NOAA aircraft
by Michael Black
(tropical storm-force conditions)

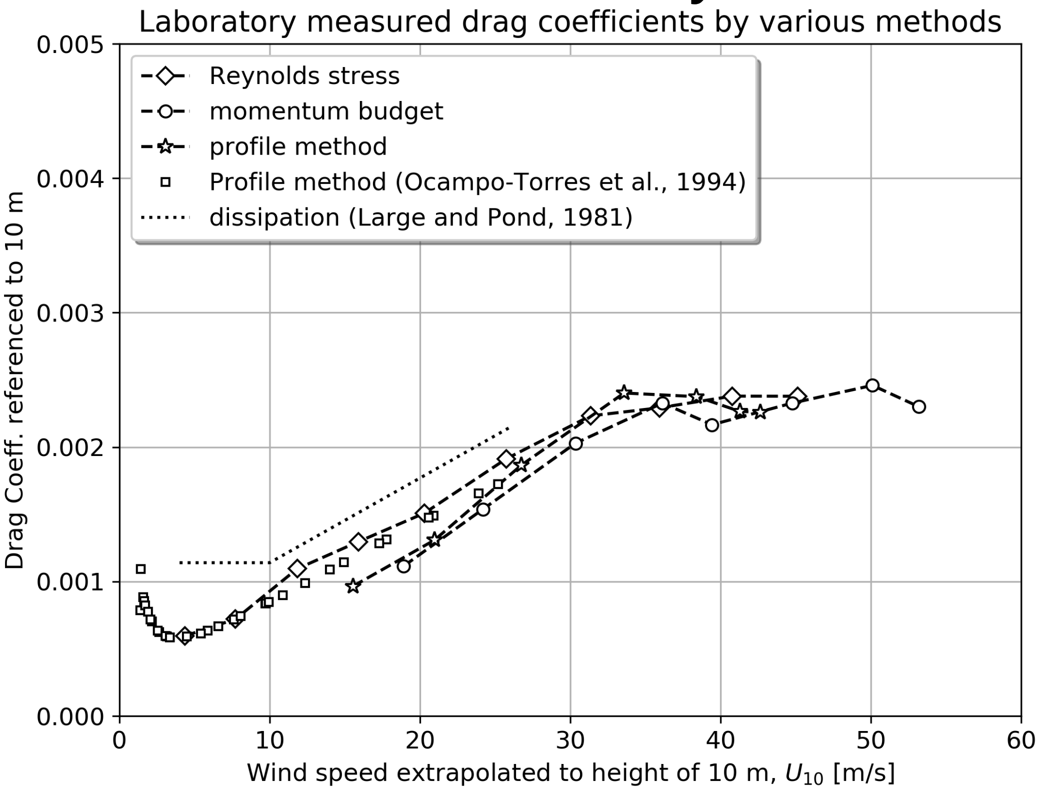
Drag saturates in strong winds

Field (dropsondes)



Powell et al. (2003), Nature

Laboratory



Donelan et al. (2004), GRL

$$\tau = \rho_a C_D U_{10}^2$$

High impact result! Implemented in weather and ocean prediction models soon after (e.g. WRF, Davis et al. 2007)

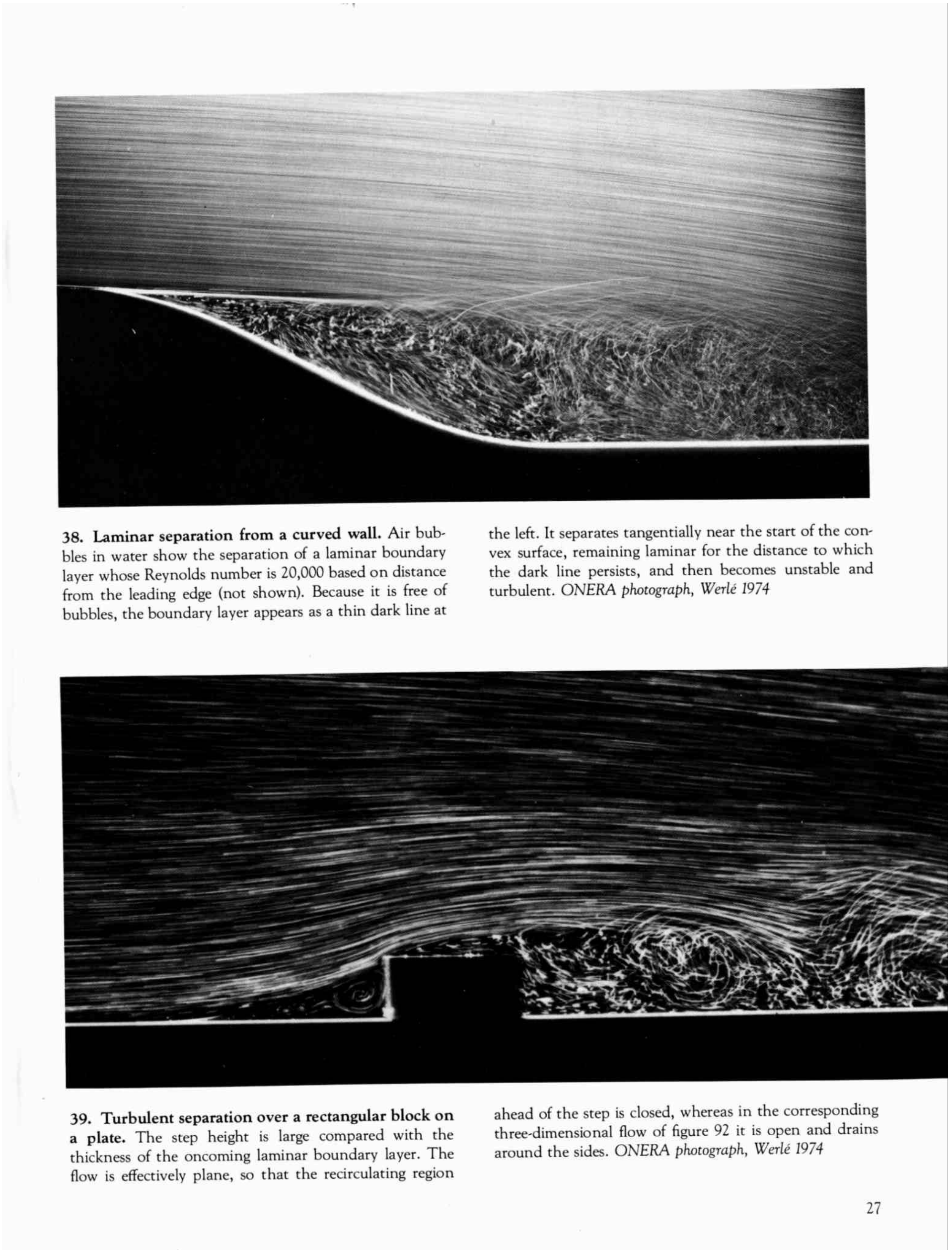
Why does drag saturate in strong winds?

Sheltering and flow separation?

Spray and bubles form a multiphase layer that suppresses turbulence?

Wave tearing from direct impact by wind?

Sheltering and flow separation



38. **Laminar separation from a curved wall.** Air bubbles in water show the separation of a laminar boundary layer whose Reynolds number is 20,000 based on distance from the leading edge (not shown). Because it is free of bubbles, the boundary layer appears as a thin dark line at the left. It separates tangentially near the start of the convex surface, remaining laminar for the distance to which the dark line persists, and then becomes unstable and turbulent. *ONERA photograph, Werlé 1974*

39. **Turbulent separation over a rectangular block on a plate.** The step height is large compared with the thickness of the oncoming laminar boundary layer. The flow is effectively plane, so that the recirculating region ahead of the step is closed, whereas in the corresponding three-dimensional flow of figure 92 it is open and drains around the sides. *ONERA photograph, Werlé 1974*

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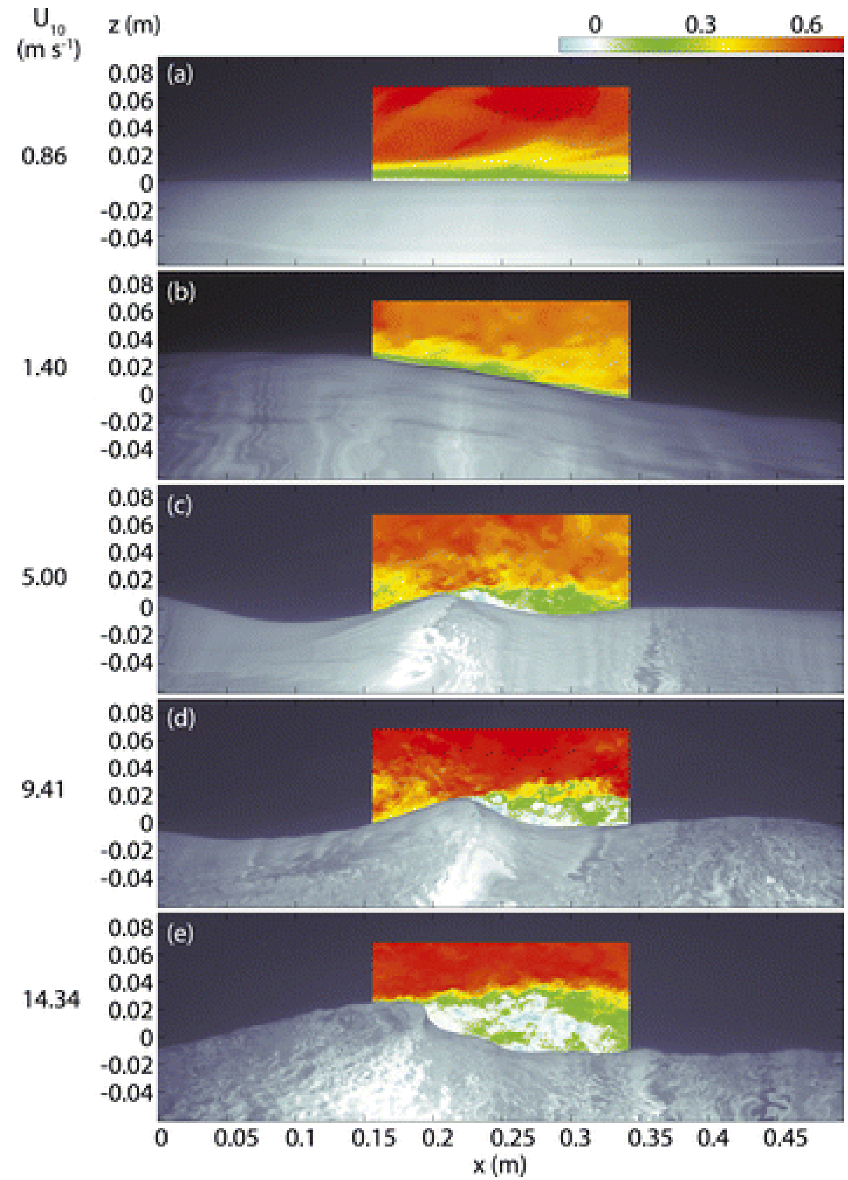
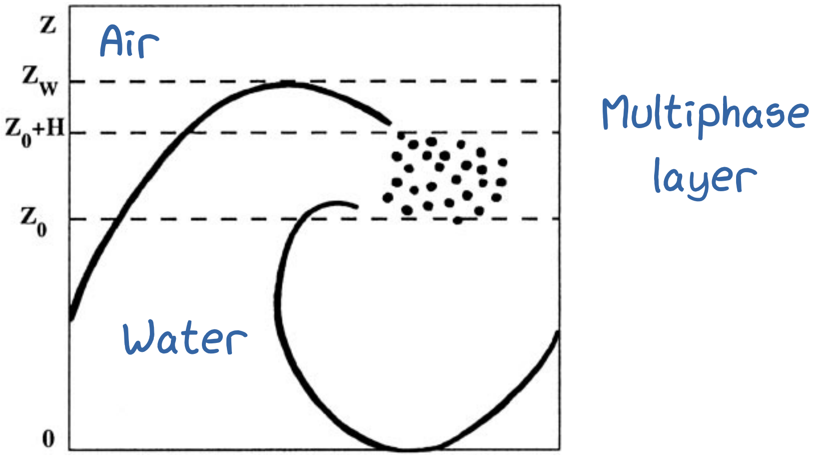


Van Dyke, An Album of Fluid Motion (1982)

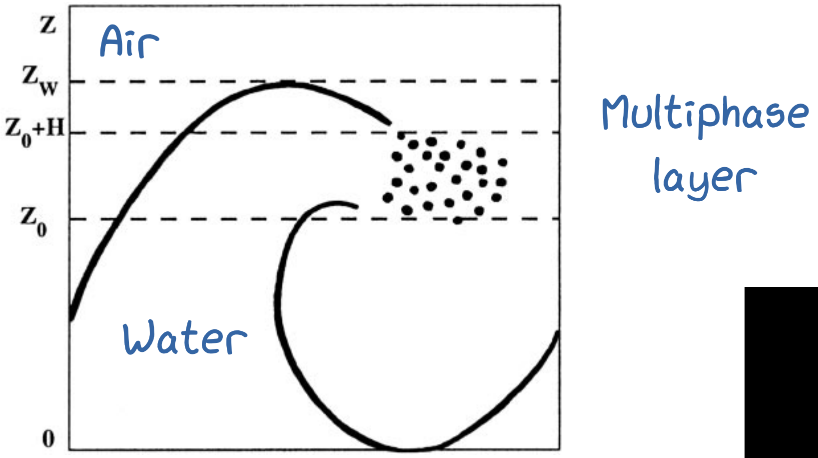
Buckley and Veron (2016), JPO

Spray and bubbles form a multiphase layer that suppresses turbulence

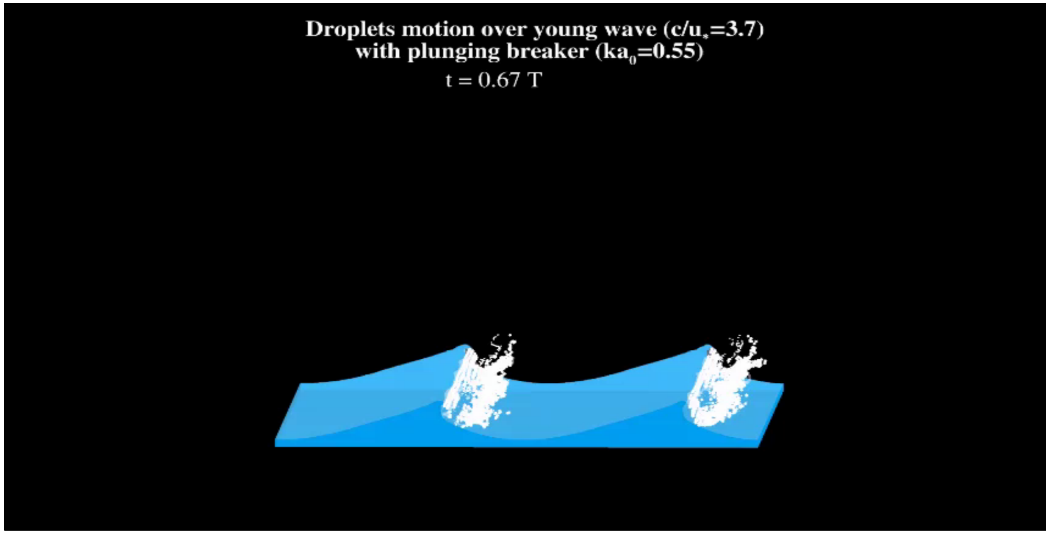


Barenblatt et al. (2005), PNAS

Spray and bubbles form a multiphase layer that suppresses turbulence

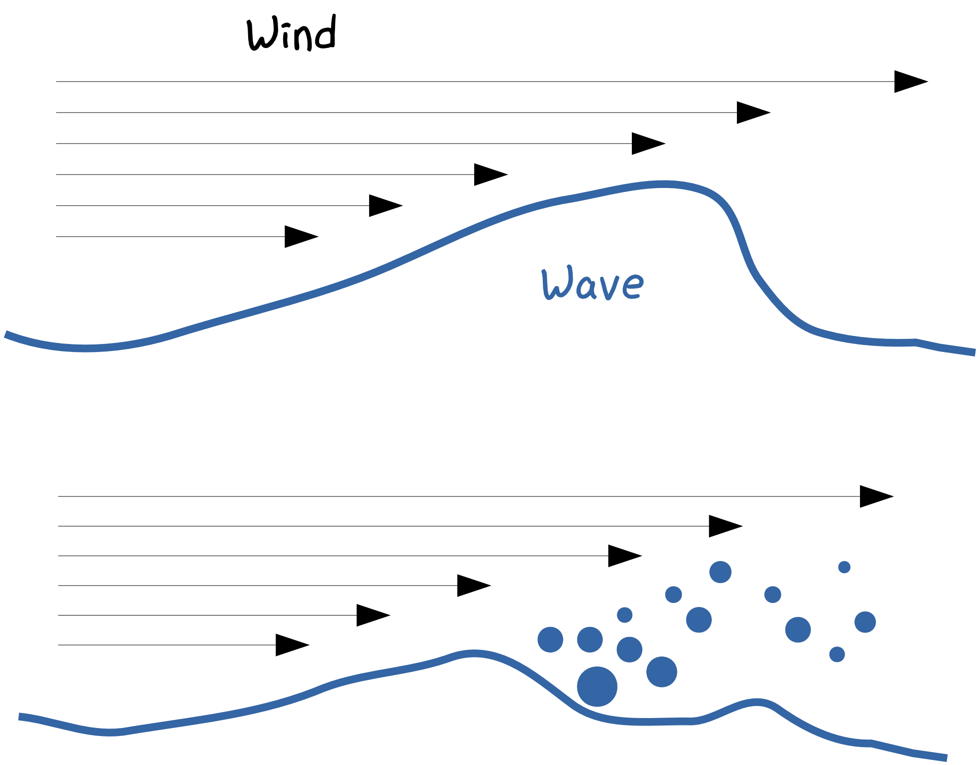


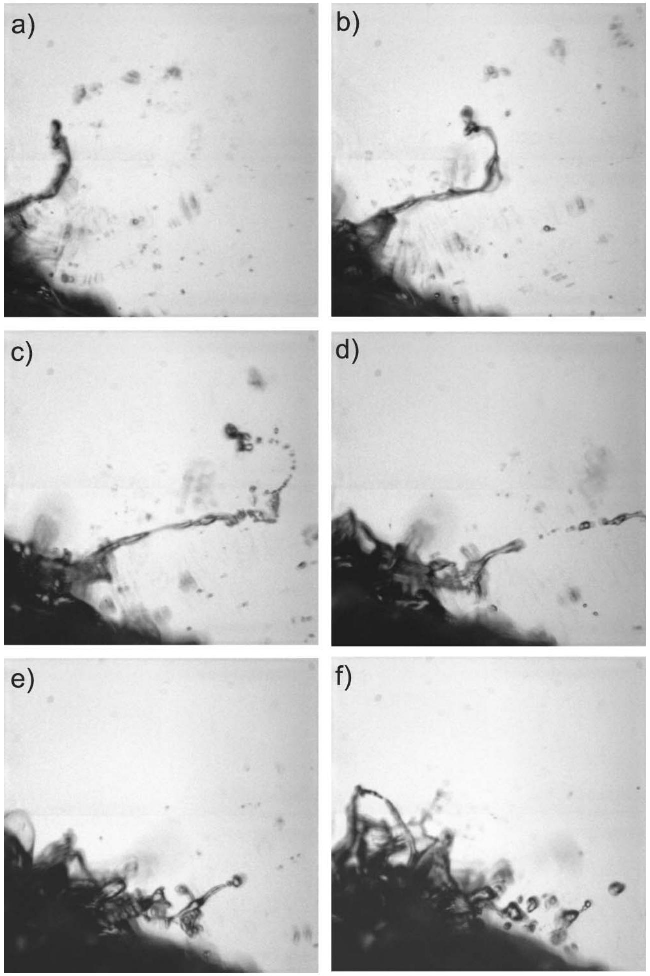
Barenblatt et al. (2005), PNAS



Tang et al. (2017), Atmosphere

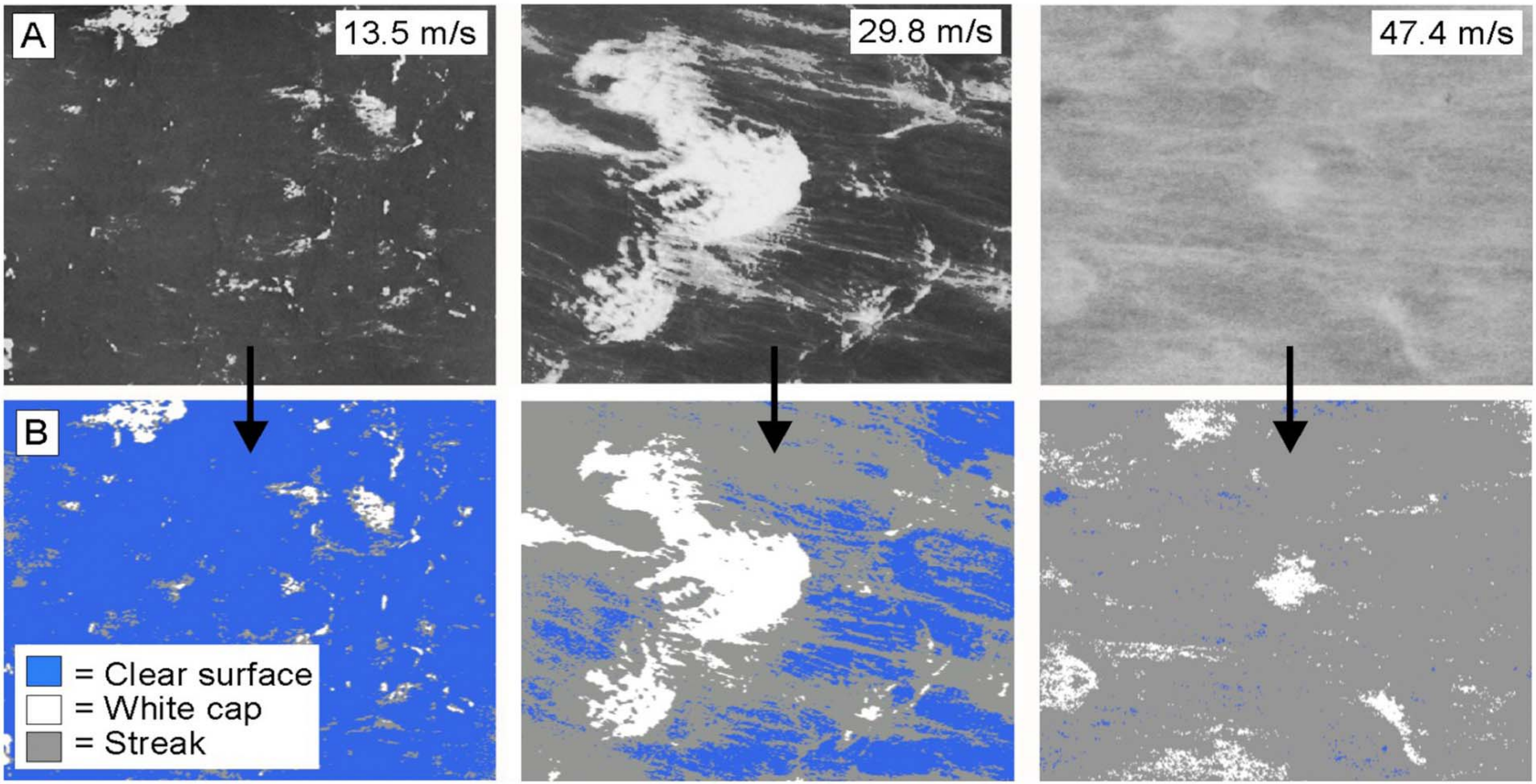
Wave tearing by direct wind impact creates spume and streaks





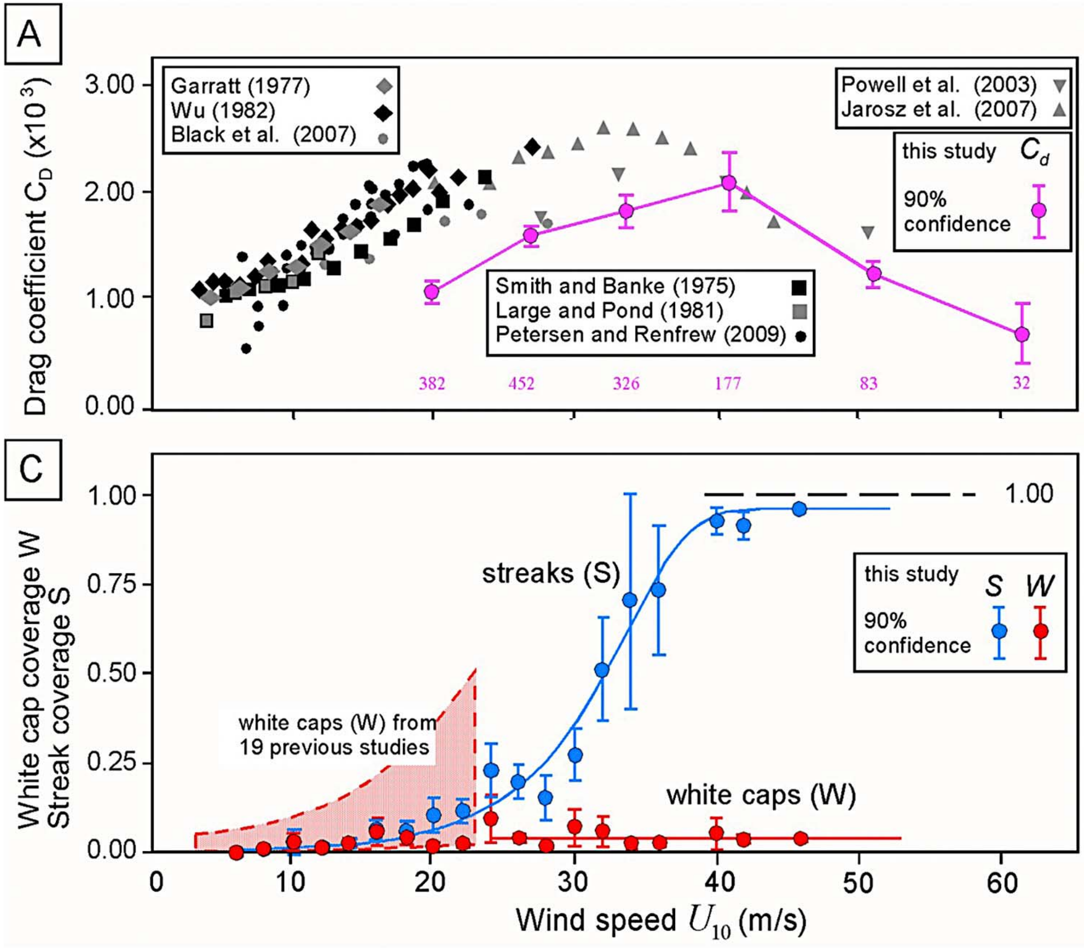
Veron et al. (2012), GRL

Whitecaps and *streaks*



Holthuijsen et al. (2012), JGR-Oceans

Whitecaps and *streaks*



Holthuijsen et al. (2012), JGR-Oceans

2012: Important year for waves and stress

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C00J23, doi:10.1029/2011JC007787, 2012

Modeling waves and wind stress

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C09003, doi:10.1029/2012JC007983, 2012

Wind and waves in extreme hurricanes

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MTLSS Research Building
and SUSTAIN laboratory
led by Brian Haus and colleagues

Air-Sea Momentum Transfer in Extreme Wind Conditions

3-year NSF project with Brian Haus to quantify and parameterize drag in extreme winds

First year completed, two to go

This presentation is a summary of what we learned so far

Air-Sea Momentum Transfer in Extreme Wind Conditions

Year 1: Reproduce the momentum budget results by Donelan et al. (2004) with improved instruments and methods, and give error estimates

Year 2: Measure drag in extreme (Cat 5 hurricane) wind and waves, and derive the first wave growth parameterization

Year 3: Revise existing wave growth function and evaluate it in coupled atmosphere-wave-ocean simulations of real hurricanes

Momentum budget in the laboratory

$$\underbrace{\cancel{\frac{\partial \rho u}{\partial t}}}_{\text{Tendency}}^{\text{Steady state}} + \underbrace{\cancel{\frac{\partial \rho u^2}{\partial x}}}_{\text{Advection}}^{\text{Small}} + \underbrace{\frac{1}{h}\frac{S_{xx}}{\partial x}}_{\text{Wave radiation stress}} = \underbrace{-\rho g \frac{\partial \overline{\eta}}{\partial x} - \frac{\partial p_a}{\partial x}}_{\text{Pressure gradient}} + \underbrace{\frac{\partial \tau}{\partial z}}_{\text{Surface stress}}$$

$$\tau = \underbrace{\rho g h \frac{\partial \overline{\eta}}{\partial x}}_{\text{Mean surface slope}} + \underbrace{h \frac{\partial p_a}{\partial x}}_{\text{Pressure gradient}} + \underbrace{\frac{S_{xx}}{\partial x}}_{\text{Wave radiation stress}} + \underbrace{\tau_B}_{\text{Bottom stress}}$$

Momentum budget in the laboratory

$$\tau = \rho g h \frac{\partial \overline{\eta}}{\partial x} + h \frac{\partial p_a}{\partial x} + \frac{S_{xx}}{\partial x} + \tau_B$$

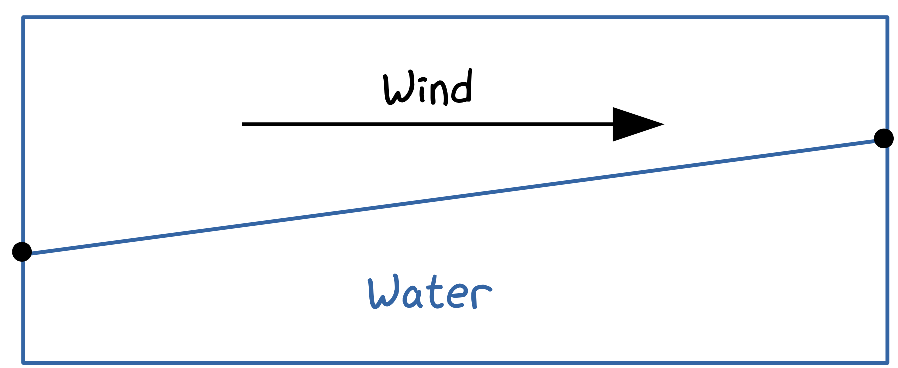
Mean surface slope

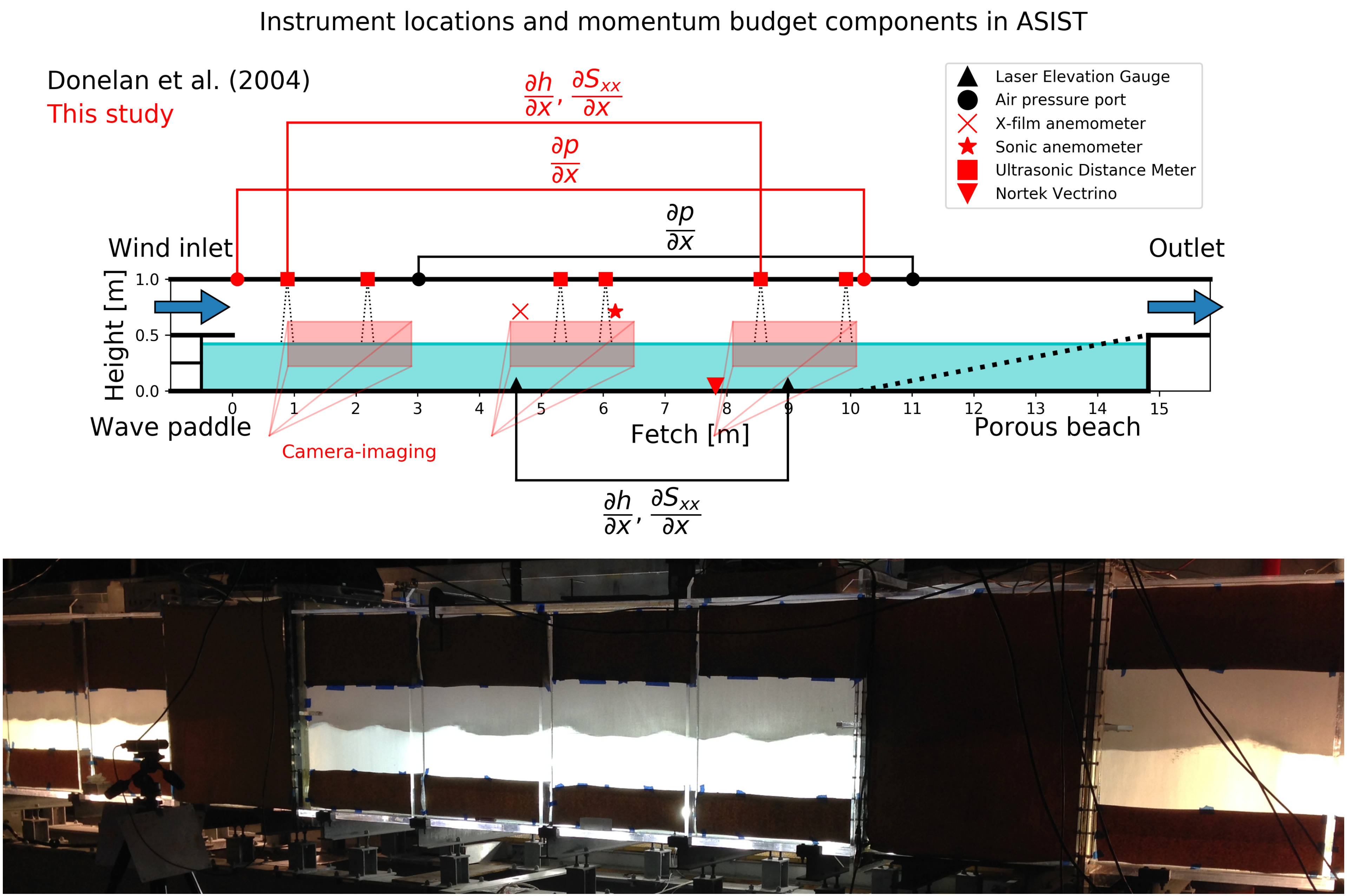
Pressure gradient

Wave radiation stress

Bottom stress

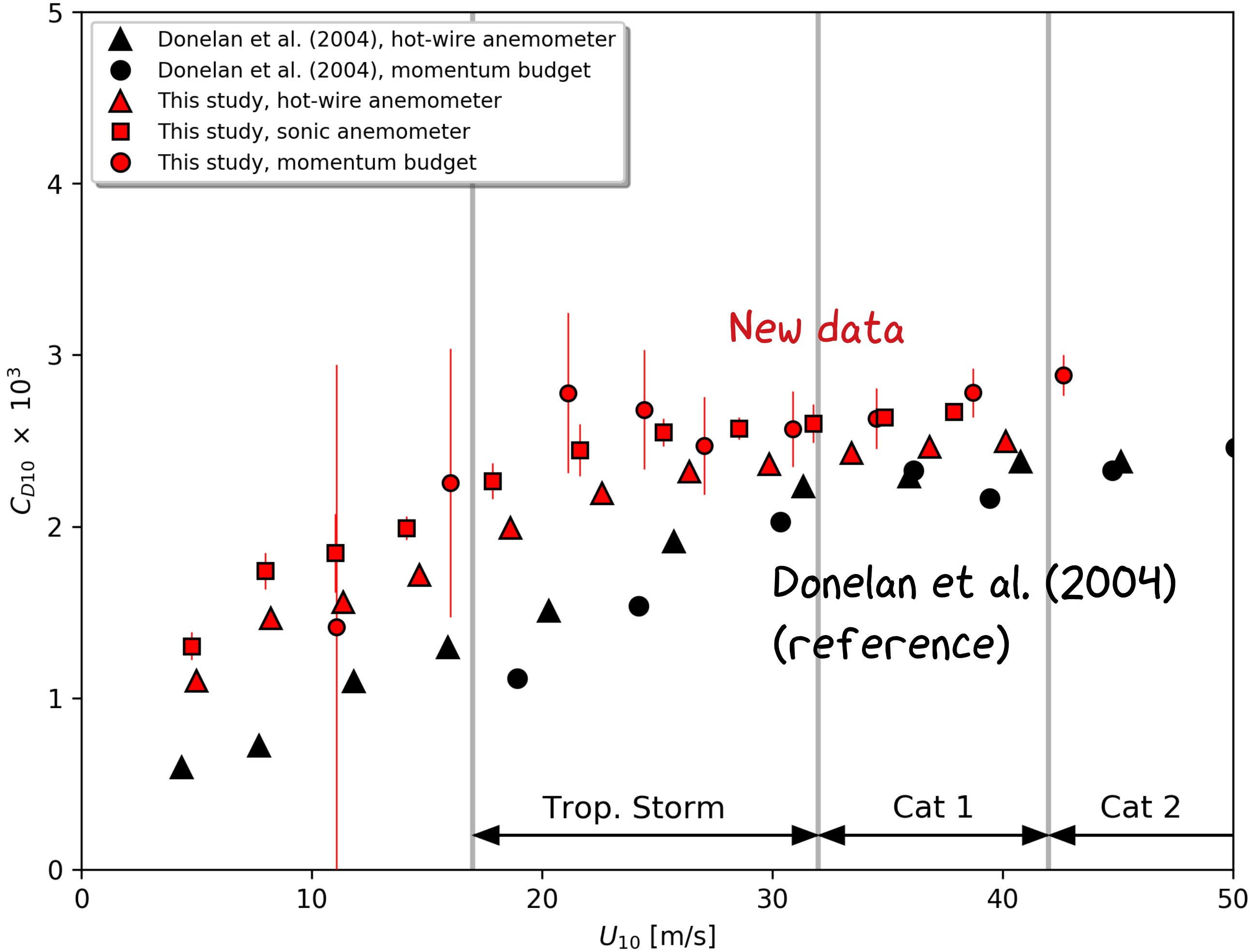
Measure air pressure
And water surface elevation
at control sections



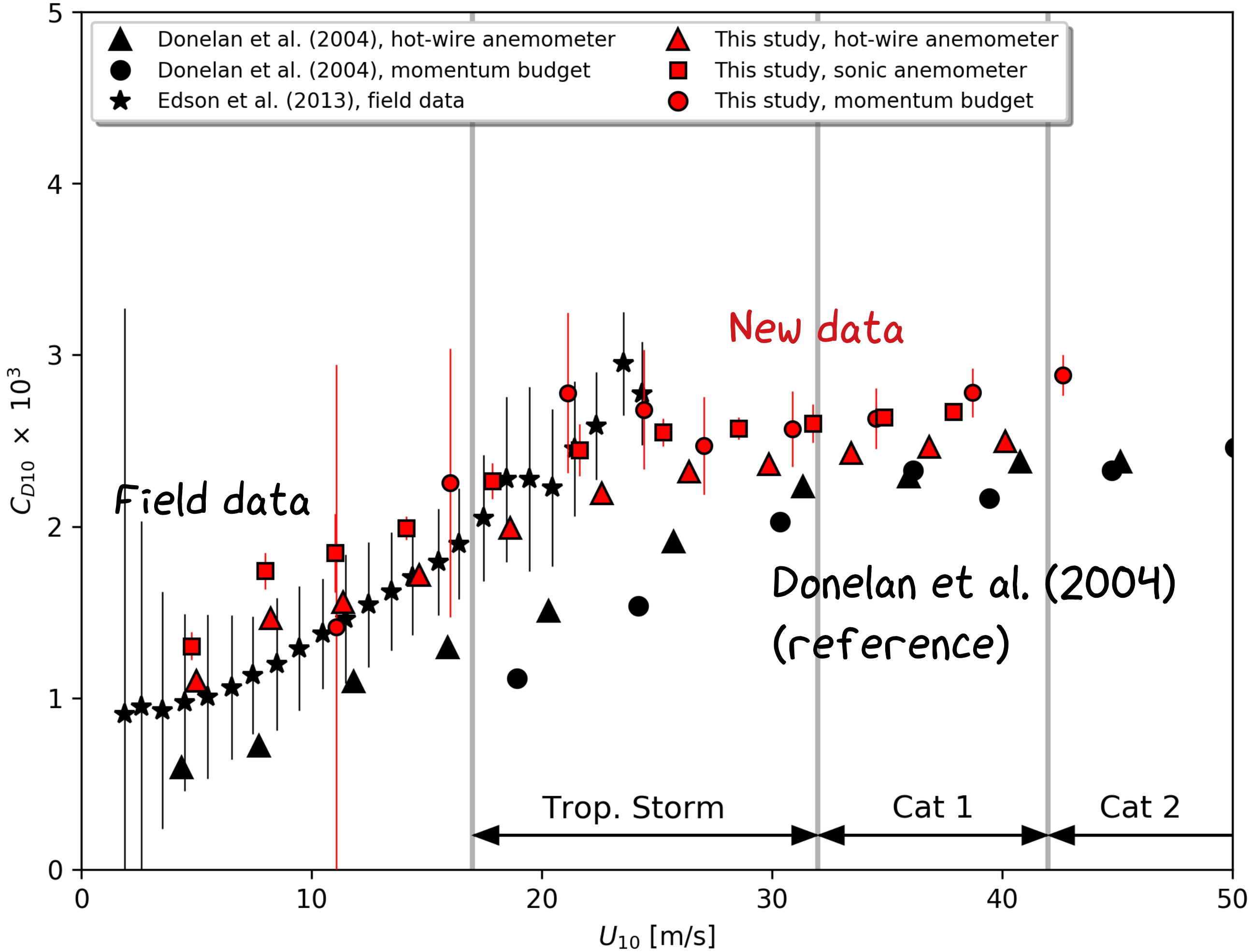


Instrument locations and momentum budget components in ASIST
Donelan et al. (2004)
This study
$\frac{\partial h}{\partial x}, \frac{\partial S_{xx}}{\partial x}$
$\frac{\partial p}{\partial x}$
$\frac{\partial p}{\partial x}$
Laser Elevation Gauge
Air pressure port
X-film anemometer
Sonic anemometer
Ultrasonic Distance Meter
Nortek Vectrino
Wind inlet
Outlet
Height [m]
1.0
0.5
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Wave paddle
Fetch [m]
Porous beach
Camera-imaging
$\frac{\partial h}{\partial x}, \frac{\partial S_{xx}}{\partial x}$

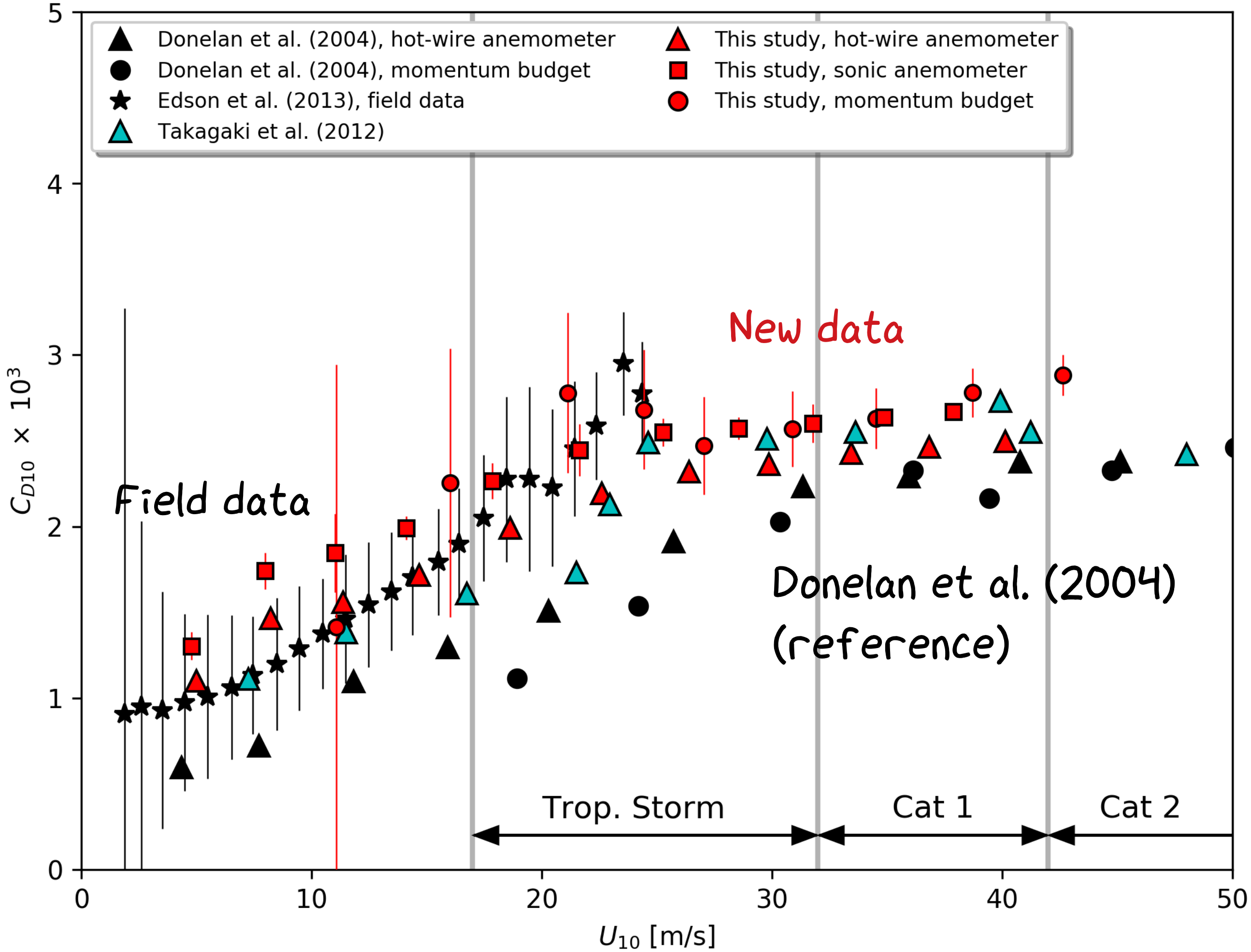
Drag coefficient in ASIST



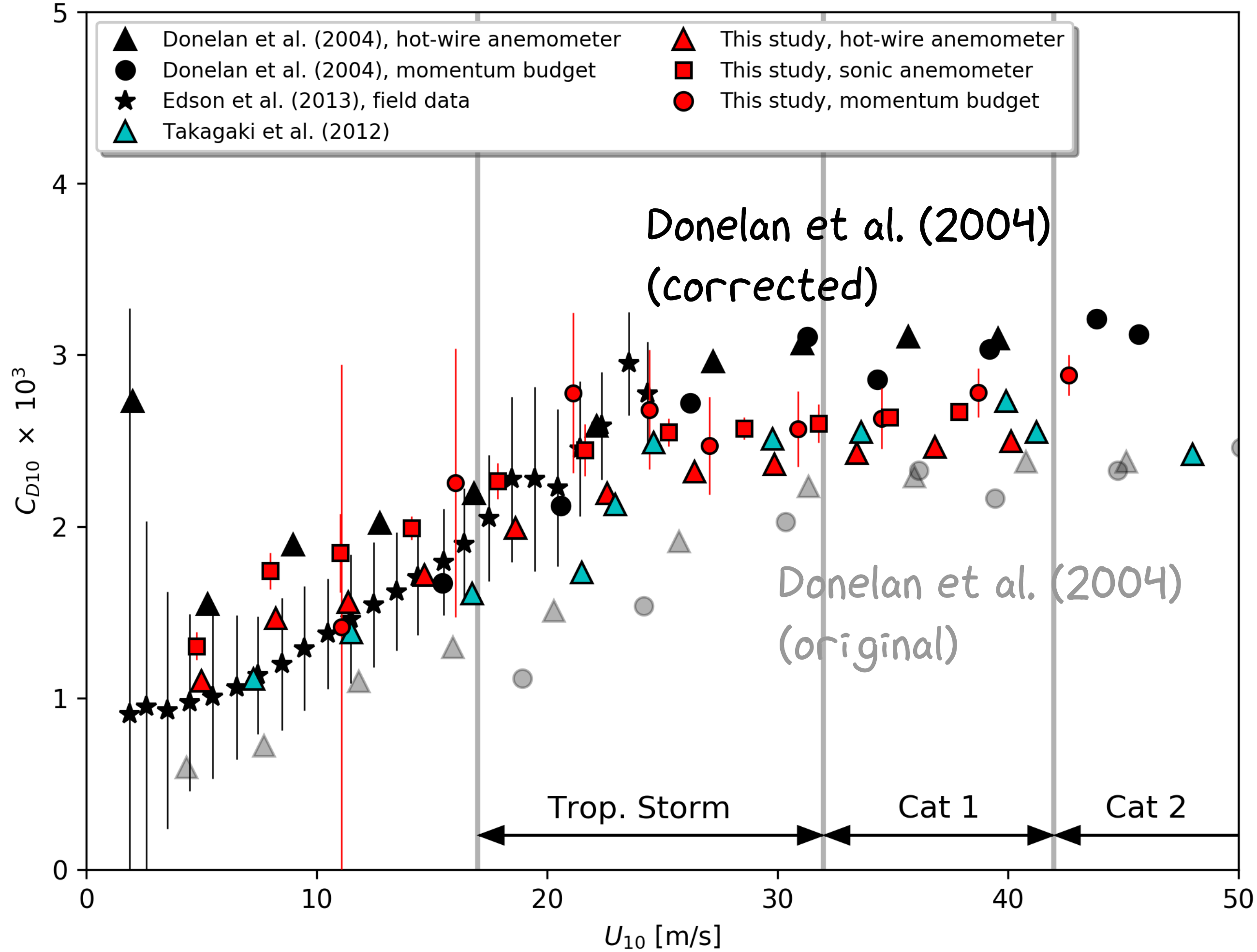
Drag coefficient in ASIST



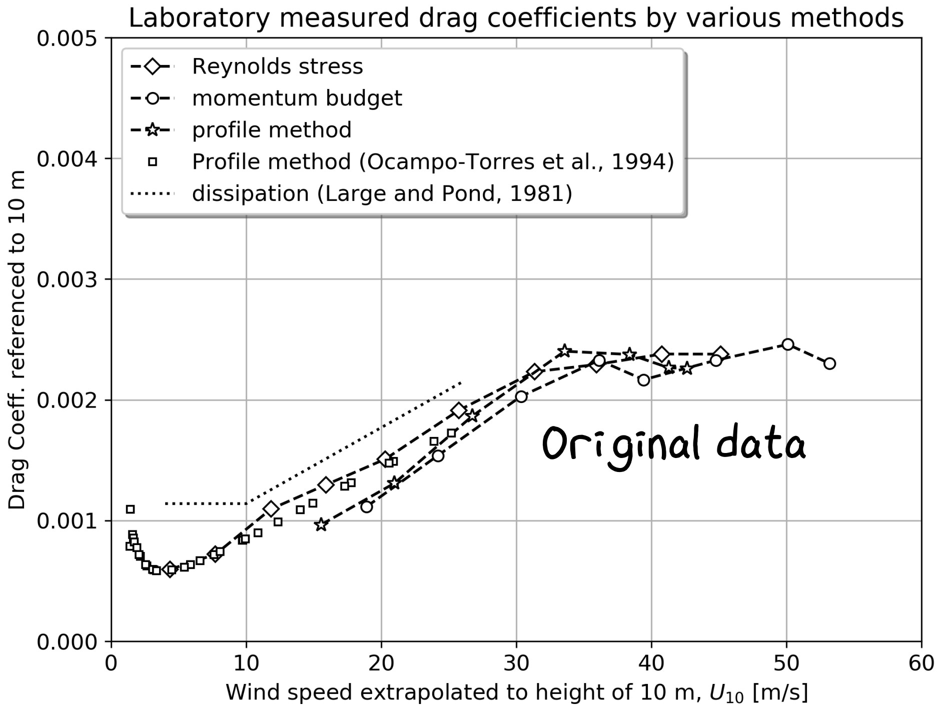
Drag coefficient in ASIST

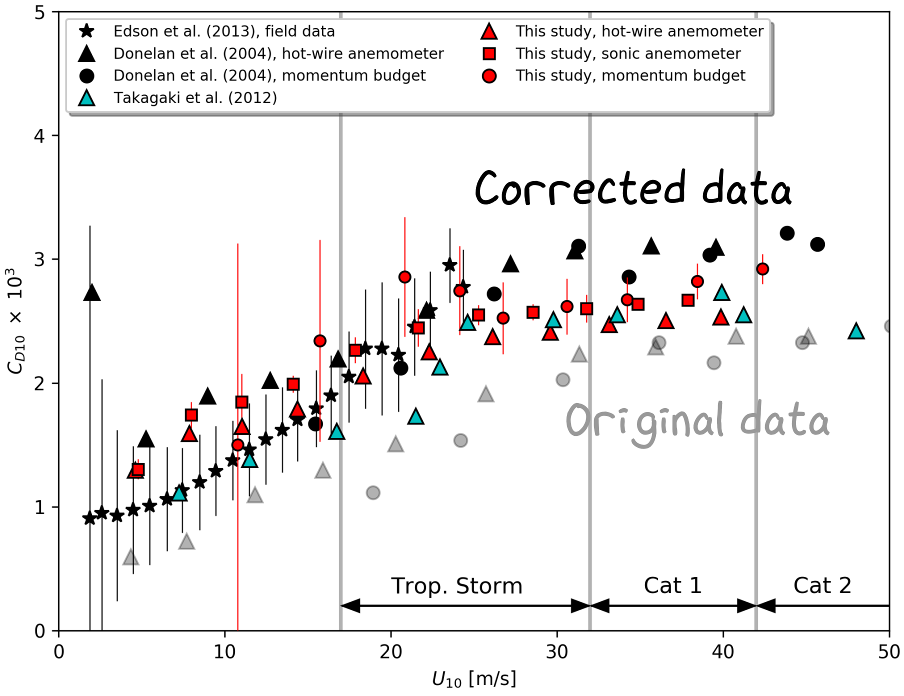


Drag coefficient in ASIST



Correction to Donelan et al. (2004) data





We have the original data, and we have the original code...

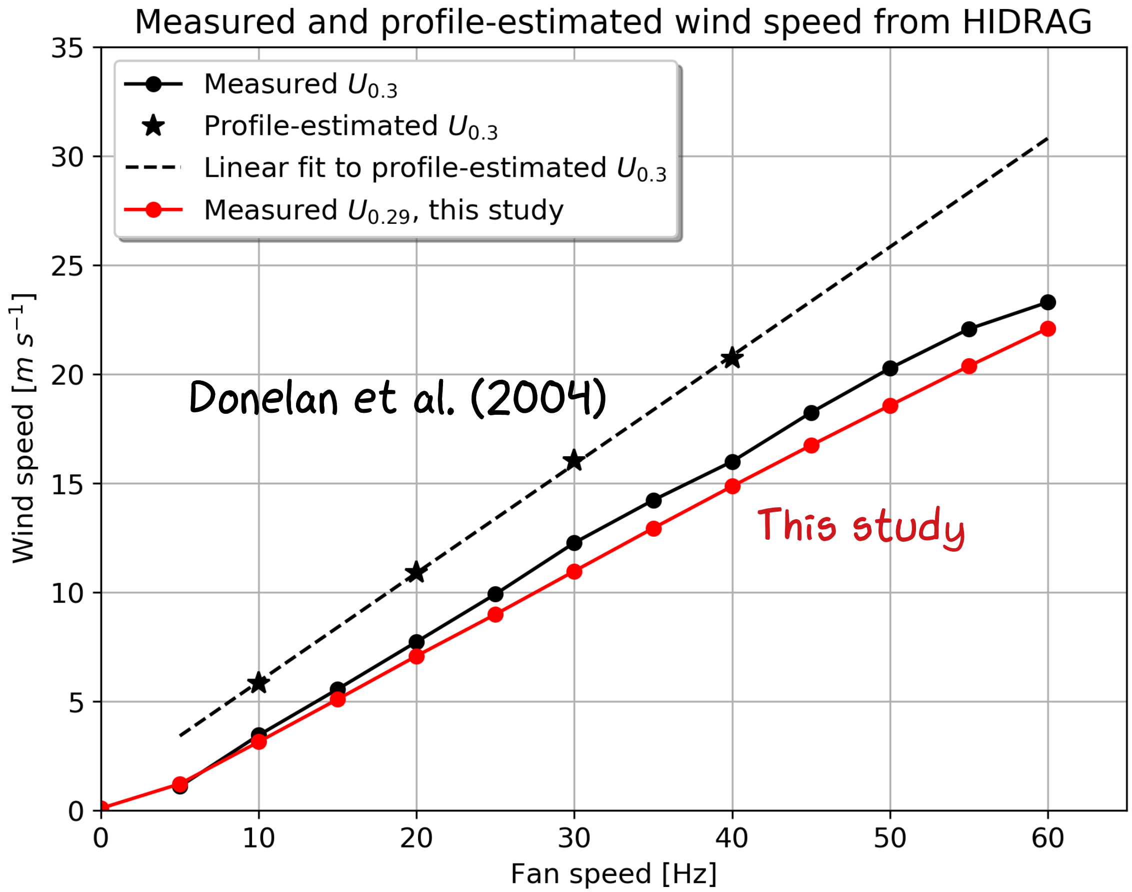
Scaling wind and stress to reference height

Friction velocity

$$U_{10} = U_z + \frac{u_*}{\kappa} \log\left(\frac{10}{z}\right)$$

Measured wind speed

$$C_D = \frac{u_*^2}{{U_{10}}^2}$$



Correction to Donelan et al. (2004) data

Compute friction velocity from original data:

$$u_* = \sqrt{C_D} U_{10}$$

Compute new 10-meter wind speed using measured wind speed and friction velocity:

$$U_{10} = U_z + \frac{u_*}{\kappa} \log\left(\frac{10}{z}\right)$$

Compute new 10-meter drag coefficient using corrected 10-meter wind speed and friction velocity:

$$C_D = \left(\frac{u_*}{U_{10}}\right)^2$$

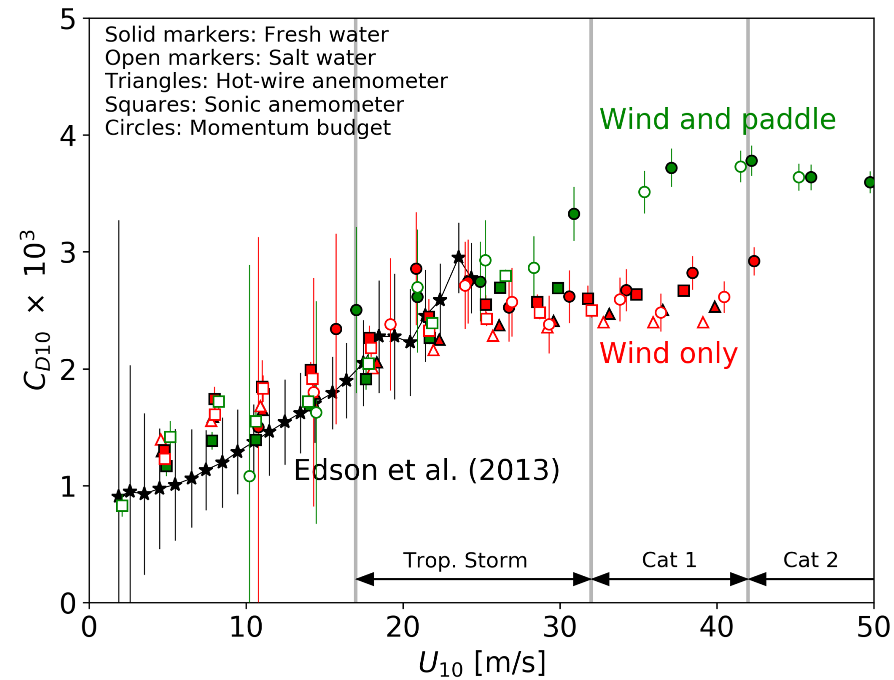
Influence of paddle waves on drag coefficient

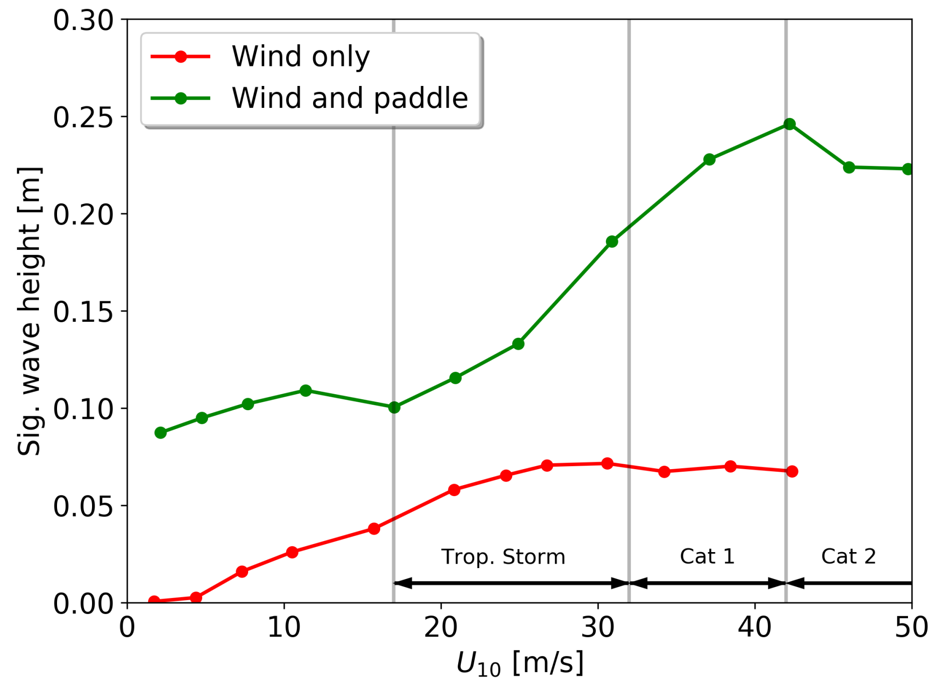
Monochromatic paddle wave:
- 0.08 m significant height
- 1 s period

Example snapshot from high-speed imaging

- Drag saturates at a higher level and at higher wind speed

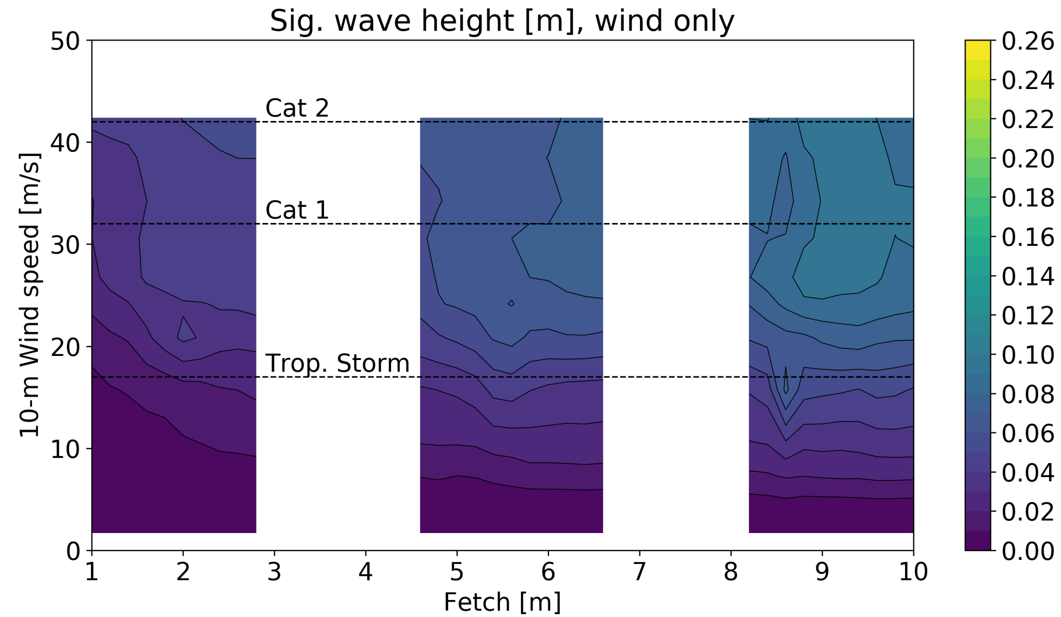
- Drag saturation is correlated with saturation in wave development

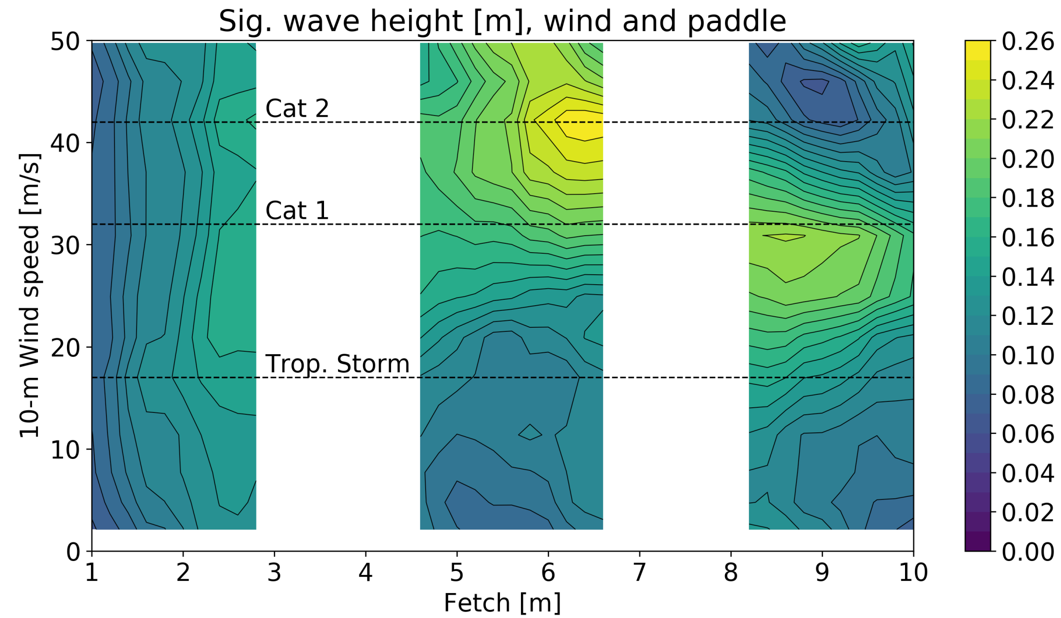


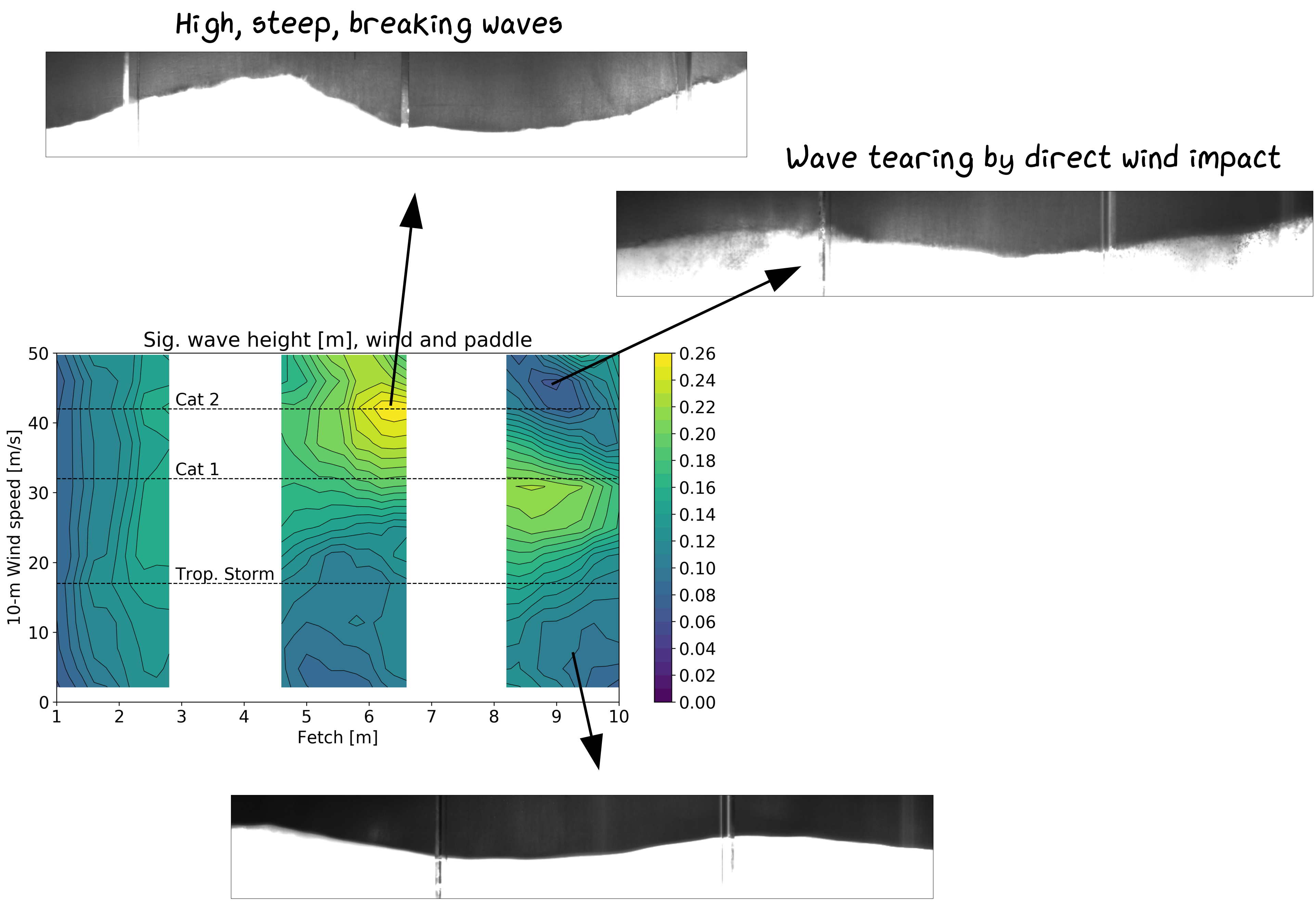


Fetch-limited growth
from high-speed camera imaging

- Wave heights saturate at U10 ~ 25 m/s in wind-only experiments
- Waves can grow well beyond the previous limit when we introduce a background paddle wave
- Wave saturation is fetch-dependent

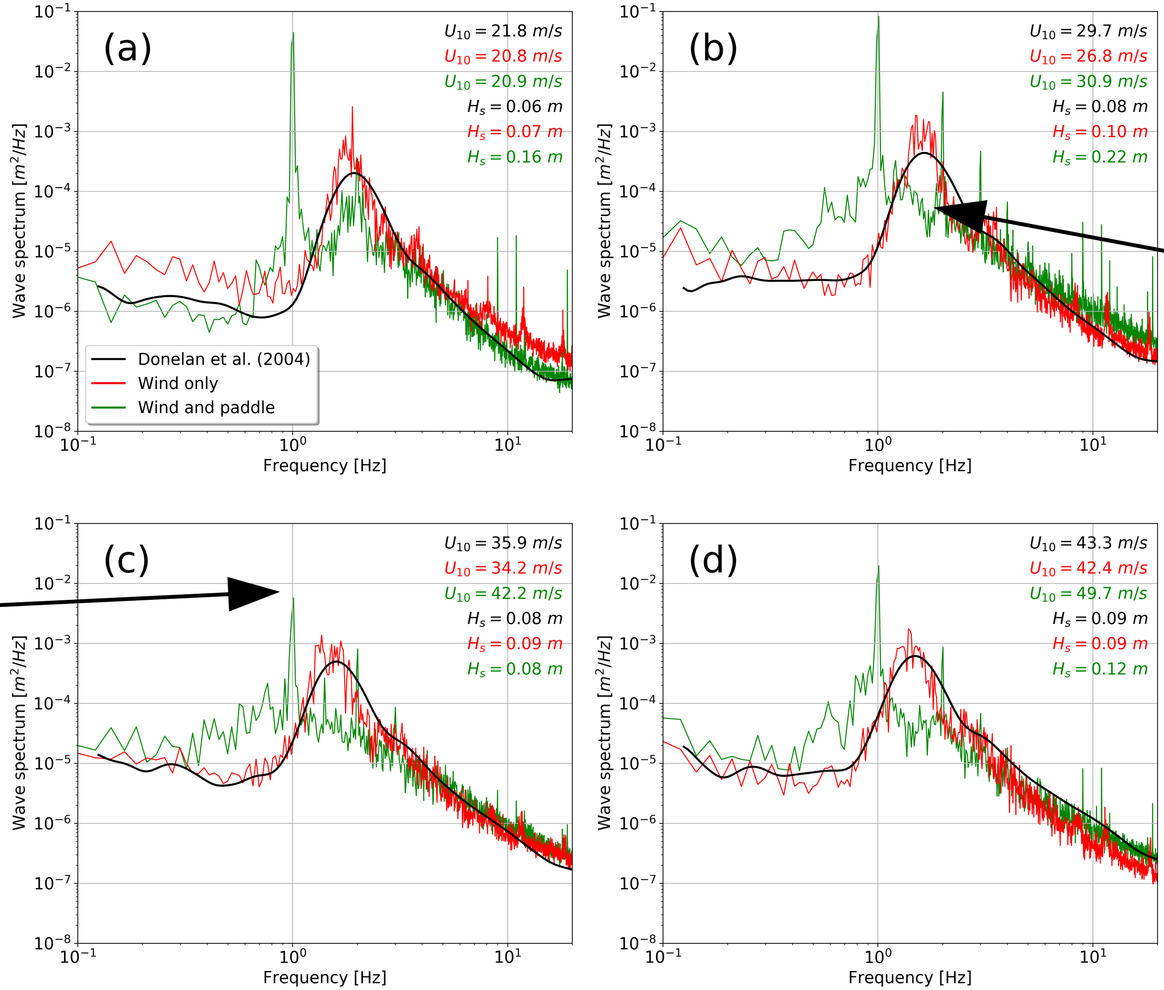






High, steep, breaking waves
Wave tearing by direct wind impact
Sig. wave height [m], wind and paddle
Cat 2
Cat 1
Trop. Storm
10-m Wind speed [m/s]
Fetch [m]
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26

Evidence of sheltering and wave tearing by wind

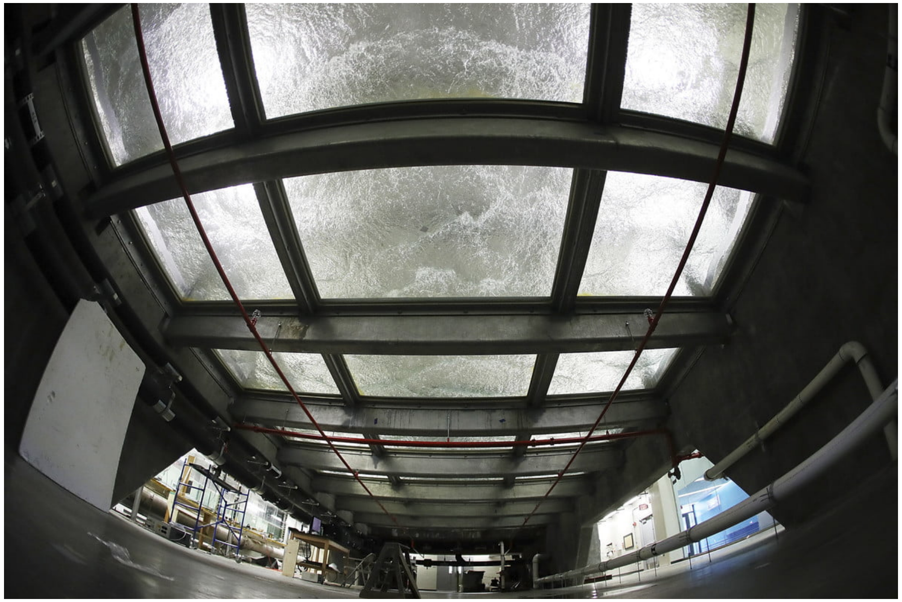


Sheltering by the paddle wave

Intense wave tearing by wind

Next steps

The SUSTAIN wind-wave tank



Connecting waves and stress

Wave energy balance (models):

$$\frac{\partial F}{\partial t} + \frac{\partial(\mathbf{C_g} F)}{\partial \mathbf{x}} + \frac{\partial(\dot{k} F)}{\partial k} + \frac{\partial(\dot{\theta} F)}{\partial \theta} = S_{in} + S_{ds} + S_{nl}$$

Wave growth function:

$$S_{in}(k,\theta) = A \left| U_{\lambda/2} \cos\phi - C_p \right| \left(U_{\lambda/2} \cos\phi - C_p \right) \frac{k\omega}{g} \frac{\rho_a}{\rho_w} F(k,\theta)$$

Sheltering coefficient

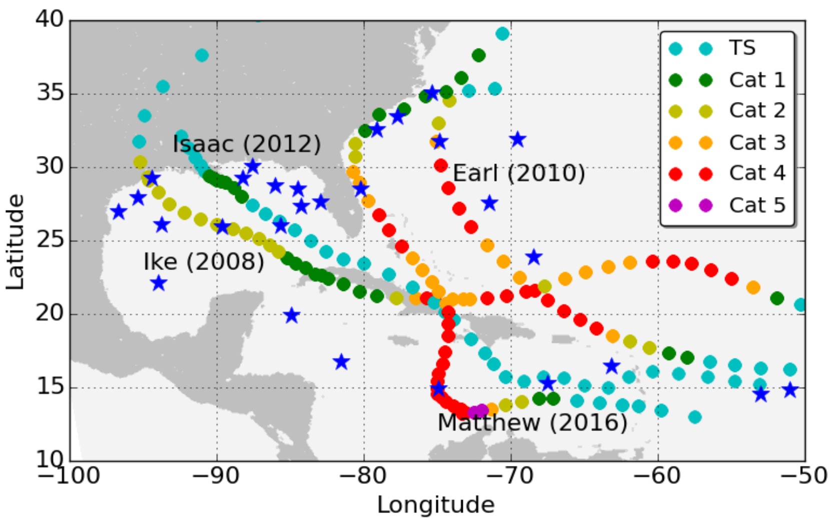
A tunable parameter or a complex function?

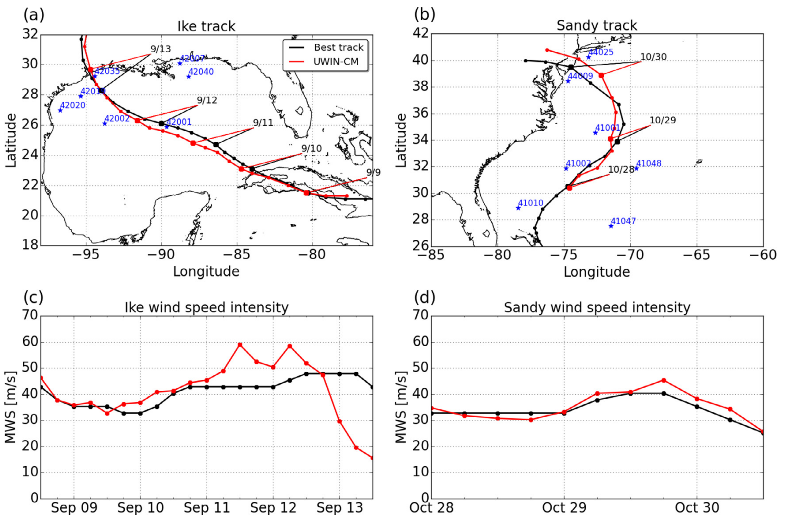
Form drag (vector!):

$$\tau_{\mathbf{f}} = \rho_w g \int_0^{2\pi} \int_0^{\infty} \frac{S_{in}}{C_p} \mathbf{k} \, dk \, d\theta$$

Donelan et al. (2012), JGR

Evaluate the new air-sea physics using coupled modeling of real hurricanes

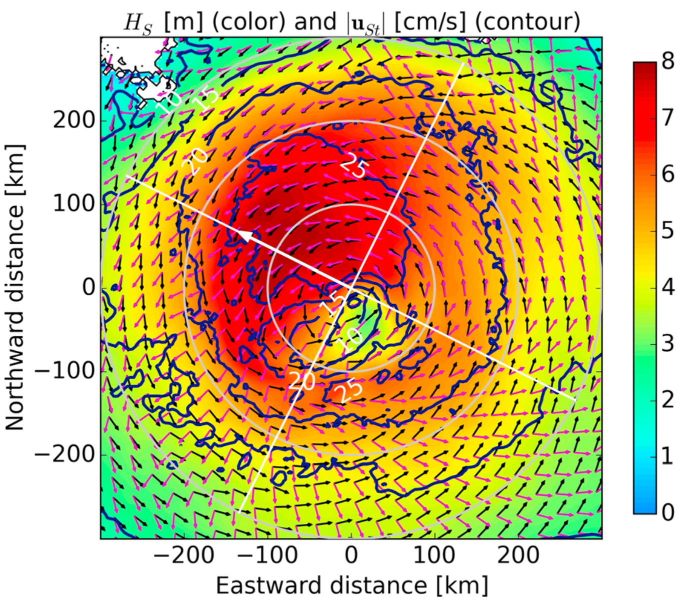




Chen and Curcic (2016), Oce. Mod.

- Focus on hurricanes:
  - Matthew (2016)
  - Irma (2017)
  - Maria (2017)
  - Michael (2018)
  - Dorian (2019)

- Coupled atmosphere-wave-ocean simulations with WRF and University of Miami Wave Model @ ~ 1 km resolution



Curcic et al. (2016), GRL

Takeaways

We can reproduce drag saturation in the laboratory,
previously discovered by Donelan et al. (2004)

In the process, we found an error in the previous results
and propose a correction

The correction may have important implications
for weather and ocean prediction

Wave growth and drag in strong winds is sensitive
to the presence of background paddle waves

Preparing to measure drag and waves
in extreme (Cat 5) hurricane conditions in SUSTAIN

Thanks!

(it takes a village)

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