New Platforms for the Development of COARE 4.0

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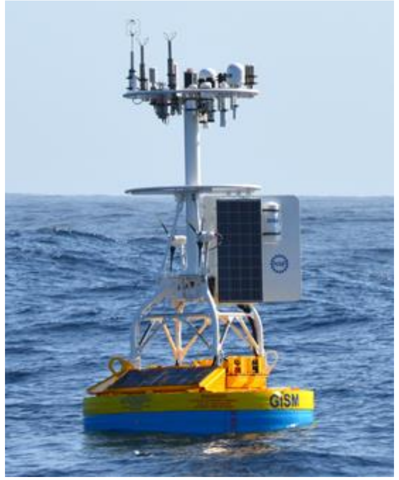
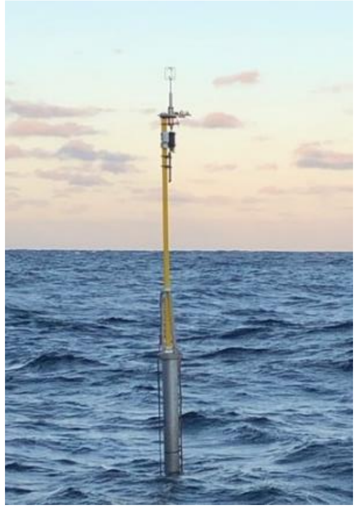
CLIMODE
Year long



OOI
Real-time Fluxes

SPURS
Latent Heat Flux



X-Spar
Long duration
Real-time Fluxes

Saildrone
Long duration
Mobile

Direct measurement of momentum, heat and moisture exchange (fluxes) in the marine surface layer

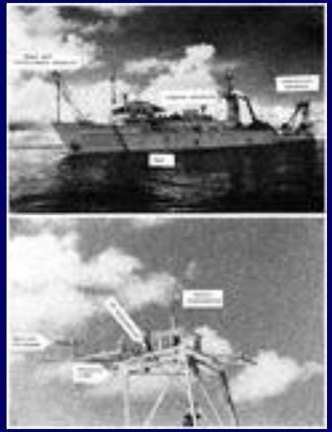
Momentum Flux: $\tau_o = \rho_a \overline{uw} = \rho_a C_D S_r \Delta U$ — Drag Coefficient

Sensible Heat Flux: $Q_H = \rho_a c_p \overline{wT} = \rho_a c_p C_H S_r \Delta \Theta$ — Stanton Number

Latent Heat Flux: $Q_E = \rho_a L_v \overline{wq} = \rho_a L_v C_E S_r \Delta Q$ — Dalton Number

- Moving platforms require motion correction of anemometers
- Minimize flow distortion
- Add capabilities $\mathrm{E} = Q_E/(\rho_w L_v)$

Saildrone
Mobile Fluxes



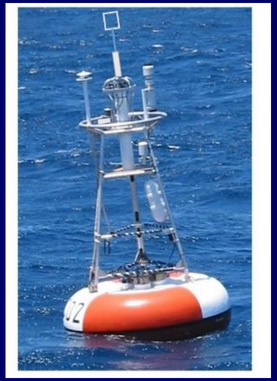
1992 TOGA COARE

2017 NASA SPURS

Air-Sea Interaction Spar (ASIS)

CLIMODE
Year long

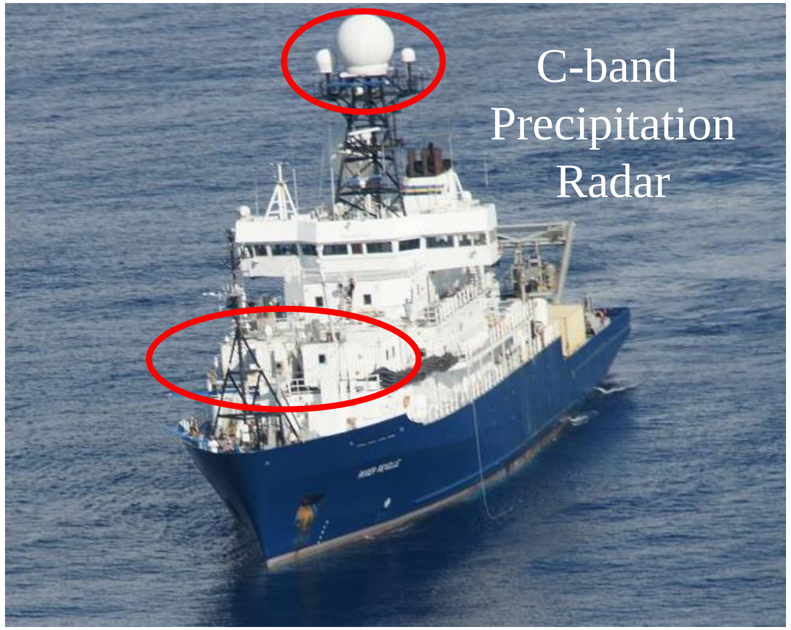
SPURS
Latent Heat Flux

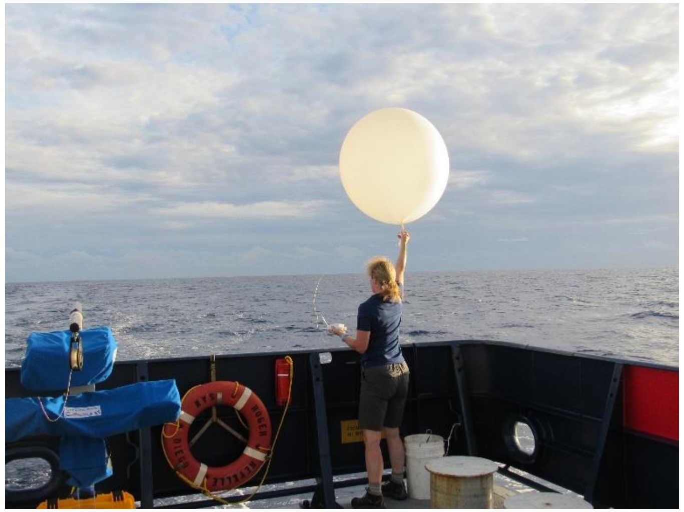


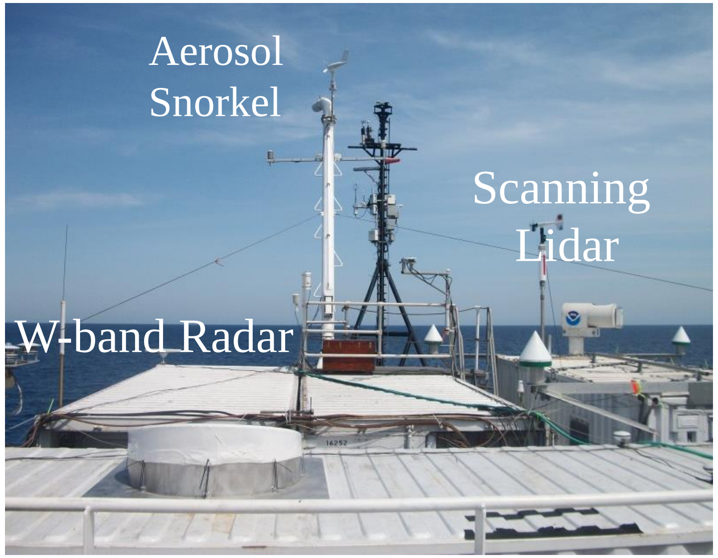
OOI, TPOS & XSpar
Real-time Fluxes

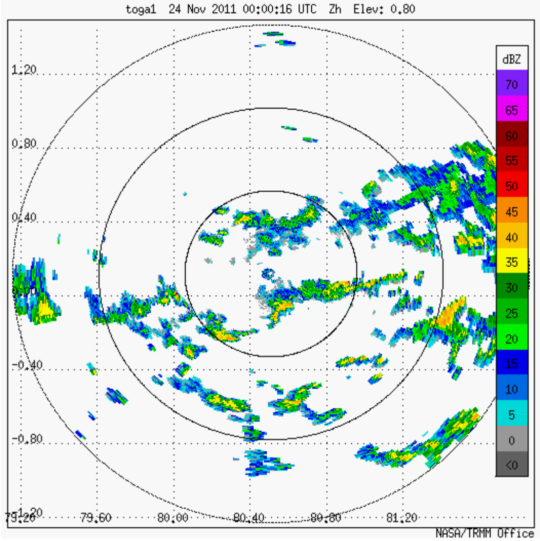
Ships

- Ships will remain an important component of air-sea interaction research for the foreseeable future
- They support instrumentation to estimate fluxes (bulk and DC).
- They support systems for remote sensing of the MABL and OBL
- Facilitate balloon soundings.



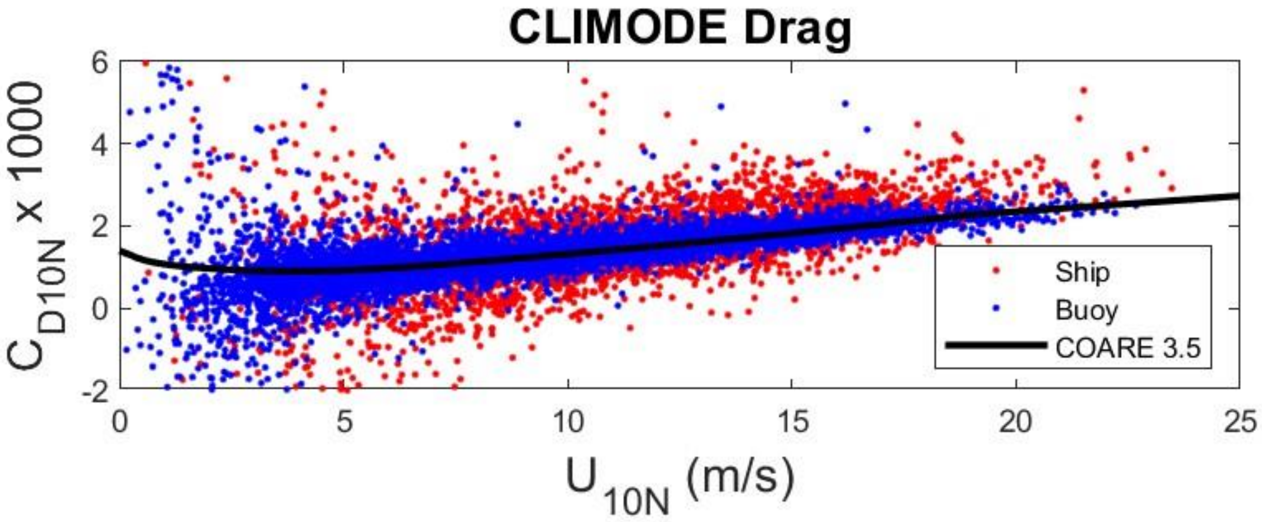


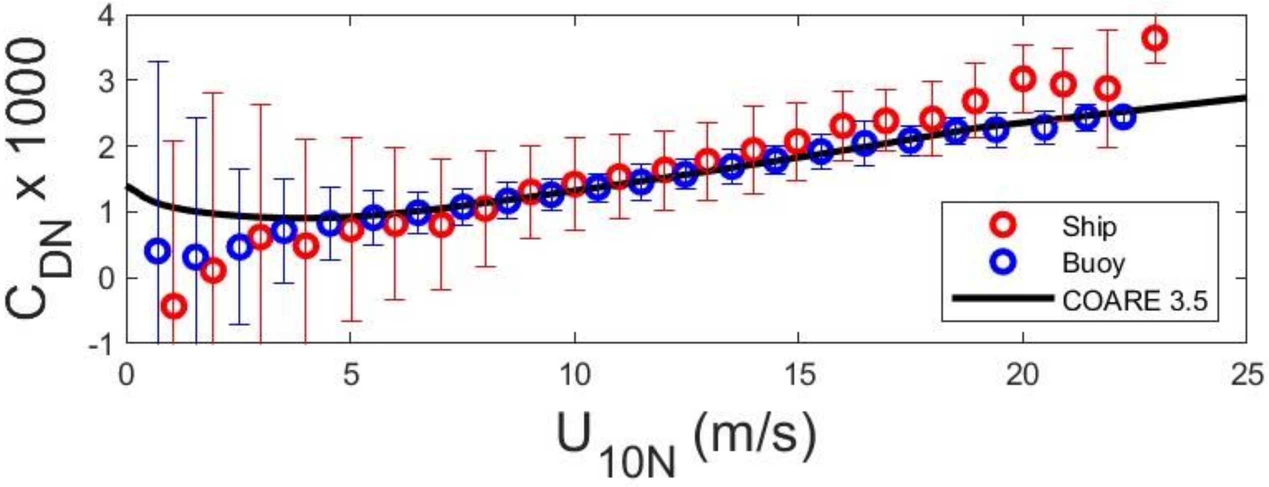




Ship Drag Coefficient – Flow Distortion

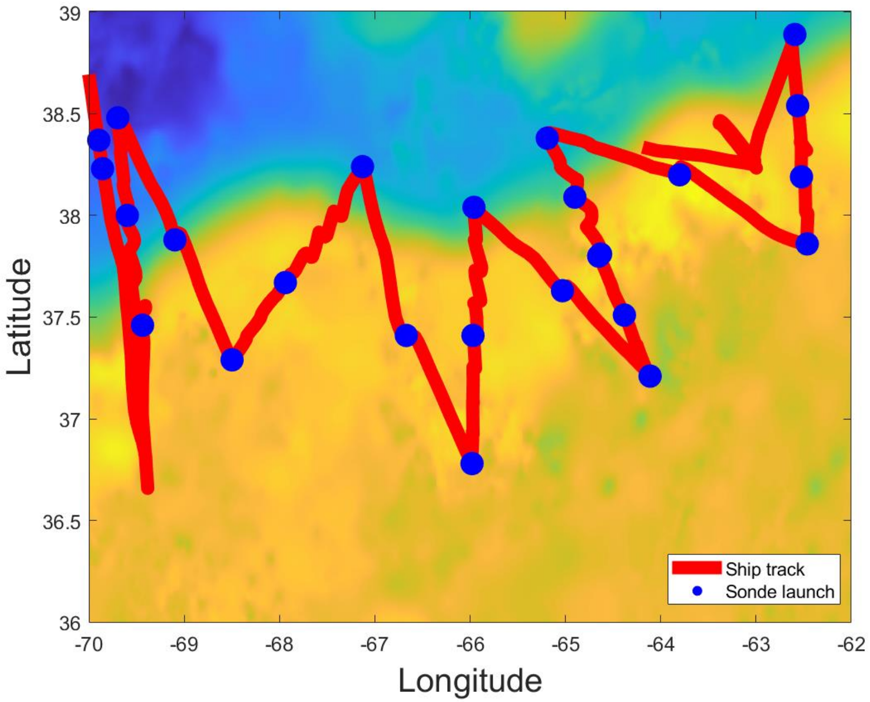
- Optimal placement of sensors based on wind tunnel results and high-resolution models.
- Empirical corrections for flow distortion on the means based on LIDAR and other measurements.
- New methodologies for reduced flow distortion such as:
  - Landwehr, S., N. O'Sullivan, and B. Ward, 2015: Direct flux measurements from mobile platforms at sea: Motion and airflow distortion corrections revisited. J. Atmos. Oceanic. Tech., 32, 1163- 1178.



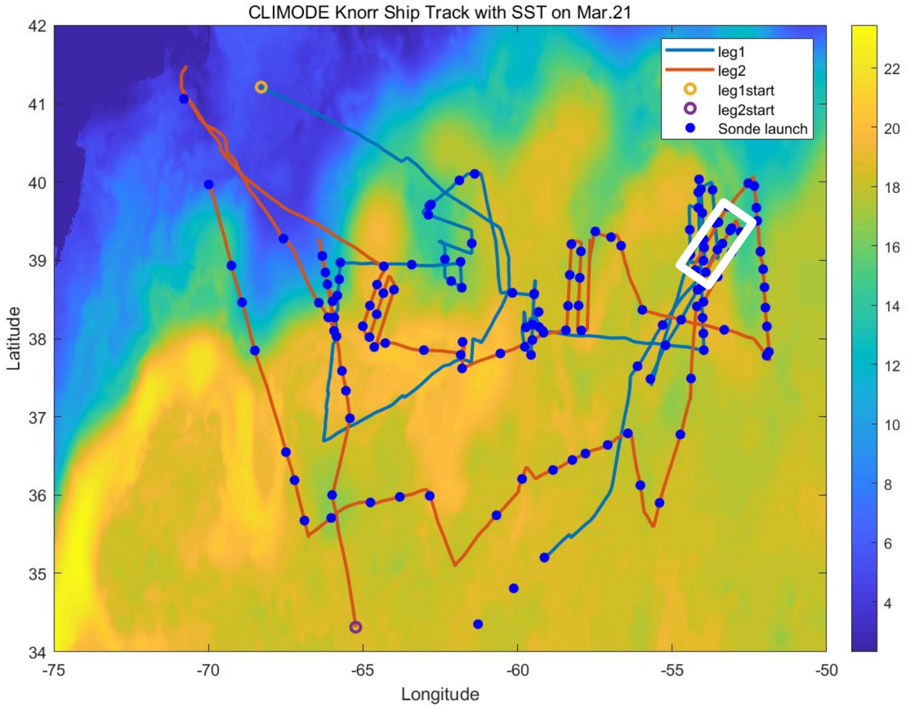


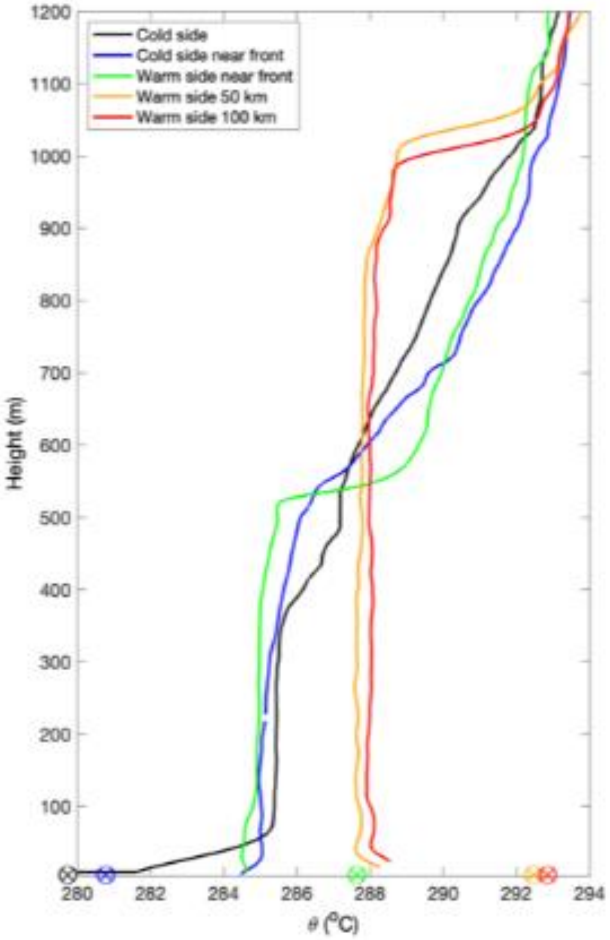
Ship Transects

CLIMODE Pilot Cruise (2006)



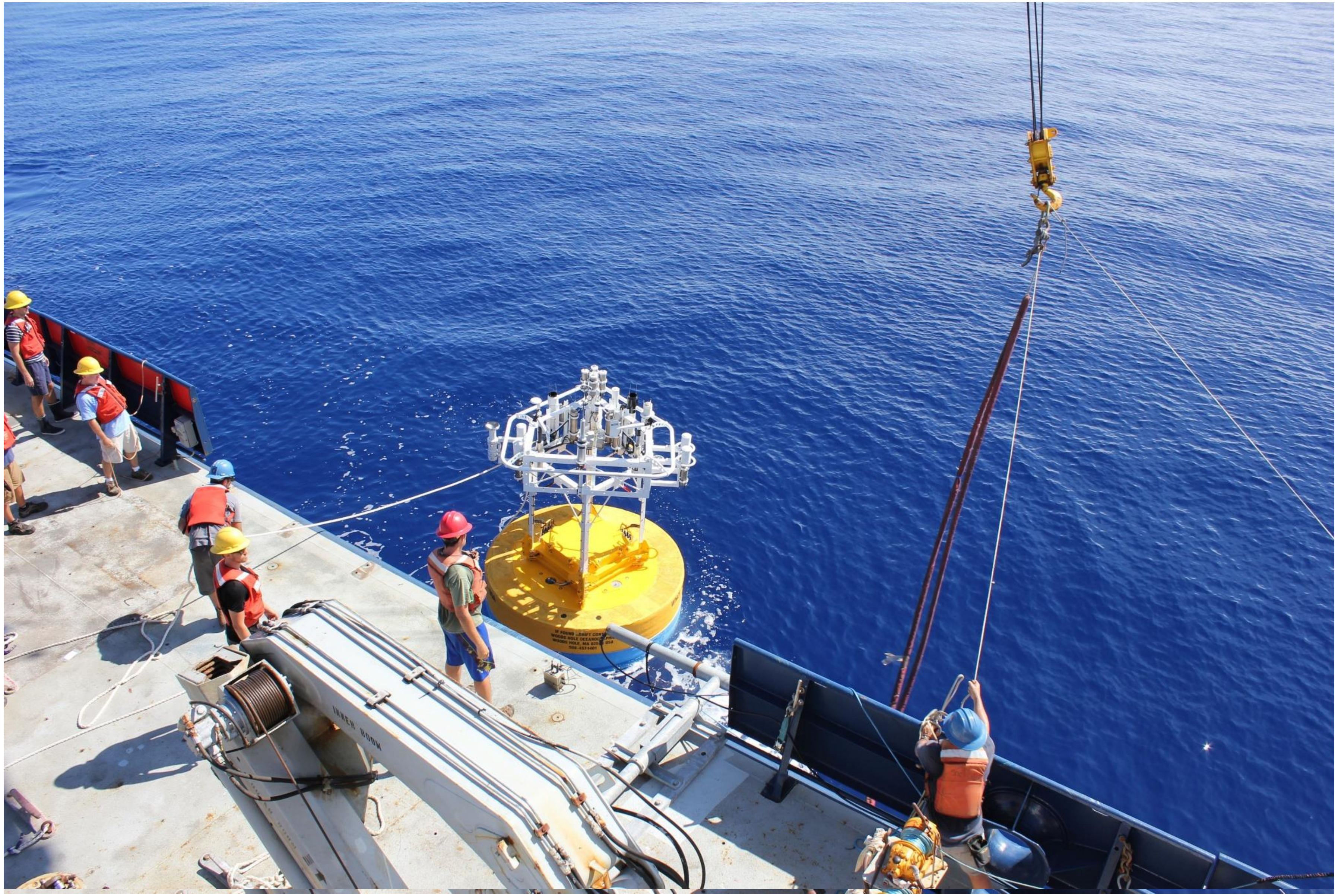
CLIMODE Main Cruise (2007)



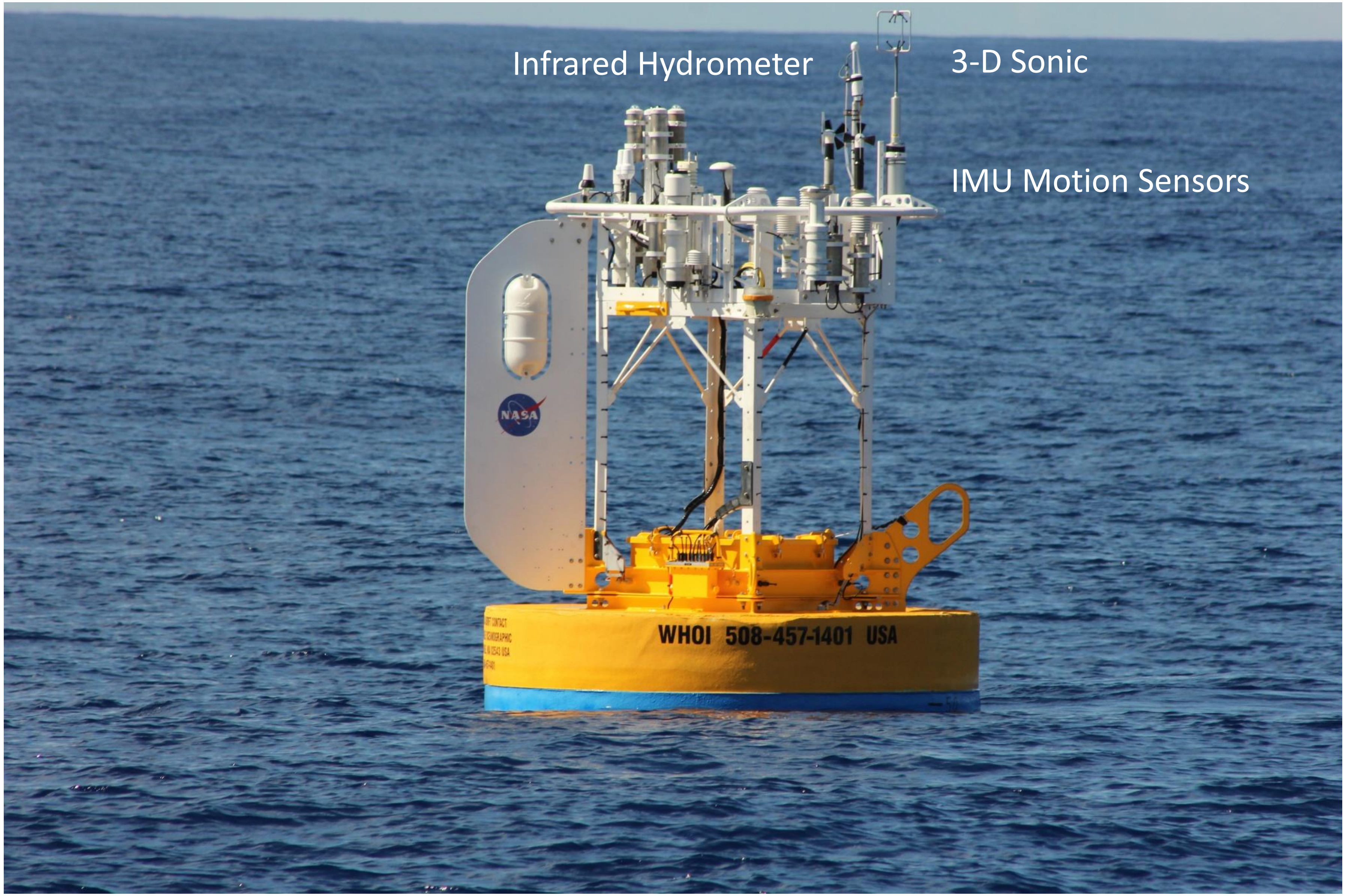


Some cruises need to be dedicated to Air-Sea Interaction

Surface Moorings from Ships



Surface Moorings



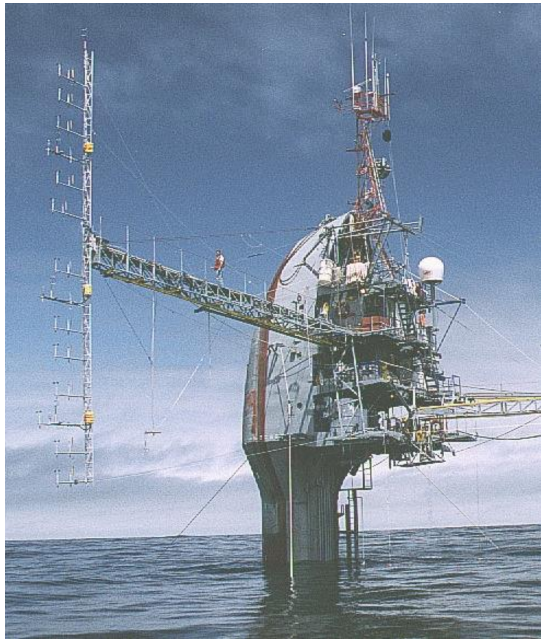
COARE

A semi-empirical bulk algorithm

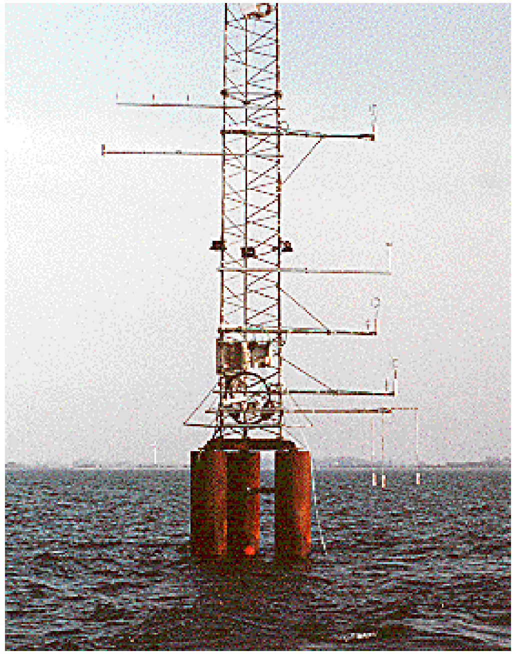
MBL/CBLAST Objectives

- When and where is Monin-Obukhov Similarity theory valid over the ocean?
- When, where and why does it fail?

R/P FLIP



RASEX Tower



ASIT/MVCO

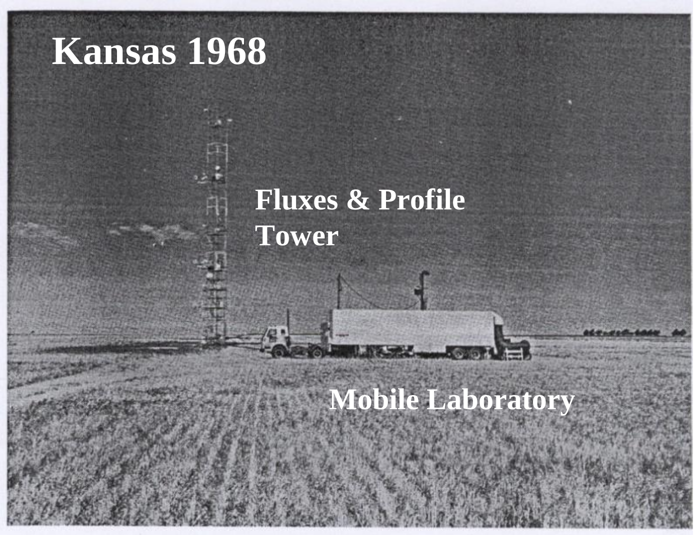
BBTower

Monin-Obukhov Similarity

The structure of the turbulence flow in the surface layer is influenced by both **mechanical** and **thermal** forcing. Monin and Obukhov (1954) were the first to describe a similarity hypothesis that allows us to superimpose the influence of these two forcing mechanisms.

$$\varepsilon = -\overline{uw}\frac{\partial U}{\partial z} + g\left(\frac{\overline{w\theta_v}}{\Theta_v}\right) - \frac{\partial \overline{we}}{\partial z} - \frac{1}{\overline{\rho}}\frac{\partial \overline{wp}}{\partial z}$$

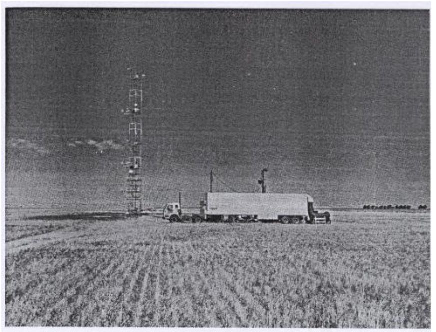
Objective of Kansas Experiment: Validate Monin-Obukhov Similarity (MOS) scaling through a carefully conducted experiment within a horizontally homogeneous atmospheric surface layer.



Monin-Obukhov Similarity

$$\frac{\kappa z}{u_*^3}\left[\varepsilon = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta_v}\overline{w\theta_v} - \frac{\partial \overline{we}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{wp}}{\partial z}\right]$$

$$\phi_\varepsilon\left(\frac{z}{L}\right) = \phi_m\left(\frac{z}{L}\right) - \frac{z}{L} - \phi_{te}\left(\frac{z}{L}\right) - \phi_{tp}\left(\frac{z}{L}\right)$$



- MOS states that various turbulent statistics are universal function of *z/L* after normalization by the appropriate scaling parameters.

- For example, the dimensionless shear

$$\frac{\kappa z}{u_*}\frac{\partial U}{\partial z} = \phi_m(z/L)$$

is predicted to be a universal functions of *z/L*.

- This hypothesis has been substantiated by a number of studies in the atmospheric boundary layer over land.

- ~40 years after Kansas, we confirmed this hypothesis over the ocean.

Monin-Obukhov Similarity

$$\frac{\kappa z}{u_*^3}\left[\varepsilon = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta_v}\overline{w\theta_v} - \frac{\partial \overline{we}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{wp}}{\partial z}\right]$$

$$\phi_\varepsilon\left(\frac{z}{L}\right) = \phi_m\left(\frac{z}{L}\right) - \frac{z}{L} - \phi_{te}\left(\frac{z}{L}\right) - \phi_{tp}\left(\frac{z}{L}\right)$$

$$\phi_m(z/L) = \frac{\kappa z}{u_*}\frac{\partial U}{\partial z}$$

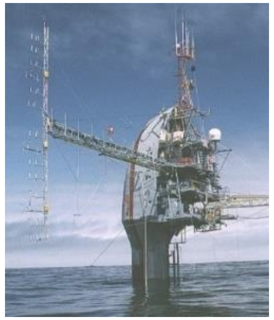
Rearrange

$$-\overline{uw} = u_*^2 = \frac{u_* \kappa z}{\phi_m(z/L)}\frac{\partial U}{\partial z} = K_m \frac{\partial U}{\partial z}$$

Integrate

$$\Delta U = \frac{u_*}{\kappa}\left[\ln(z/z_0) - \psi_m(z/L)\right]$$

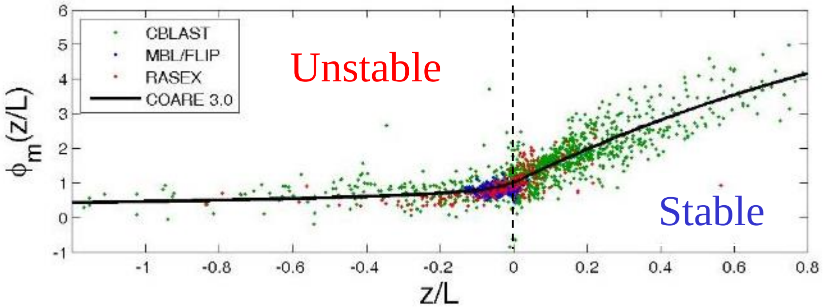
Measurement of mean and flux profiles within the offshore marine boundary layer.

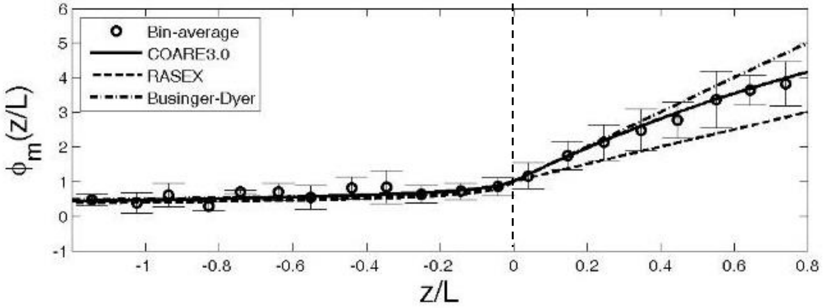


Dimensionless Shear

$$\phi_m\left(\frac{z}{L}\right) = \frac{\kappa z}{u_*}\frac{\partial U}{\partial z}$$

The Ocean is Kansas-like in the mean, with κ ~ 0.4 above the wave boundary layer.





Applications

1st Order Closure

$$-\overline{uw} = u_*^2 = \frac{u_* \kappa z}{\phi(z/L)}\frac{\partial U}{\partial z} = K_m \frac{\partial U}{\partial z}$$

Stability Adjusted Log Profile

$$U(z) = U(z_o) + \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right)\right]$$

Waves & Surface Layer Turbulence

- MOS does not account for wave-induced forcing.
- Therefore, MOS functions will become increasingly inaccurate as you near the ocean surface.
- However …
  - the terrestrial and marine observation are in good agreement in the mean.
  - We observe little systematic variability about this mean due as a function of wave age with the possible exception of swell.
- This provides evidence that the WBL for momentum is shallow under the range of conditions found in the CBLAST and MBL data sets.

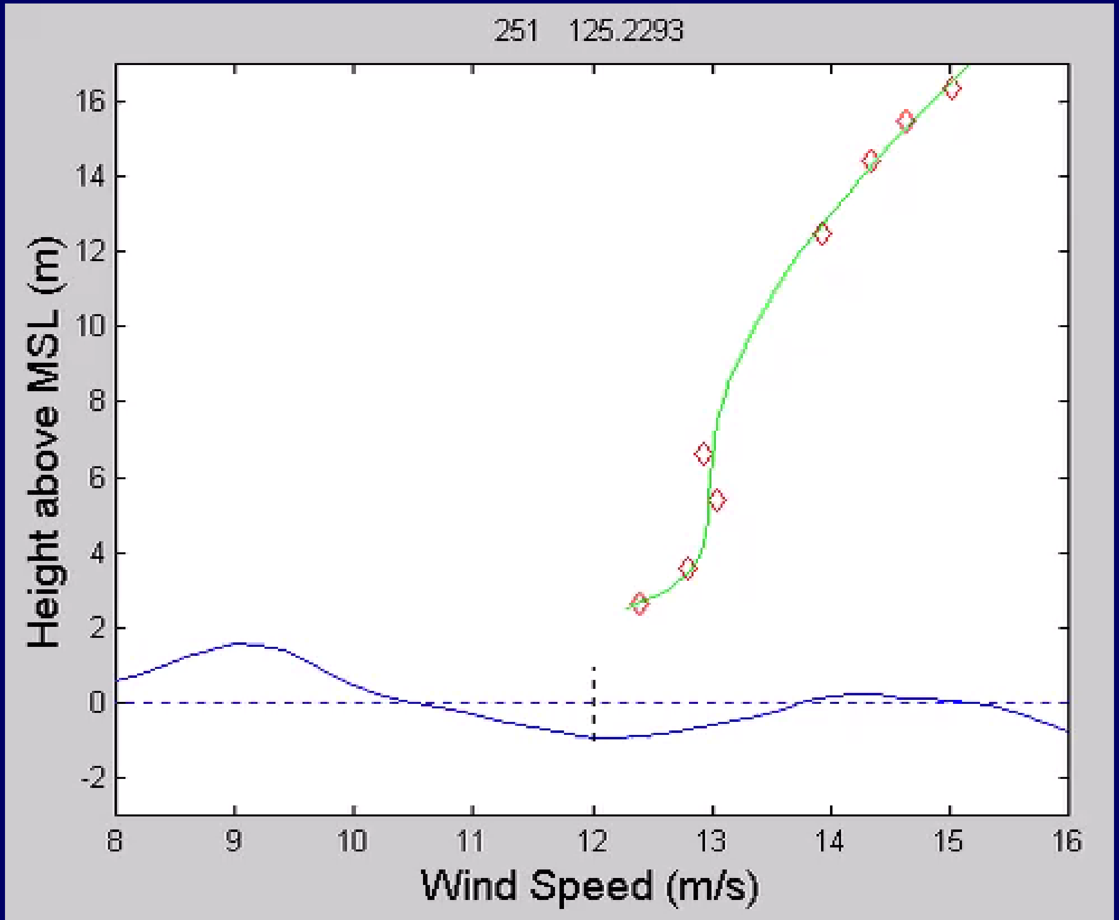
What about waves?

Let’s take a close look!

Instantaneous Wind Profile Over Waves

R/P FLIP

$$U_N(z) = U_N(z_o) + \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_o}\right)\right]$$

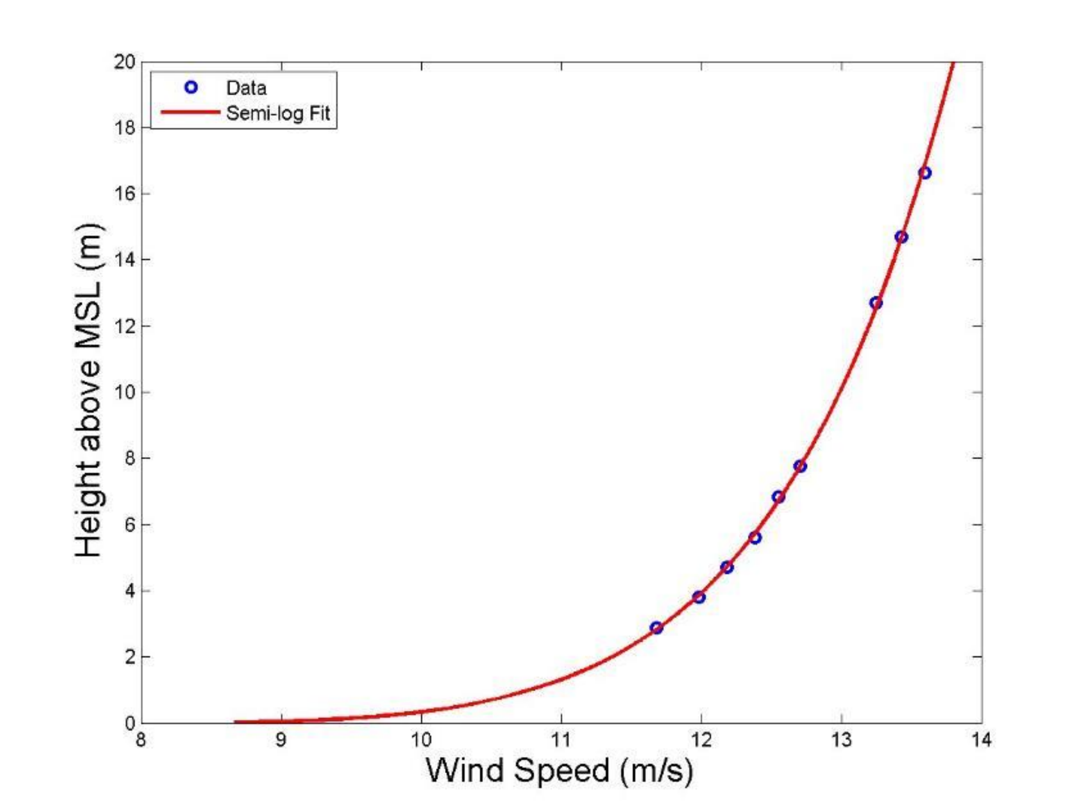


Instantaneous Wind Profile Over Waves

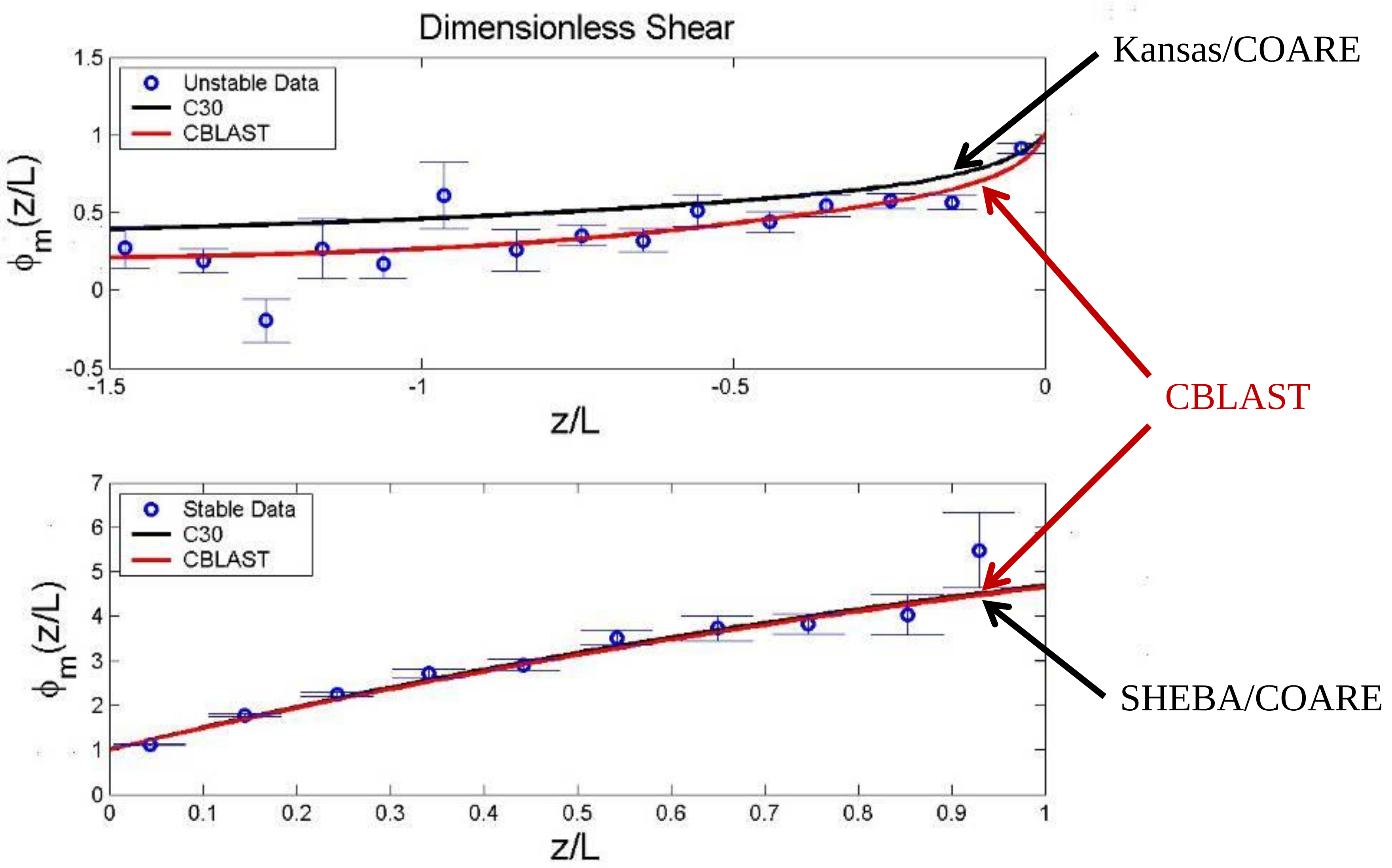
R/P FLIP

$$U_N(z) = U_N(z_o) + \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_o}\right)\right]$$

Semi-Logarithmic Profile!



Dimensionless Shear – A Closer Look



$\phi_m(z/L) = \kappa z/u_* \, \partial U/\partial z$

Monin-Obukhov Similarity

$$\frac{\kappa z}{u_*^3}\left[\varepsilon = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta_v}\overline{w\theta_v} - \frac{\partial \overline{we}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{wp}}{\partial z}\right]$$

$$\phi_\varepsilon(z/L) = \phi_m(z/L) + z/L - \phi_{te}(z/L) - \phi_{tp}(z/L)$$

$$\phi_m(z/L) = \frac{\kappa z}{u_*}\frac{\partial U}{\partial z}$$

Rearrange

$$-\overline{uw} = u_*^2 = \frac{u_* \kappa z}{\phi_m(z/L)}\frac{\partial U}{\partial z} = K_m \frac{\partial U}{\partial z}$$

Integrate

$$\Delta U = \frac{u_*}{\kappa}[\ln(z/z_0) - \psi_m(z/L)]$$

Rearrange

$$u_* = \kappa/[\ln(z/z_0) - \psi_m(z/L)]\Delta U$$

Semi-empirical Basis
for Bulk Formulae

$$u_* = C_D^{1/2}\Delta U$$

Drag Coefficient

- COARE Algorithm

$$C_D(z/z_o, z/L) = -\frac{\overline{uw}}{\Delta U S_r} = \left(\frac{\kappa}{\ln(z/z_o) - \psi_u(z/L)}\right)^2$$

Atmospheric Stability

$$C_{DN}(z/z_o) = -\frac{\overline{uw}}{\Delta U_N^2 G} = \left(\frac{\kappa}{\ln(z/z_o)}\right)^2$$

Roughness Length

- Wave Impacts
  - Waves have a modest impact on the dimensionless profiles above the WBL
  - Waves have a first order impact on the surface roughness as roughness elements.

Surface Momentum Exchange & Waves

- **Above the Wave Boundary Layer – MO Similarity expected to hold.**

$$\rho\overline{uw} = \rho\overline{u'w'}$$

- **Within the Wave Boundary Layer – MO Similarity begins to break down.**

$$\rho\overline{uw} = \rho\overline{u'w'} + \rho\overline{\tilde{u}\tilde{w}}$$

- **At the surface**

$$\rho\overline{uw} = \nu\frac{dU}{dz} + \rho\overline{\tilde{u}\tilde{w}} = \underbrace{\nu\frac{dU}{dz}}_{\text{Viscous Stress}} + \underbrace{\overline{p_0\frac{\partial\eta}{\partial x}}}_{\text{Form Drag}}$$

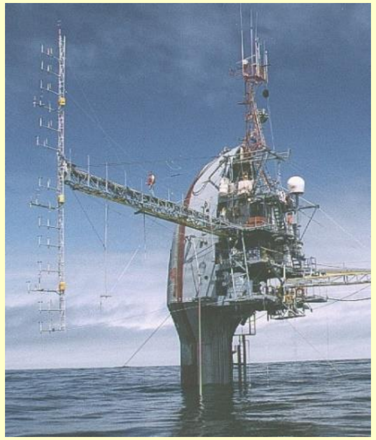
- **COARE 3.5 parameterizes this through the roughness length:**

$$z_0 = \alpha\frac{\nu}{u_*} + \boxed{\beta}\frac{u_*^2}{g} \qquad \beta = f(U_{10N})$$

Research Objectives

- To improve our understanding of the processes that control the exchange momentum, heat and mass across the air-sea interface.
- To develop platform and systems that directly measures the momentum, sensible heat and latent heat fluxes.

COARE 3.5

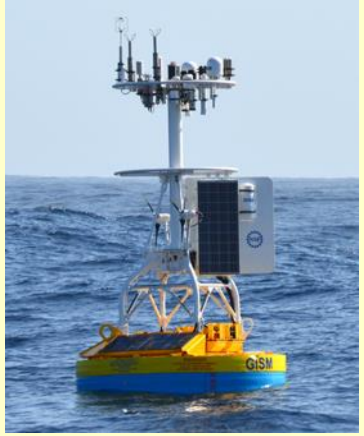


R/P FLIP

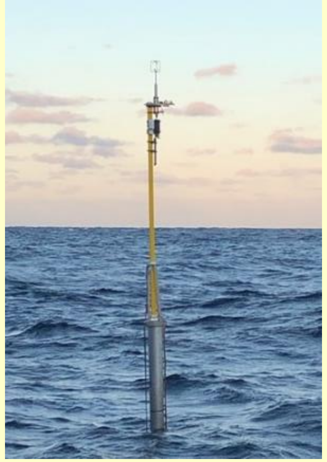
ASIT/MVCO

ASIS

Research Discus

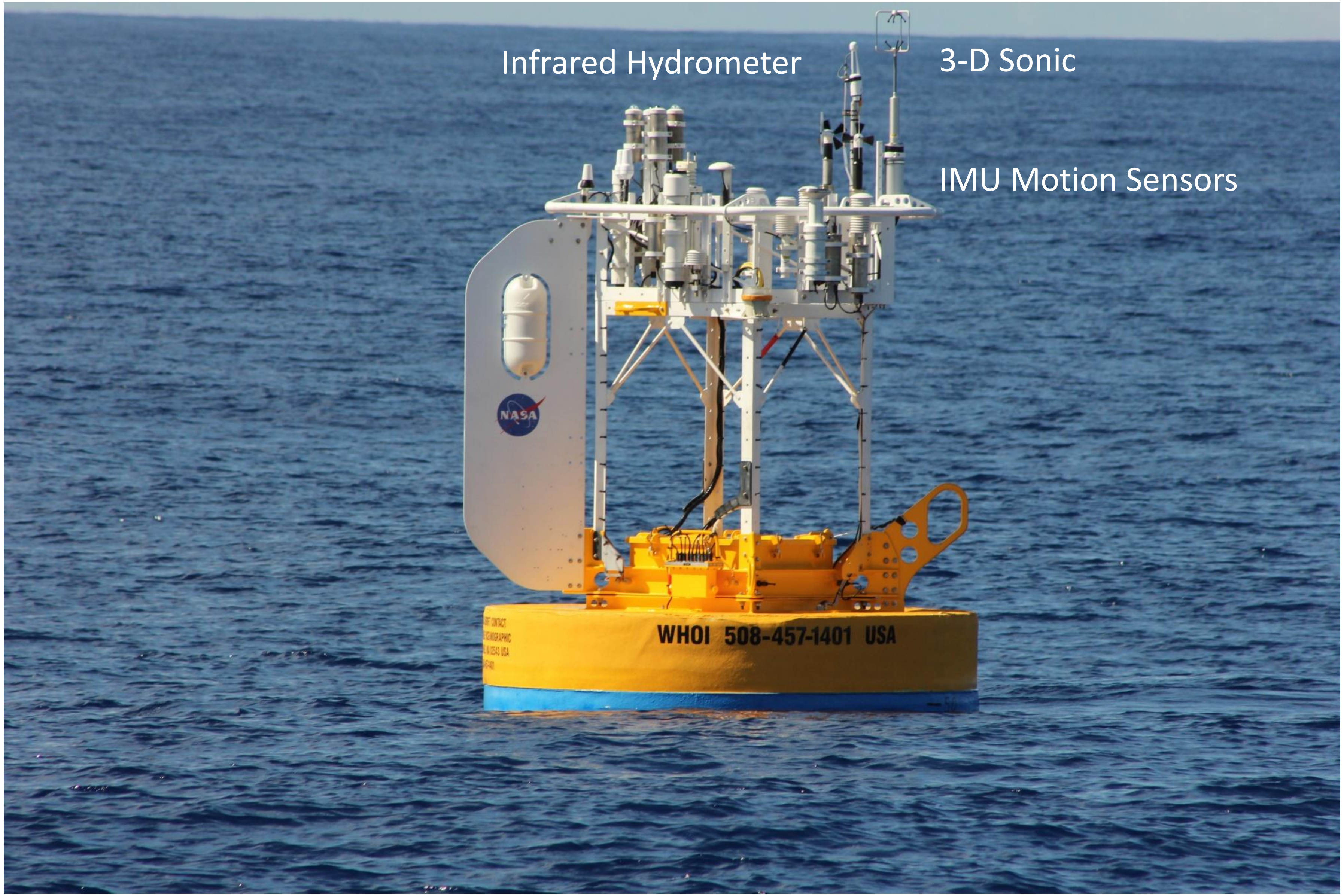


OOI Mooring

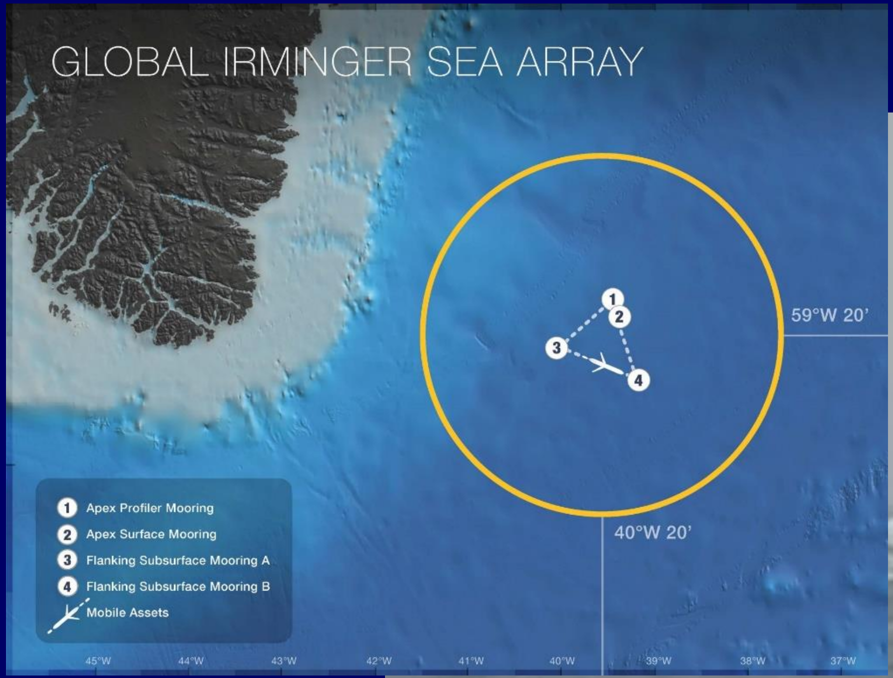


X-Spar

Surface Moorings



Platform Motion



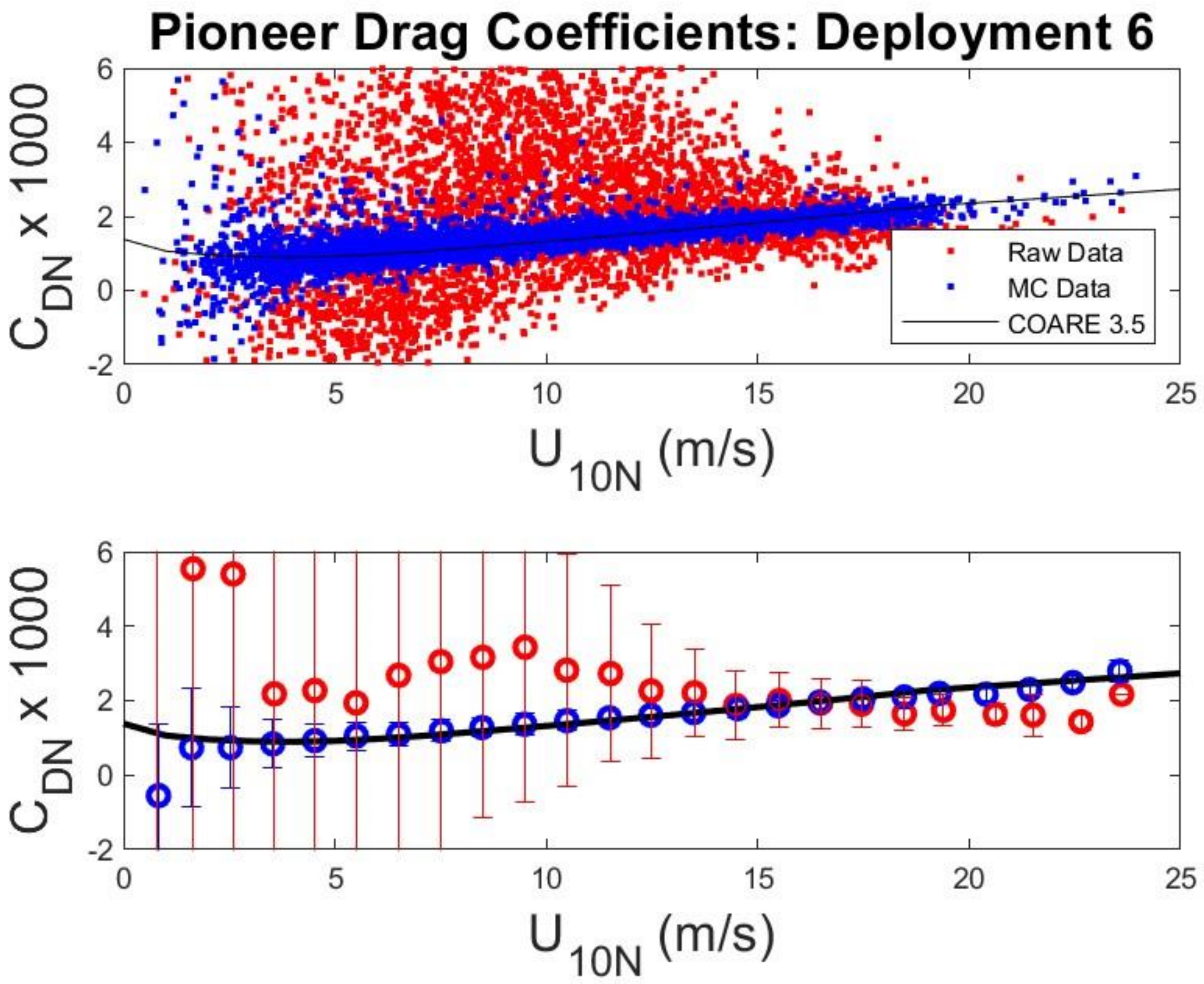
Motion Correction

$$U_{true}^{water} = T(\phi,\theta,\psi)\left[U_{obs} + \Omega_{obs} \times R\right] + V_{hp} + V_{lp}$$

b-d a b c

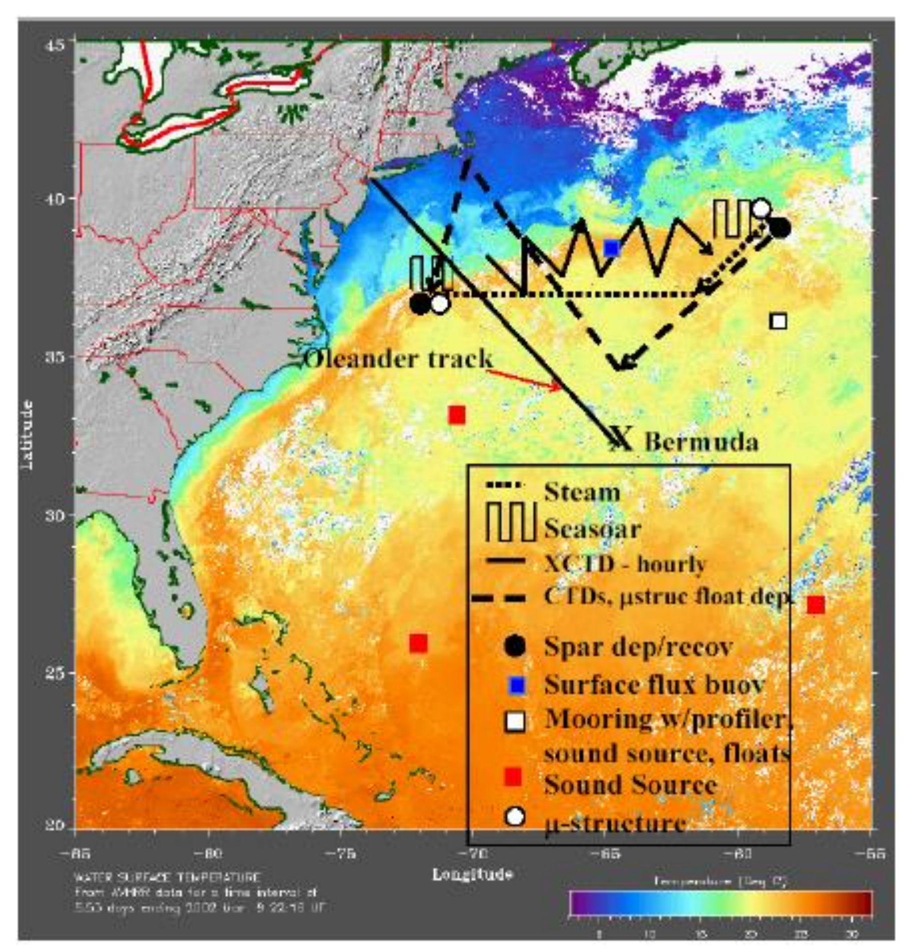
- CLIMODE Setup
  - (a) 3-axis Sonic Anemometer
  - (b) 3-axis angular Rate Sensors
  - (c) 3-axis Accelerometers
  - (d) Compass
  - Current meter
  - 2-axis anemometers
  - RH/T/P Sensors
  - Radiometers
  - Precipitation gauges
  - Sea Temperature

Motion Correction



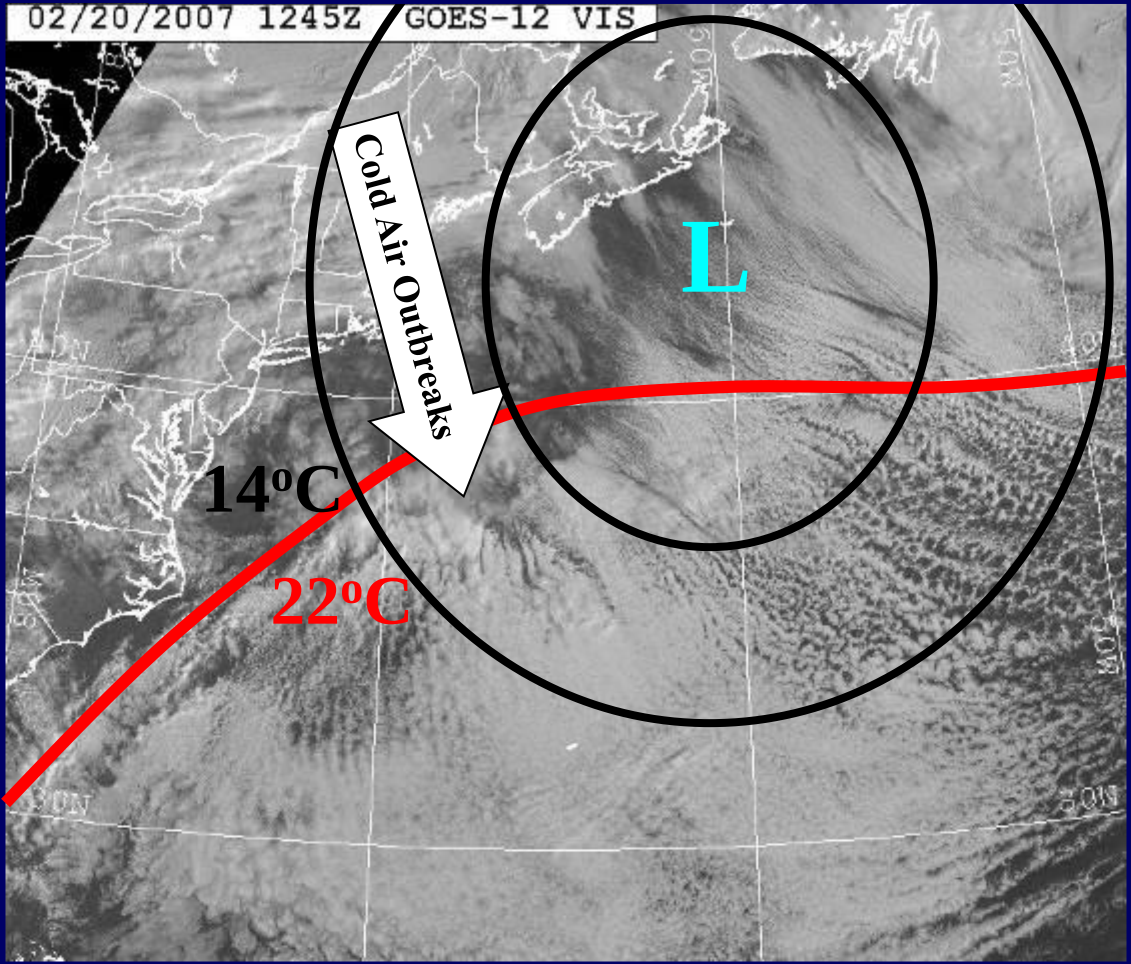
CLIMODE Deployments and Cruises

CLIMODE is designed to investigate the processes responsible for the formation, subduction and dispersal of EDW in the North Atlantic through modeling & observations.



- November 2005: Mooring & Profiler Deployment Cruise
- January 18-30, 2006: Pilot Experiment, ASIS/FILIS Deployment
- October 2006: Mooring Turnaround Cruise
- February-March 2007: 6-week Main Experiment, ASIS/FILIS Deployments, Microstructure, Surveys.
- November 2007: Mooring Recovery Cruise

The Gulf Stream



- Cold air outbreaks drive extremely active convection over the region.
- The net winter heat loss in this region is 400 W/m^2.

Momentum Fluxes

Surface Stress

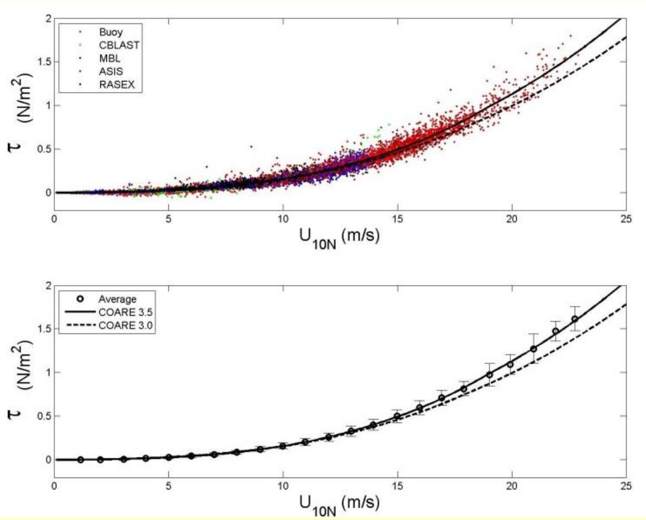
$$\tau = -\rho\overline{uw} \approx \rho C_{DN} \Delta U_N^2 G$$

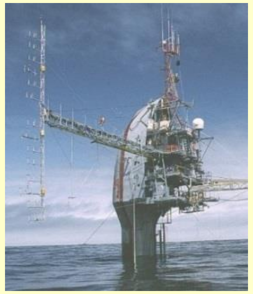
Drag Coefficient

$$C_{DN} = \frac{-\overline{uw}}{\Delta U_r^2 G} = \left(\frac{\kappa}{\ln(z/z_o)} \right)^2$$

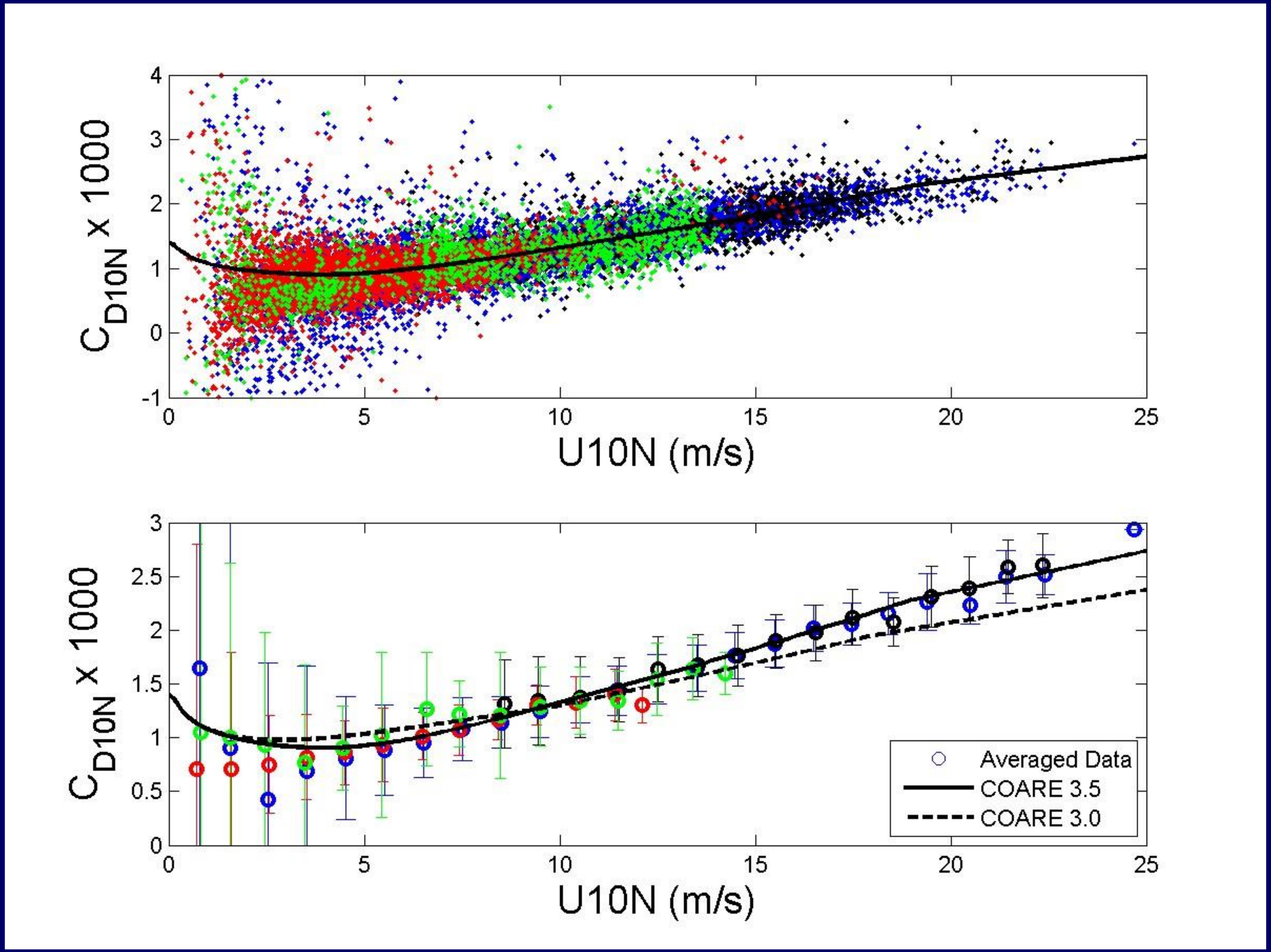
Roughness Length

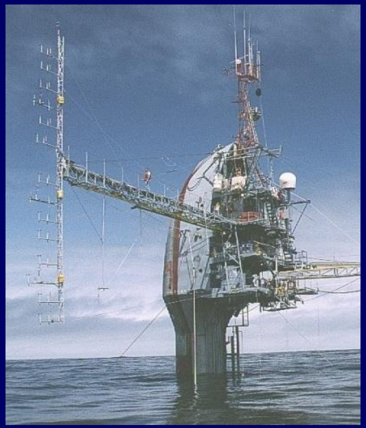
$$z_o = \alpha \frac{\nu}{u_*} + \beta\,(U_{N10}) \frac{u_*^2}{g}$$





MBL/CBLAST/CLIMODE Drag Coefficients

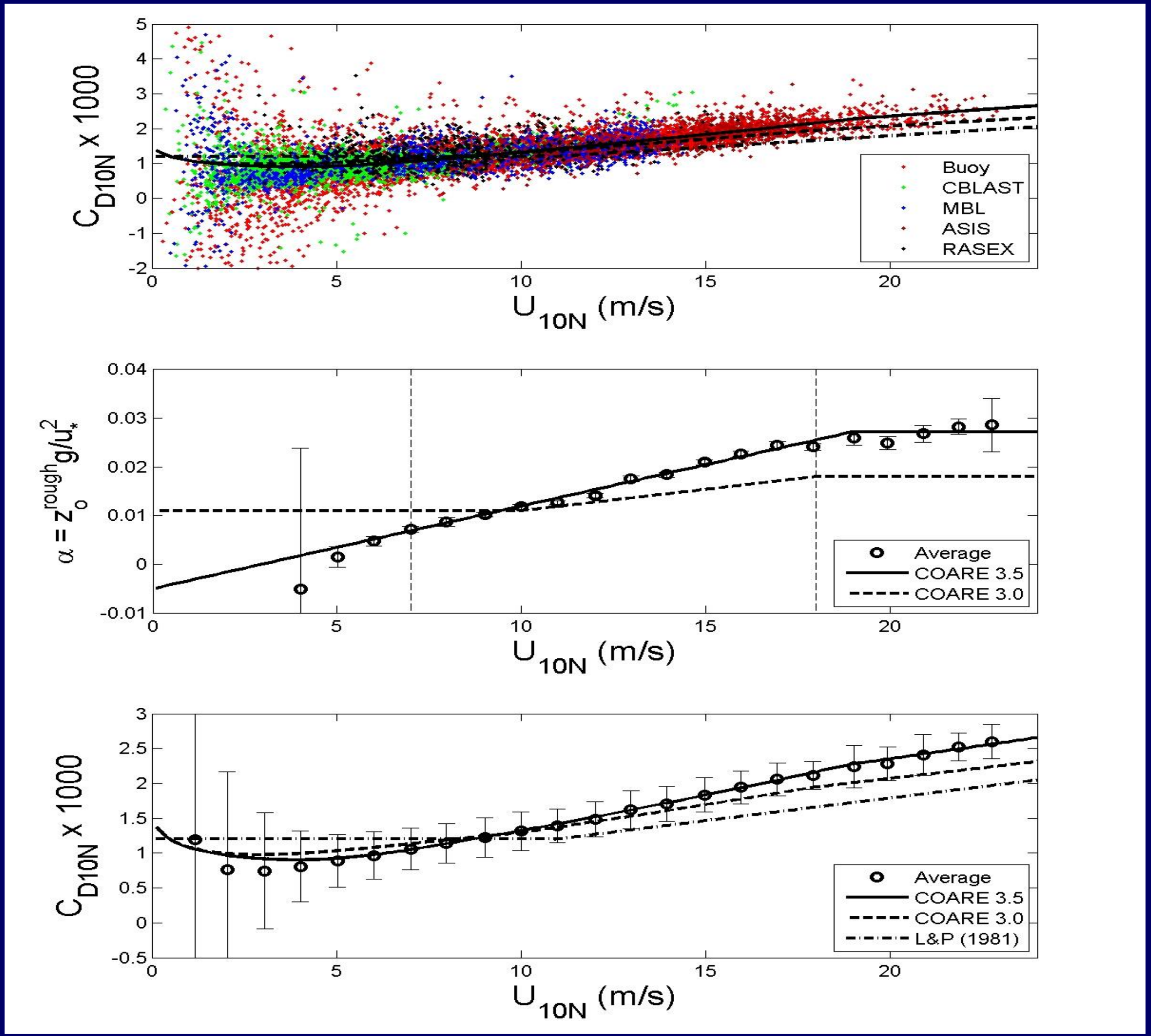


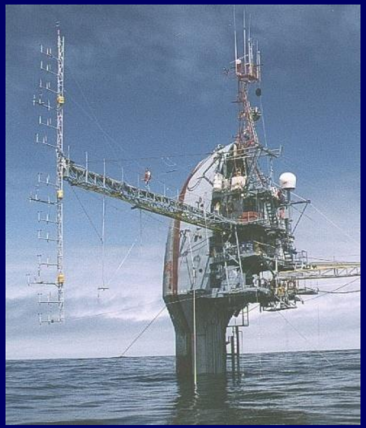


$$C_{DN}(z/z_o) = \frac{-\overline{uw}}{\Delta U_N^2 G} = \left(\frac{\kappa}{\ln(z/z_o)}\right)^2$$

$$z_0 = \alpha \frac{\nu}{u_*} + \beta \frac{u_*^2}{g}$$

MBL/CBLAST/CLIMODE Drag Coefficients





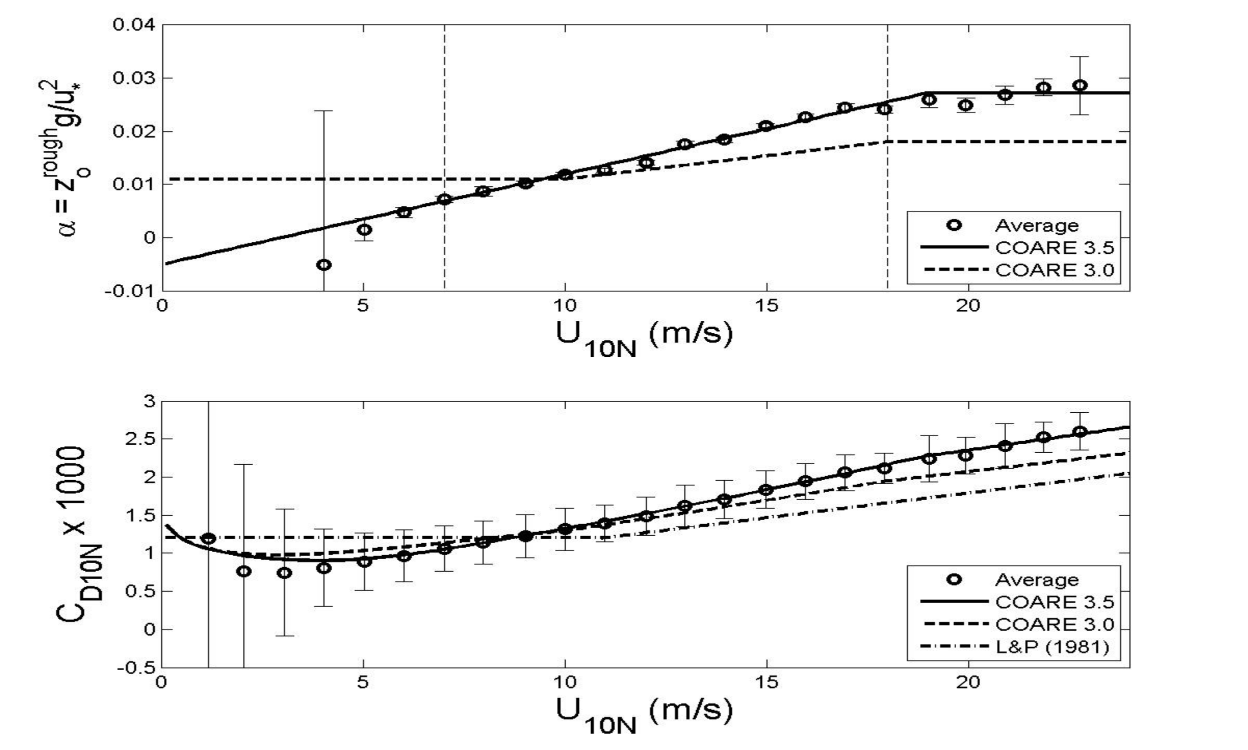
$$C_{DN}(z/z_o) = \frac{-\overline{uw}}{\Delta U_N^2 G} = \left(\frac{\kappa}{\ln(z/z_o)}\right)^2 \qquad z_0 = \alpha\frac{\nu}{u_*} + \beta\frac{u_*^2}{g}$$

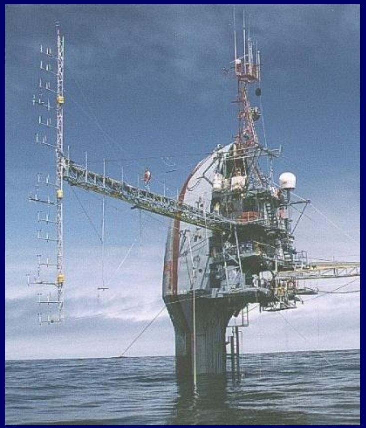
MBL/CBLAST/CLIMODE Drag Coefficients

COARE 3.5

Edson, James B., and Coauthors, 2013: On the Exchange of Momentum over the Open Ocean. *J. Phys. Oceanogr.*, **43**, 1589–1610.

doi: http://dx.doi.org/10.1175/JPO-D-12-0173.1





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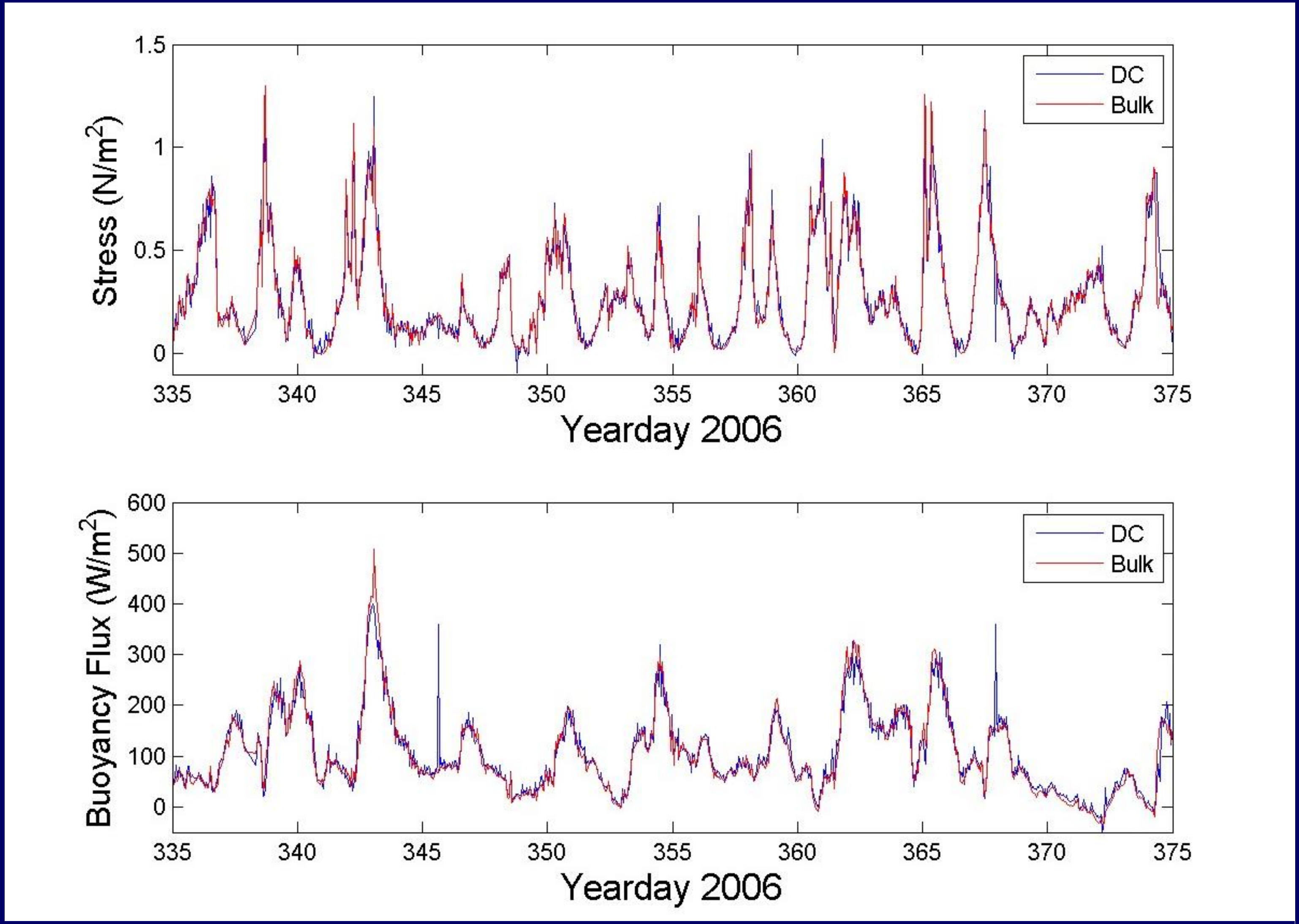
$$z_0 = \alpha \frac{\nu}{u_*} + \beta \frac{u_*^2}{g}$$

Flux Time Series

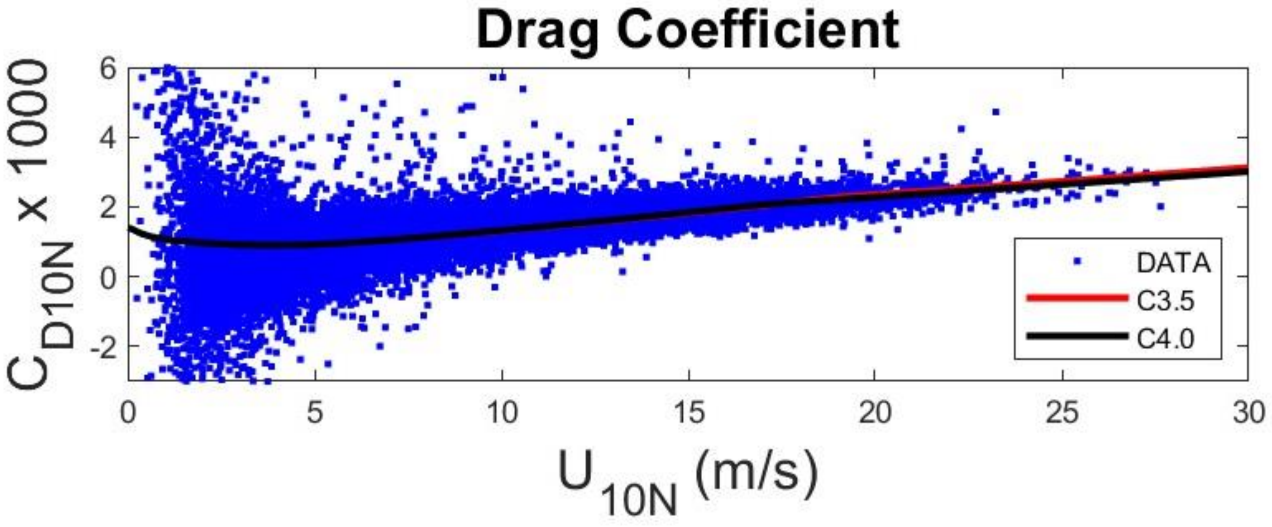


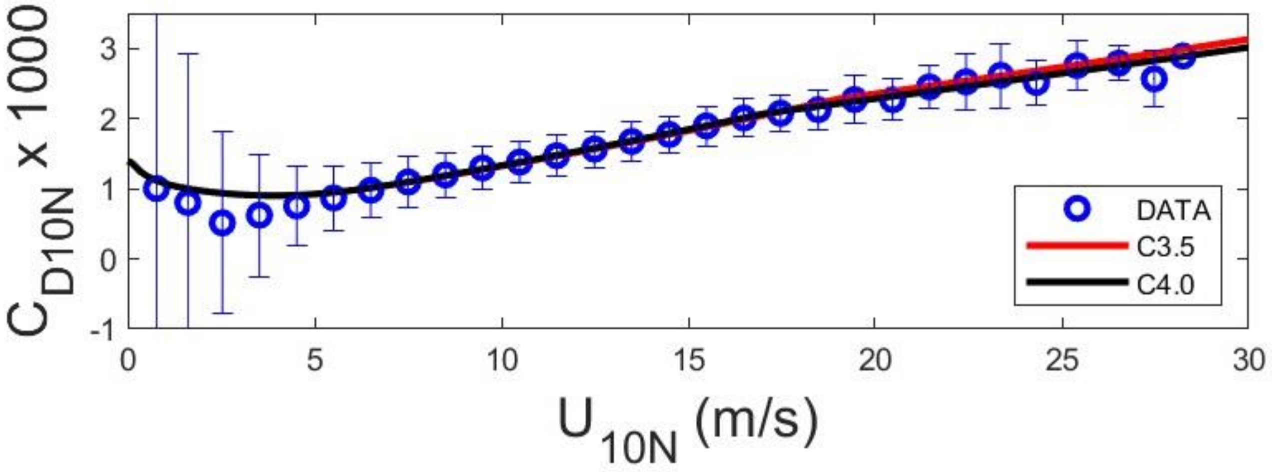
COARE 3.5

Edson, James B., and Coauthors, 2013: On the Exchange of Momentum over the Open Ocean. *J. Phys. Oceanogr.*, **43**, 1589–1610.

COARE: A Global Formulation using a Growing Global Array

$$C_{DN} = -\frac{\overline{uw}}{U_{rN}^2 G} = \left(\frac{\kappa}{\ln(z/z_0)}\right)^2 \qquad \alpha = \frac{g z_0}{u_*^2} = f(U_{10N})$$

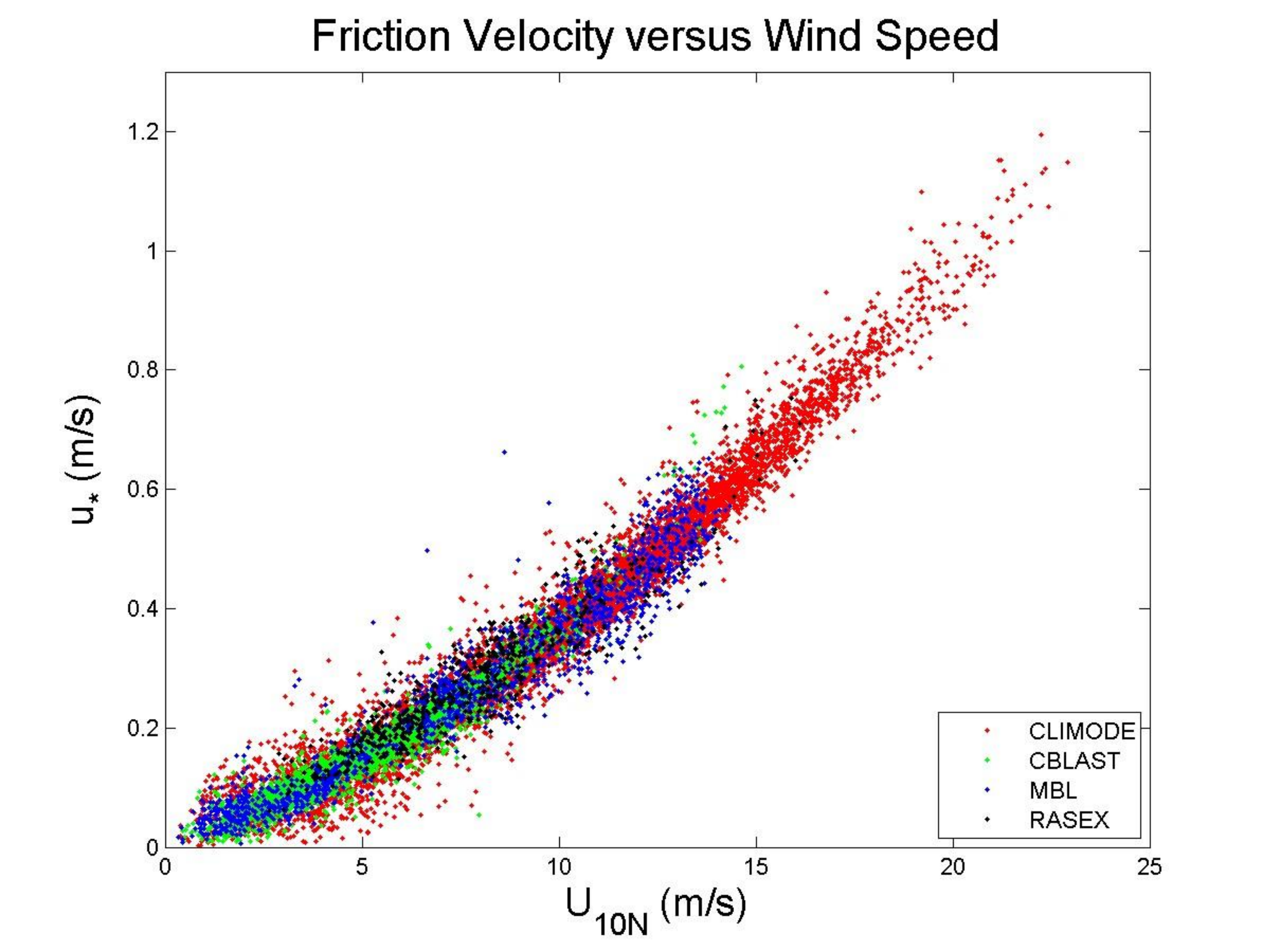


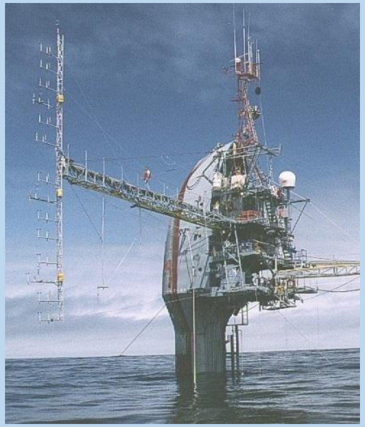


Out to High Wind

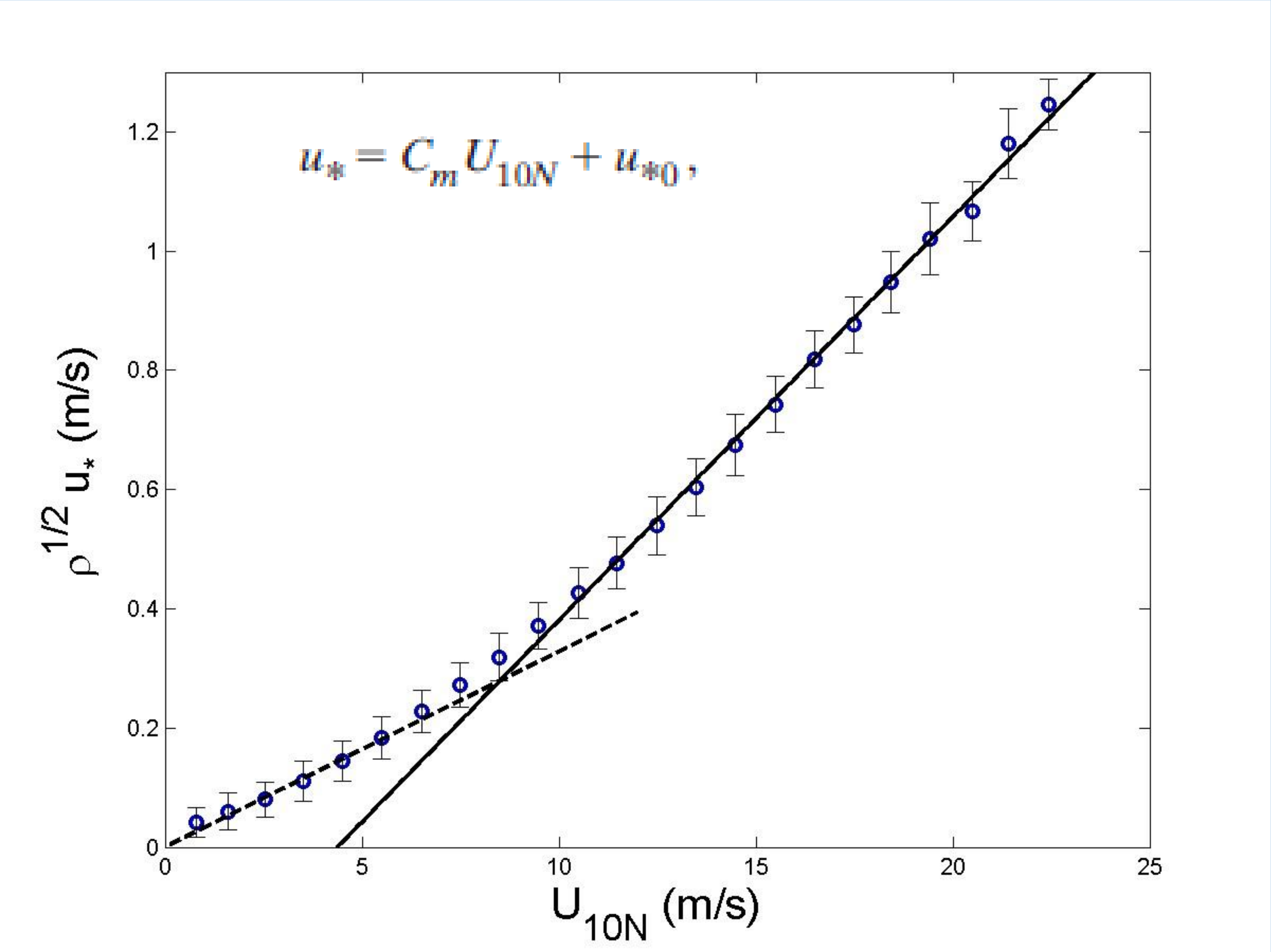
Via the Hockey Stick Extrapolation

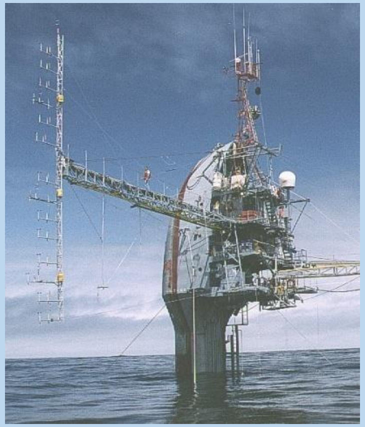
MBL/CBLAST/CLIMODE/RASEX



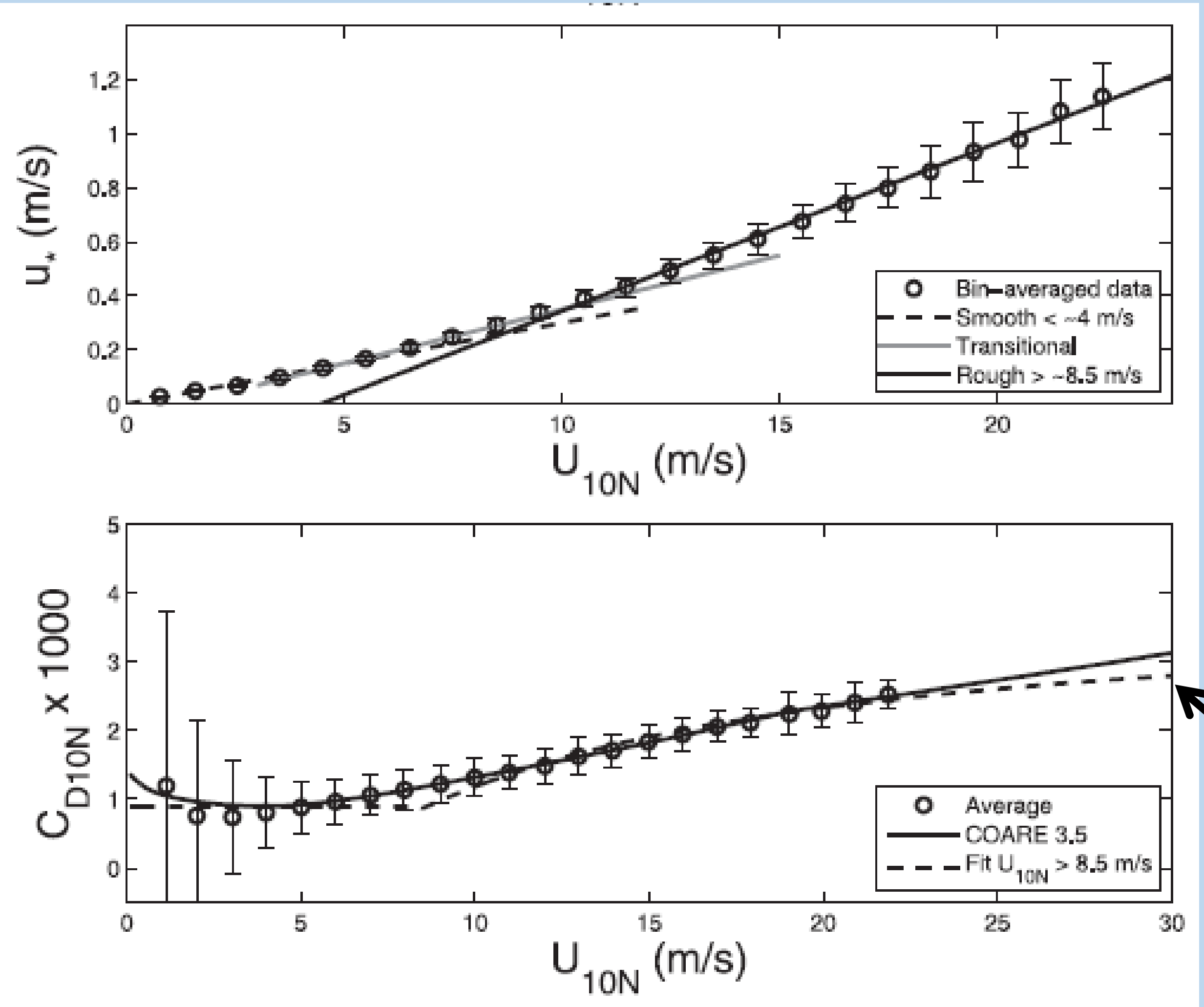


Another Hockey Stick





Drag Coefficient at High Winds

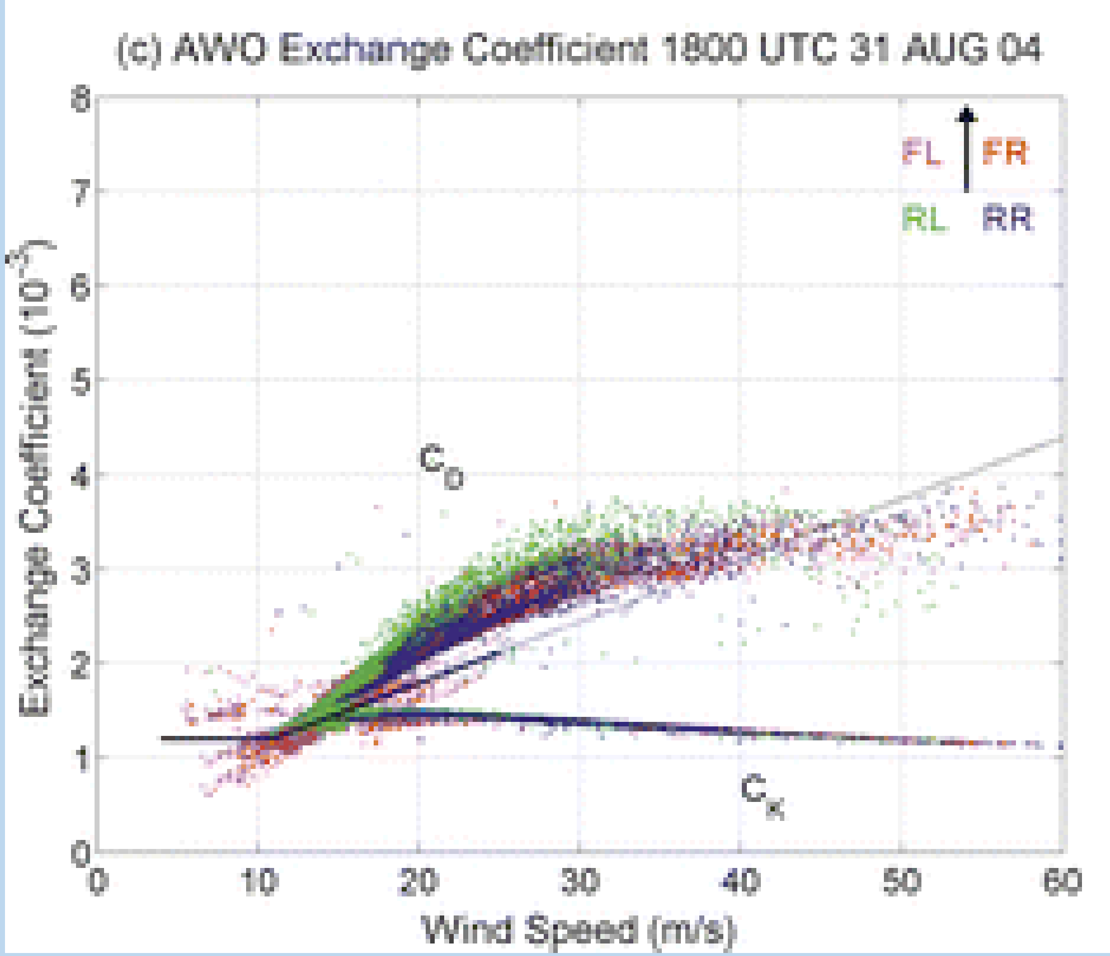


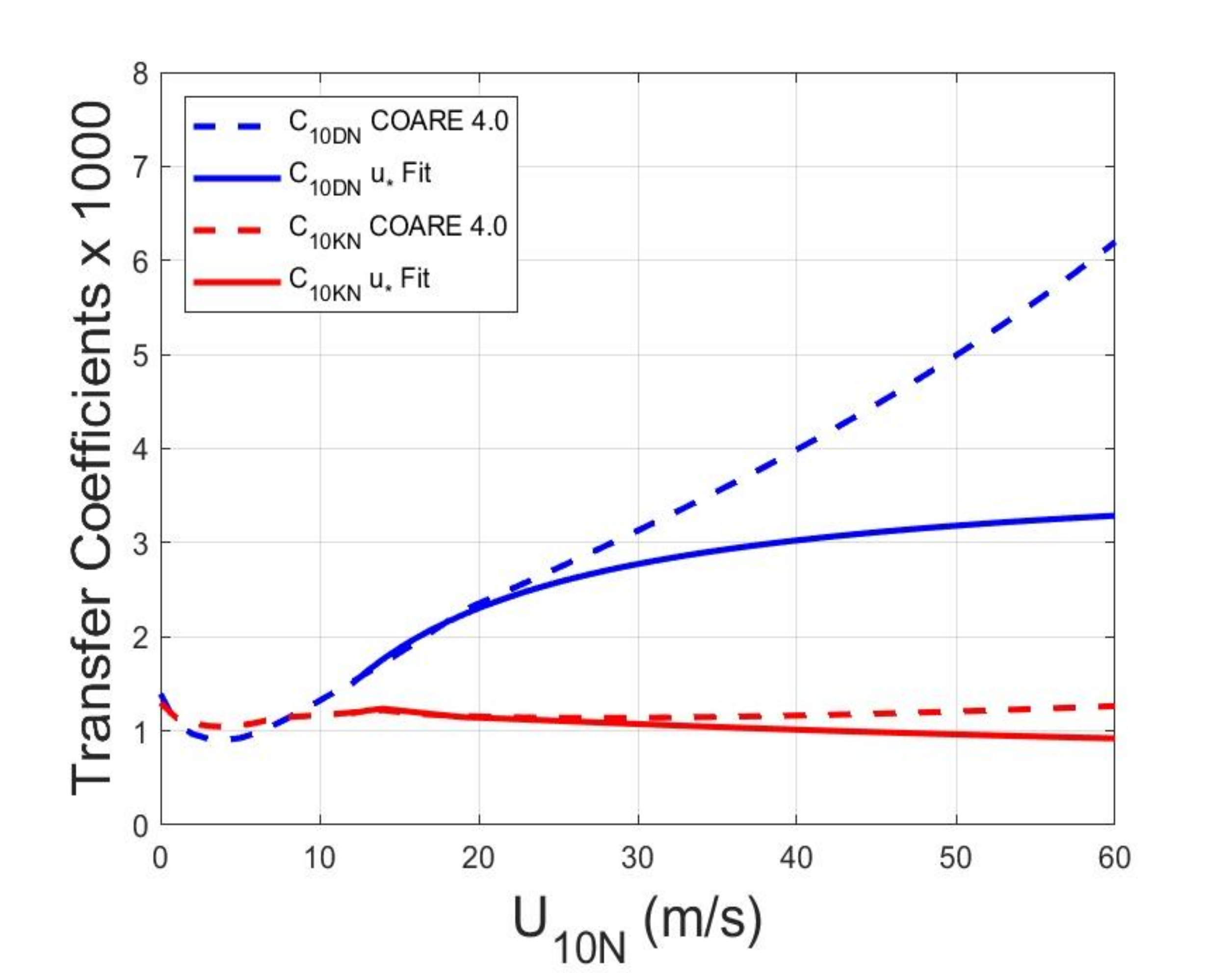
$$u_* = C_m U_{10N} + u_{*0},$$

$$C_{D10N} = \left(\frac{u_*}{U_{10N}}\right)^2 = \left(C_m + \frac{u_{*0}}{U_{10N}}\right)^2$$

Hockey Stick

Drag Coefficient at High Winds

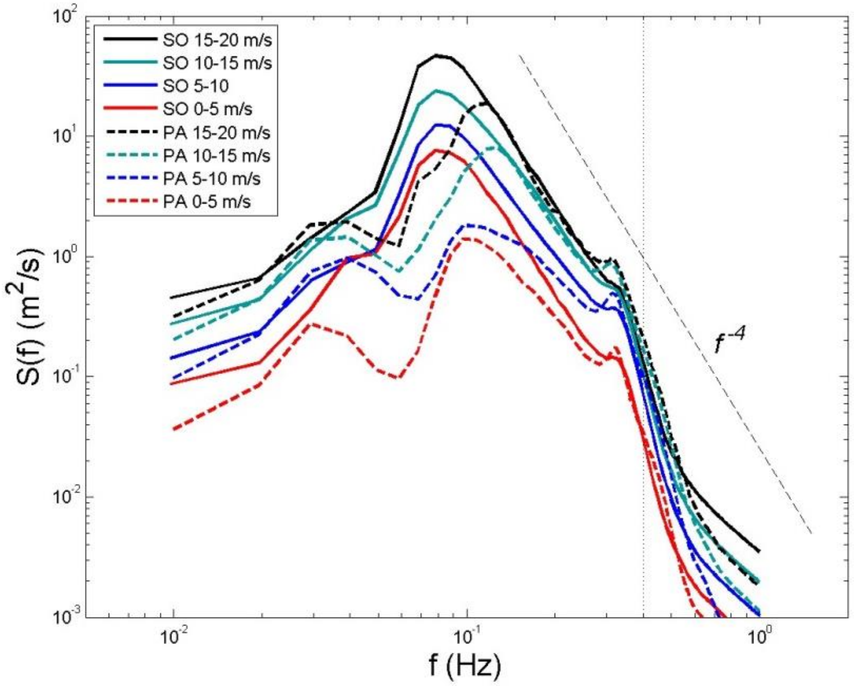


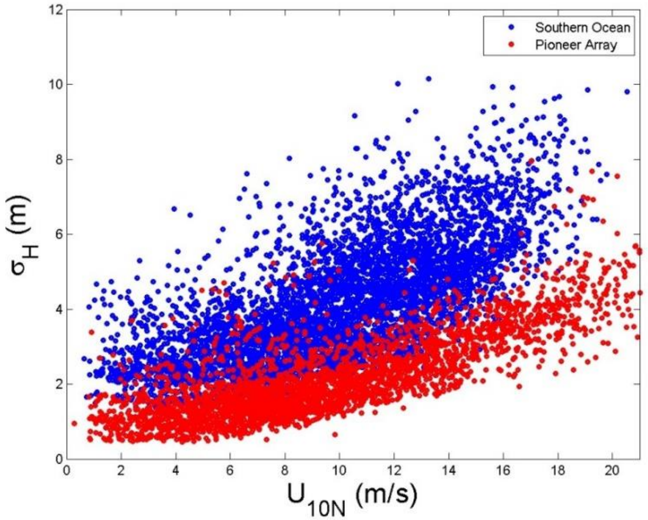


Wave-based COARE

Using wave steepness

Wave-based Parameterization





Long Wave Modulation of Surface Stress

Wave steepness dependent formulation

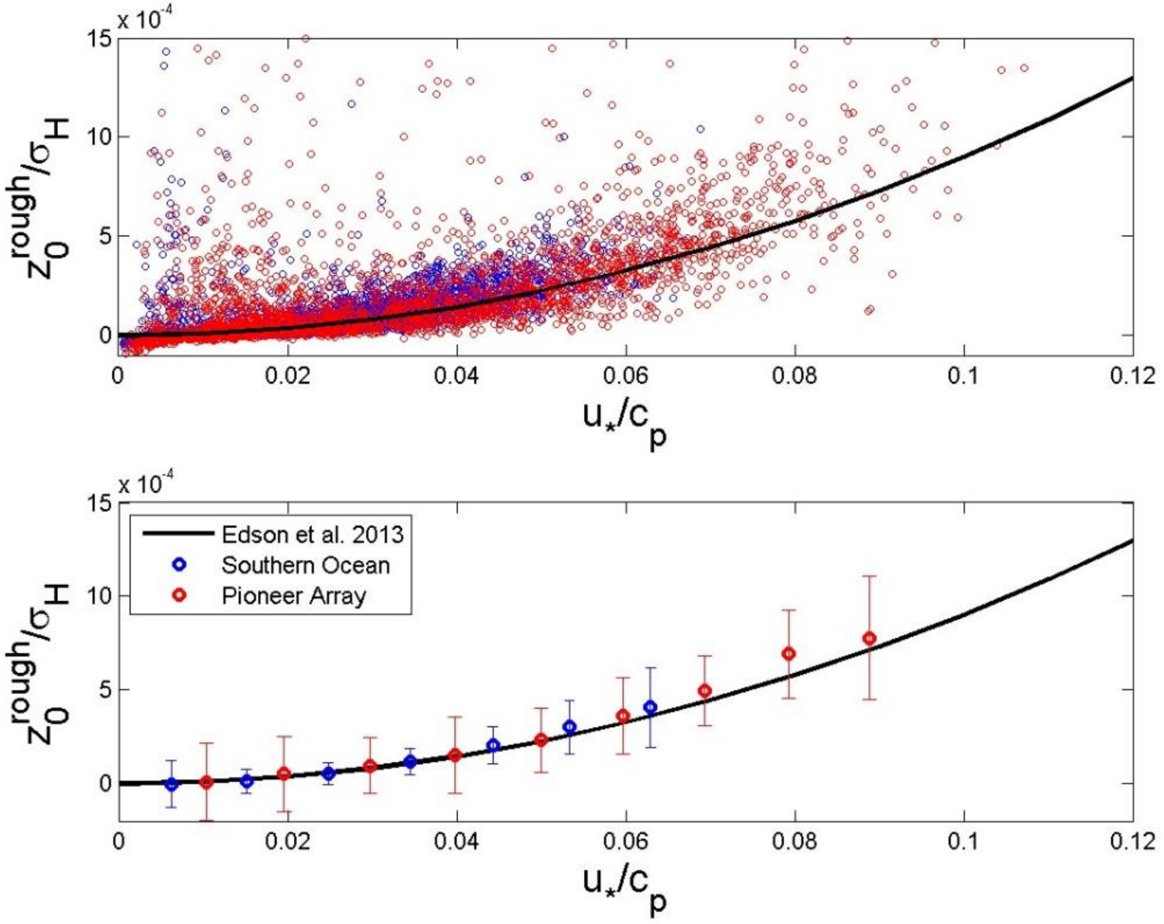
$$\beta = \frac{g\, z_0^{rough}}{u_*^2} = f(\sigma_H k_p)$$

$$\beta = \frac{g z_0^{rough}}{u_*^2} = D \sigma_H k_p$$

$$c_p^2 = \frac{g}{k_p}$$

Deep water dispersion relationship

$$\frac{z_0^{rough}}{\sigma_H} = D \left(\frac{u_*}{c_p}\right)^2$$



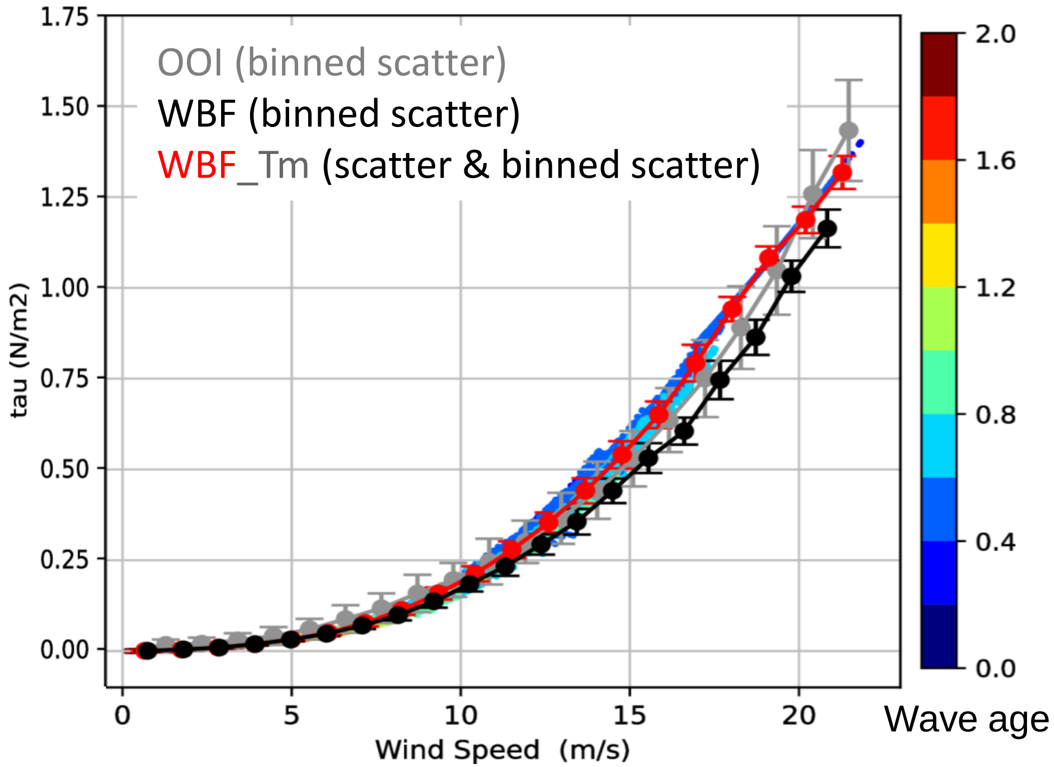
Peak Phase Speed vs Mean Phase Speed

- Investigating the **impact of sea state** on momentum flux through **coupled Ocean-Atmosphere-Wave simulations** using the sea surface fluxes parameterization **COARE3.5**
- We observed 2 different sea state regimes in the Tropical North Atlantic region :
  - **Young steep waves** tend to increase the surface roughness and stress
  - **Old flat waves** tend to decrease the surface roughness and stress
- Significant impact on near surface wind speed
- However, compared to observations, the model over predicts the impact of swell

$$\frac{z_0^{rough}}{\sigma_H} = D\left(\frac{u_*}{c_p}\right)^2$$

- Ways to alleviate low stress bias:
  - Alignment wind-waves
  - **Using the mean wave phase speed (C_m)**

$$z_{rough} = H_s \cdot 0.39 \cdot \left(\frac{u_*}{C_m}\right)^{2.6}$$



Heat Exchange

Research Objectives

- To improve our understanding of the processes that control the exchange momentum, heat and mass across the air-sea interface.
- To develop platform and systems that directly measures the momentum, sensible heat and latent heat fluxes.
- To improve parameterization of these fluxes for use in numerical models and process studies.

Momentum Flux: $\tau_0 = \rho_a \overline{uw} \cong \rho_a C_D S_r \Delta U$

Latent Heat Flux: $Q_E = \rho_a L_v \overline{wq} \cong \rho_a L_v C_E S_r \Delta Q$

Sensible Heat Flux: $Q_H = \rho_a c_{pa} \overline{wT} \cong \rho_a c_{pa} C_H S_r \Delta \Theta$

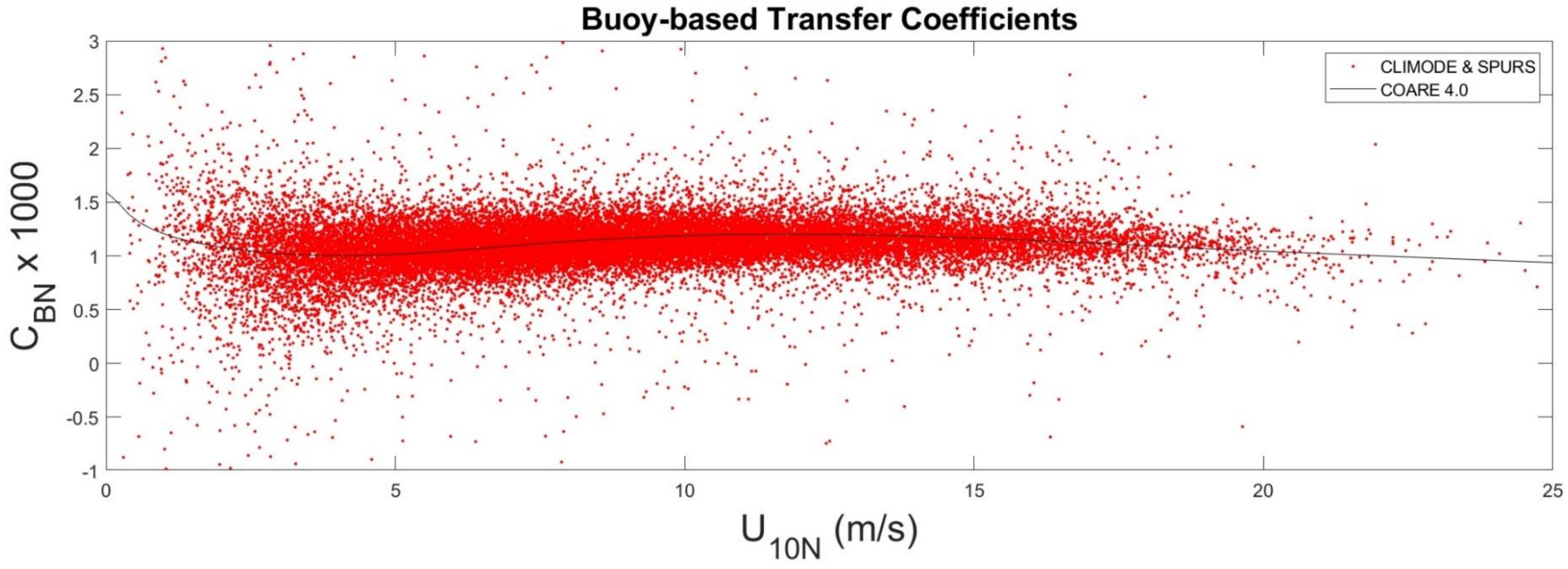
Buoyancy Flux: $Q_B \cong \rho_a c_p \overline{wT_v} \cong \rho_a c_p C_B S_r \Delta \Theta_v$

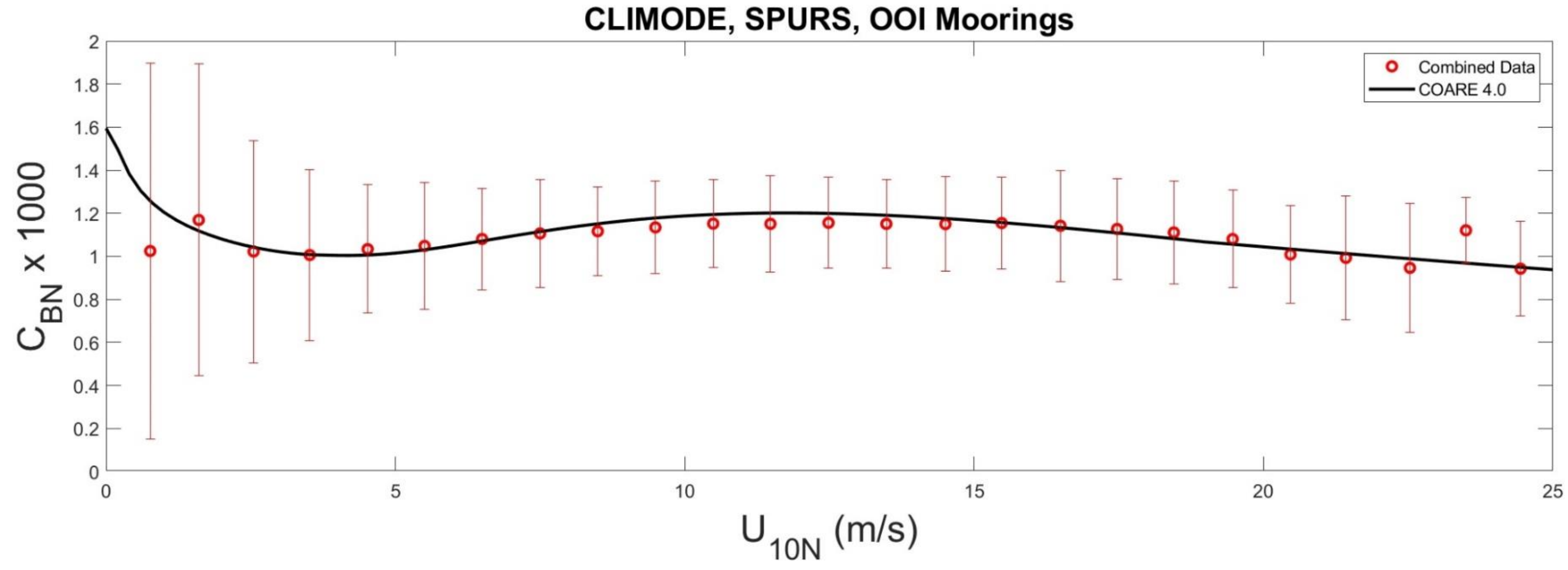
$$\cong \rho_a c_p (\overline{wT} + 0.51\Theta \overline{wq})$$

Transfer Coefficients

Buoy-based Transfer Coefficients

$$C_{BN} = -\frac{\overline{wT_v}}{\Delta\Theta_v \; \Delta U_N G} = C_{DN}^{1/2}\left(\frac{\kappa}{\ln(z/z_{oB})}\right)$$



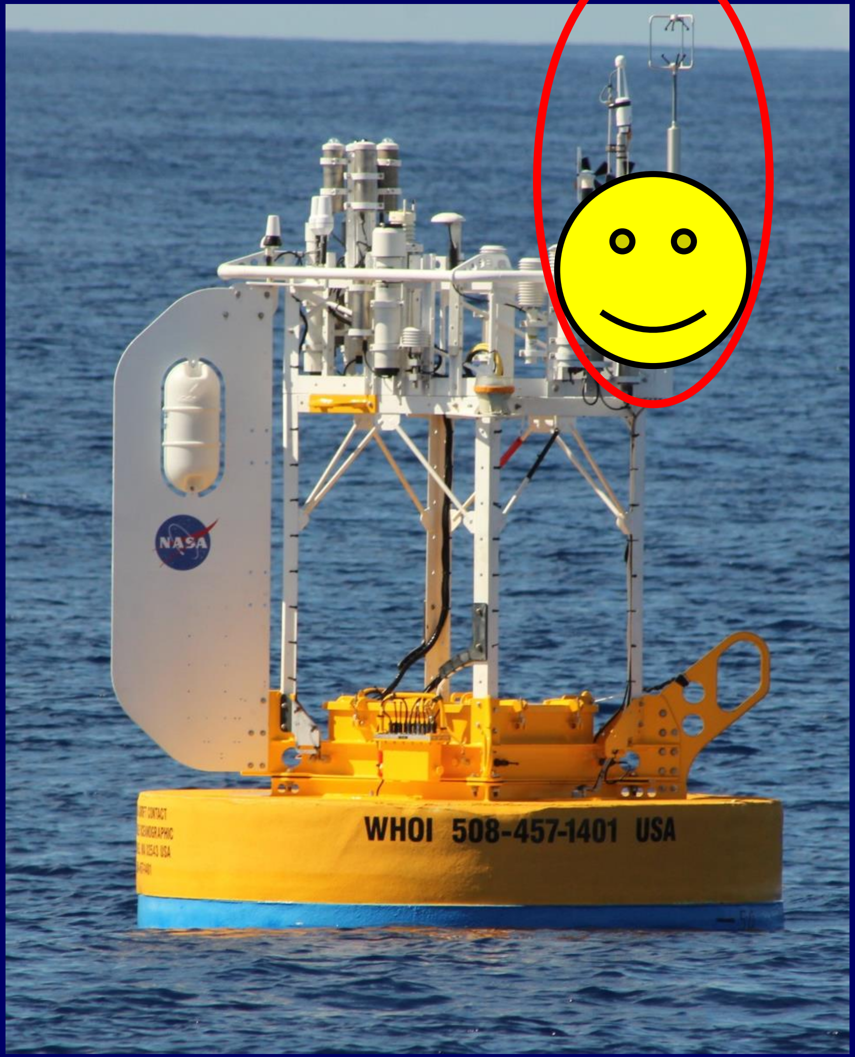


Challenge: Latent Heat Flux from Buoys

SPURS-1

Closed Path

SPURS-2



Open Path

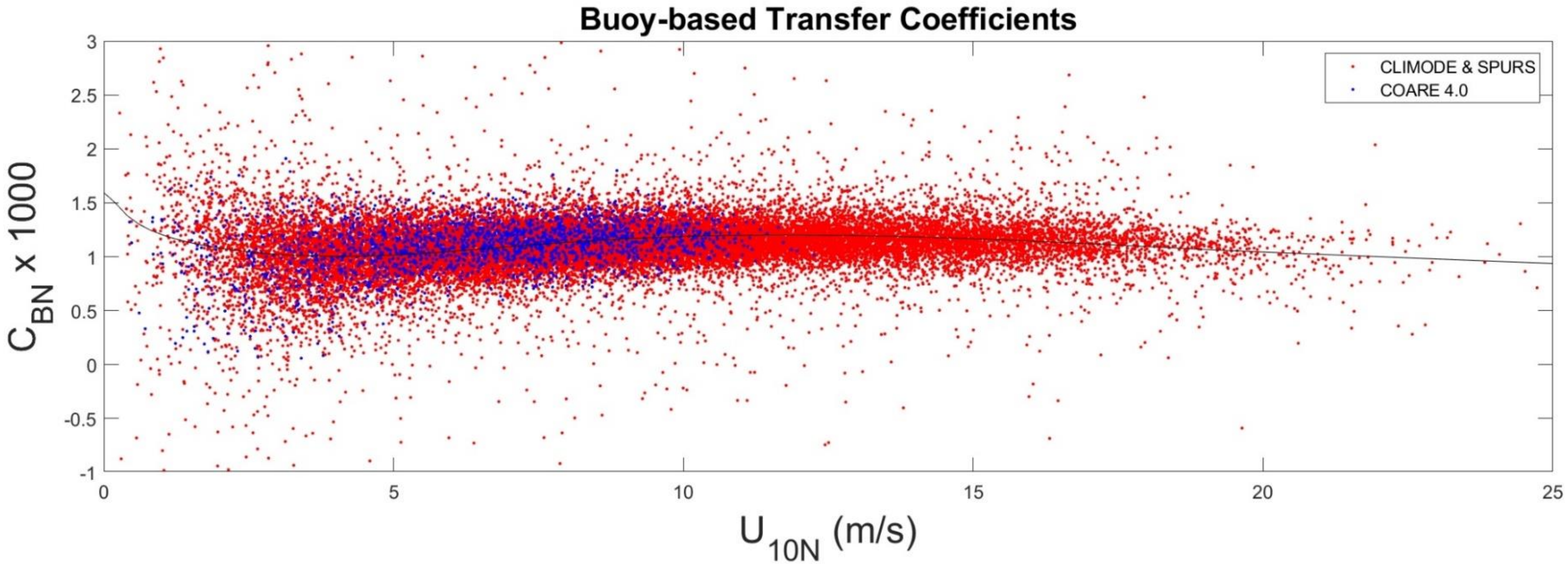
Buoy-based Transfer Coefficients

$$C_{BN} = -\frac{\overline{wT_v}}{\Delta\Theta_v\,\Delta U_N G} = C_{DN}^{1/2}\left(\frac{\kappa}{\ln(z/z_{oB})}\right)$$

$$C_{EN} = -\frac{\overline{wq}}{\Delta Q \Delta U_N G}$$

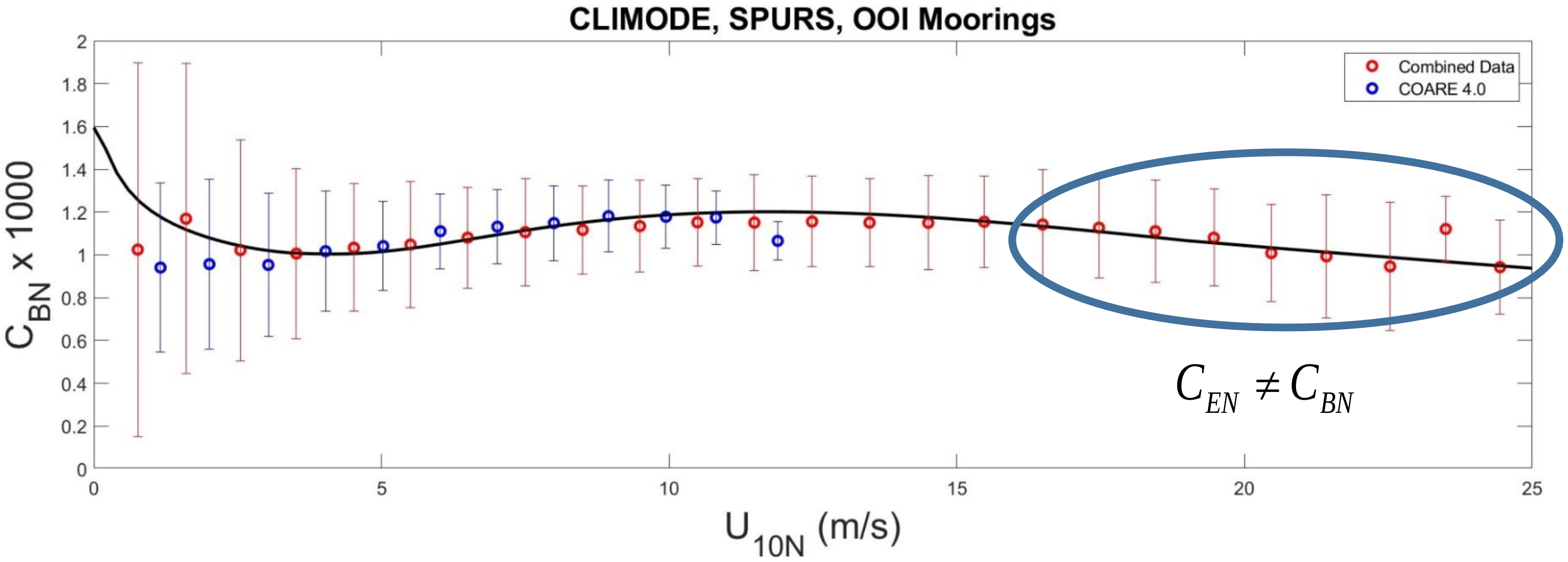
Not particularly different from COARE 3.5

Drag coefficient is in very good agreement with COARE 3.5



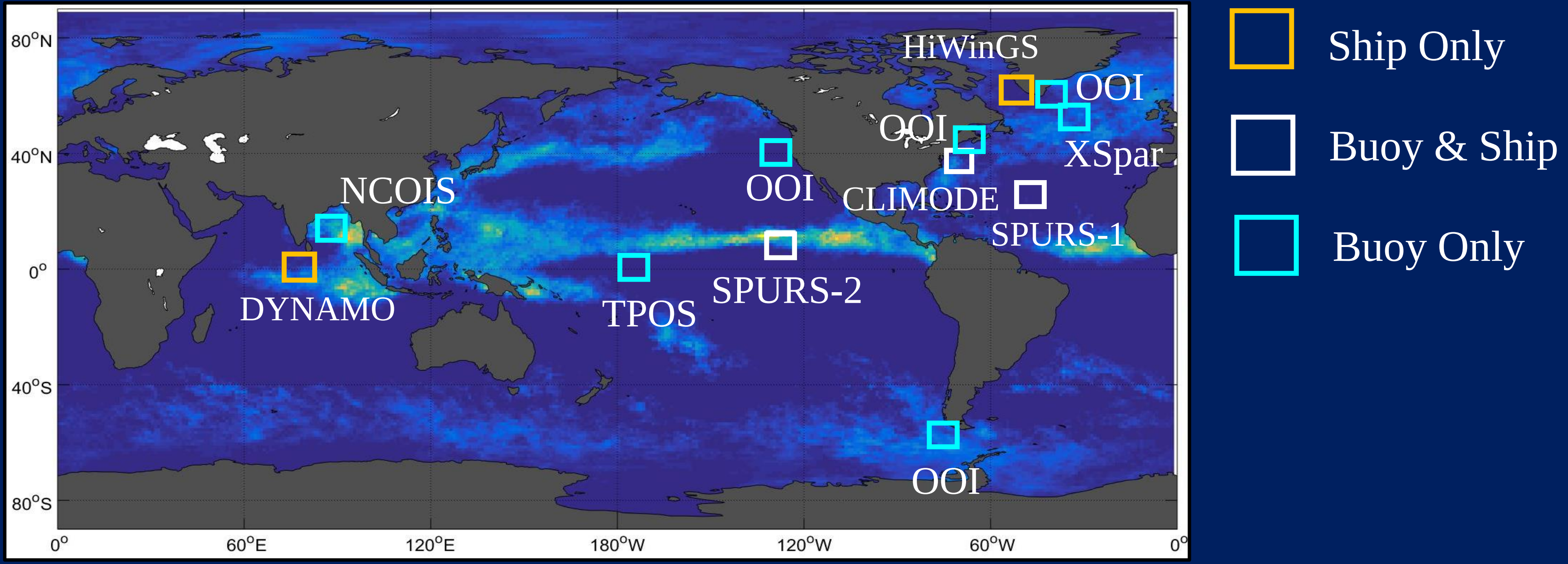
INCOIS Mooring looks very promising.

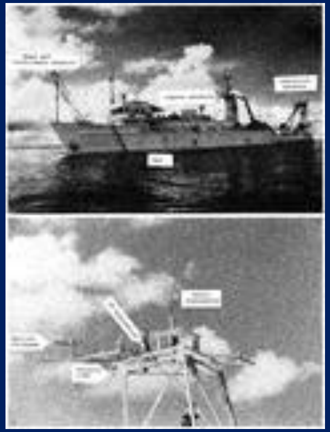
Hope to add a IRGA to XSpar



Combine Buoy & Ship Fluxes to Parameterize the Dalton & Stanton Numbers

Air-Sea Interaction Field Studies





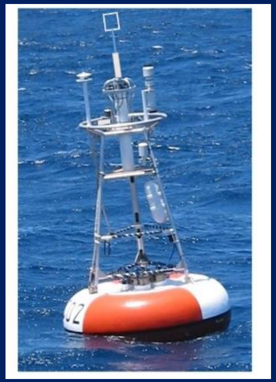
1992 TOGA COARE

2017 NASA SPURS

Air-Sea Interaction Spar (ASIS)

CLIMODE Year long

SPURS Latent Heat Flux



OOI, TPOS & XSpar Real-time Fluxes

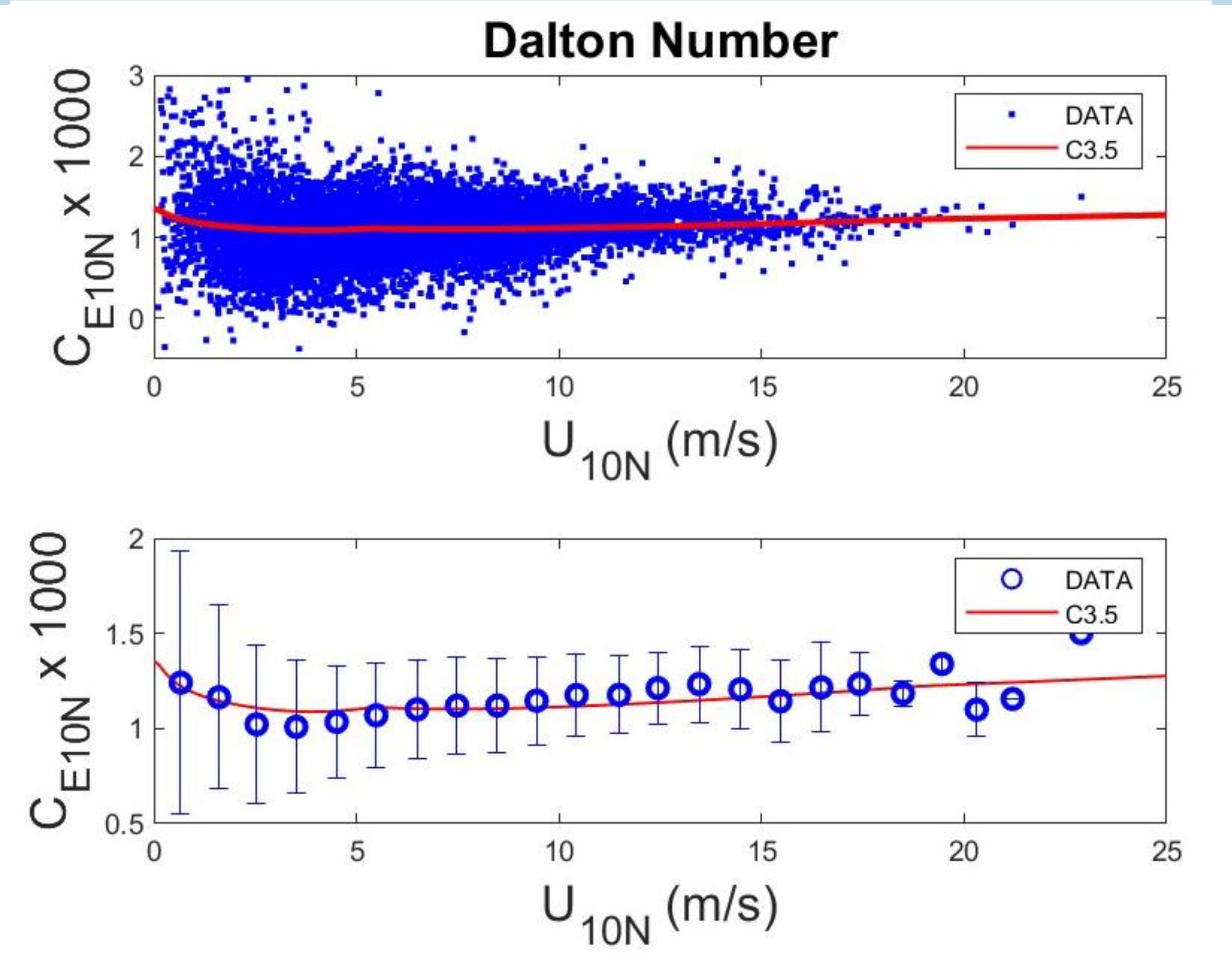
Ship-based Flux Systems

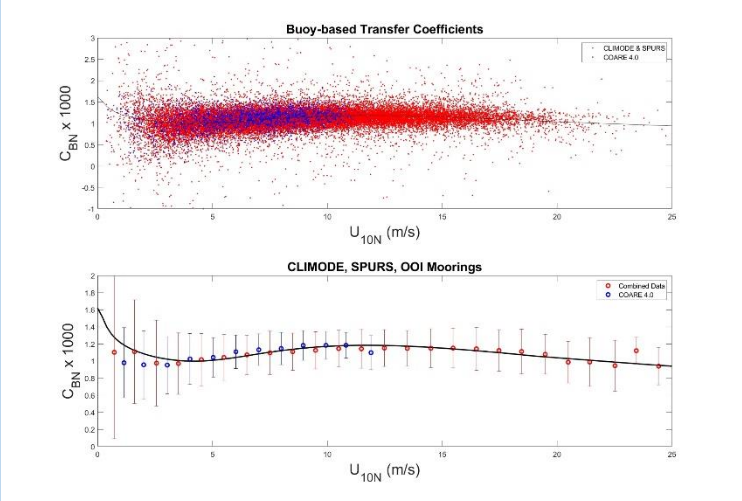
- DCFS.
- Open path hygrometers
- Closed path hygrometer
- Aspirated RH/T sensors
- Solar/IR sensors
- Optical rain gauge
- Self-siphoning rain gauge

Challenge: Reduce Flow Distortion

- Optimal placement of sensors based on wind tunnel results and high-resolution models.
- Empirical corrections for flow distortion on the means based on LIDAR and other measurements.
- New methodologies for reduced flow distortion such as
  - Landwehr, S., N. O'Sullivan, and B. Ward, 2015: Direct flux measurements from mobile platforms at sea: Motion and airflow distortion corrections revisited. J. Atmos. Oceanic. Tech., 32, 1163- 1178.

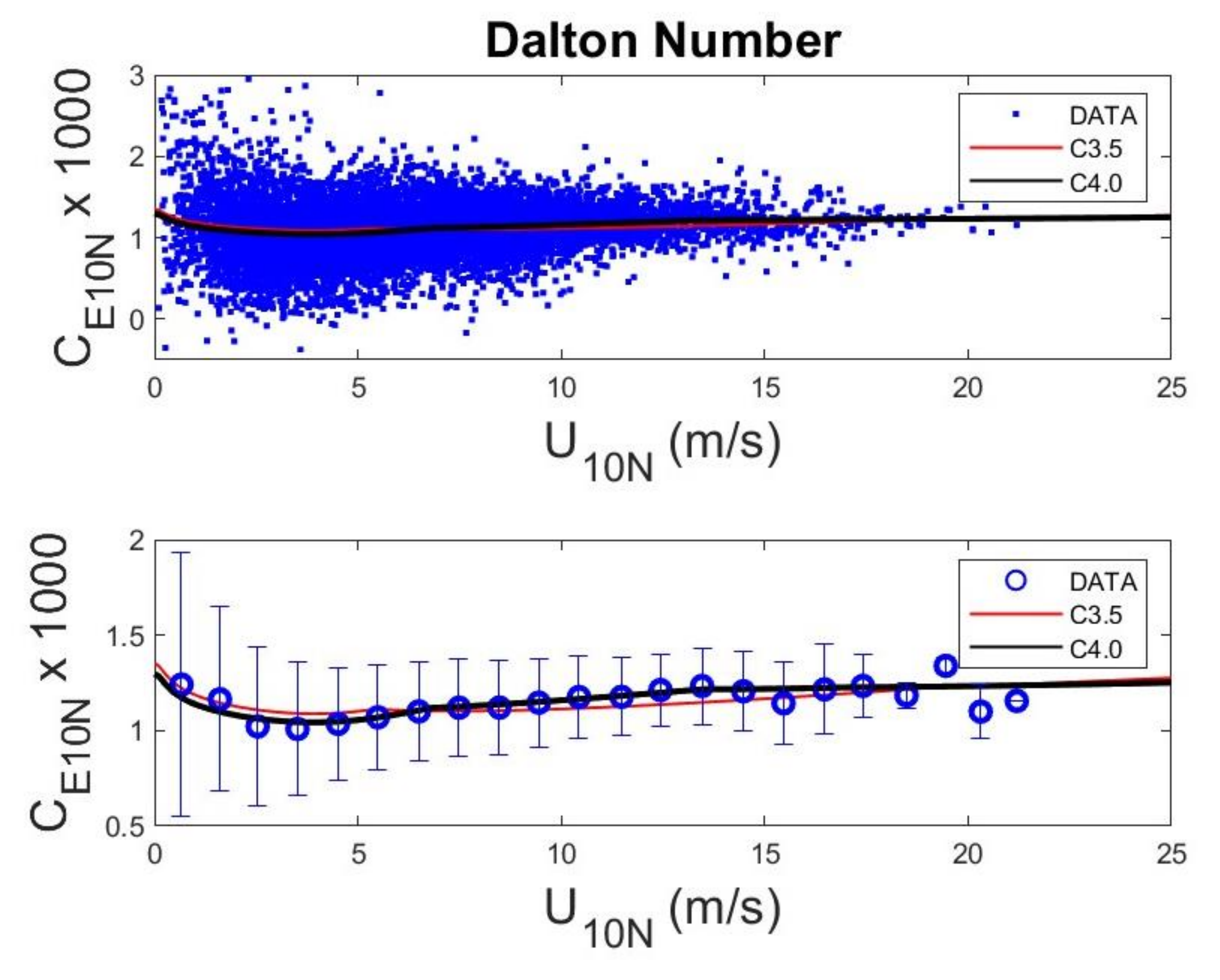
Ship & Buoy-based Dalton Numbers

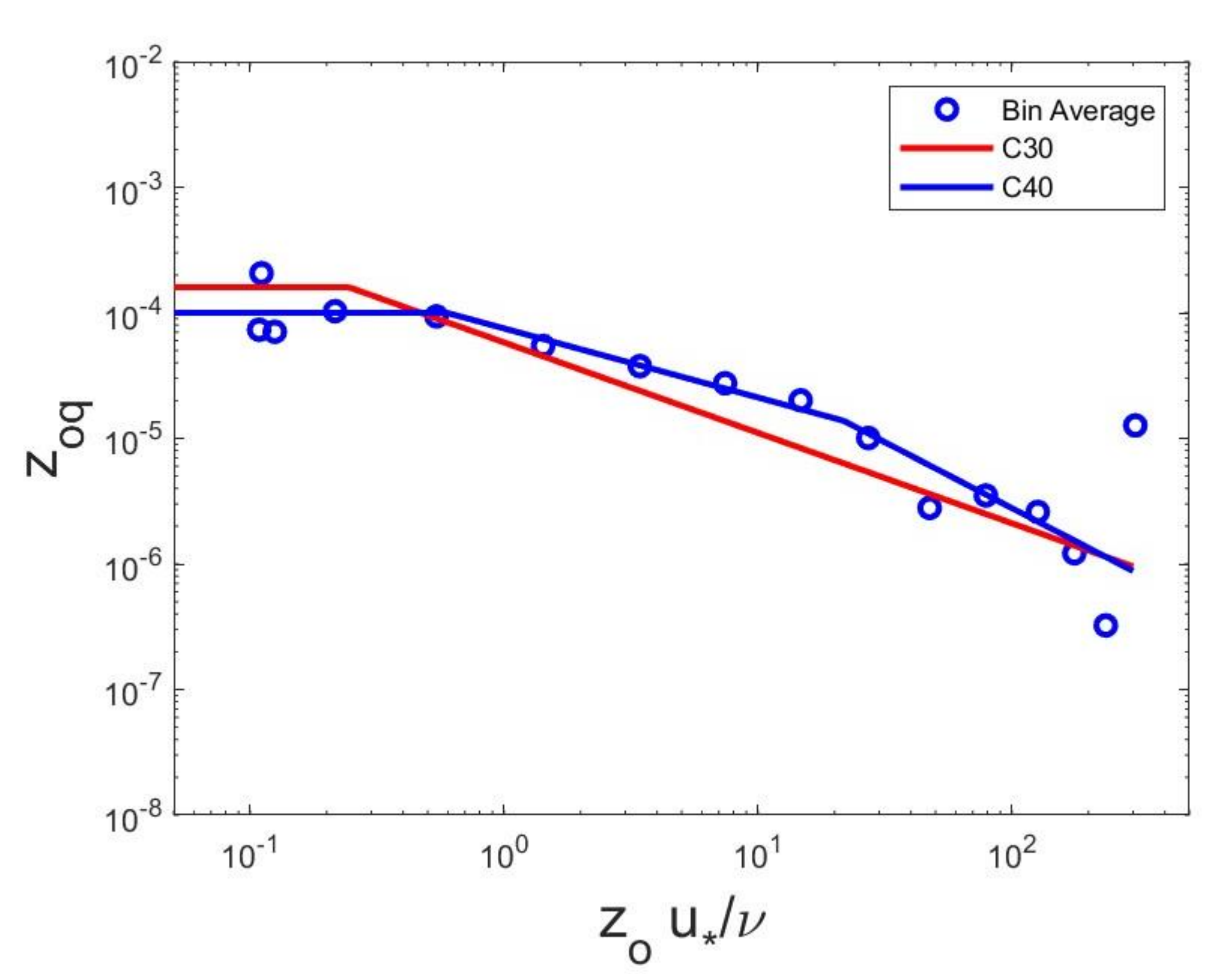




$$C_{EN} = -\frac{\overline{wq}}{\Delta Q\,\Delta U_N\,G} = C_{DN}^{1/2}\left(\frac{\kappa}{\ln(z/z_{oq})}\right)$$

Ship & Buoy-based Dalton Numbers

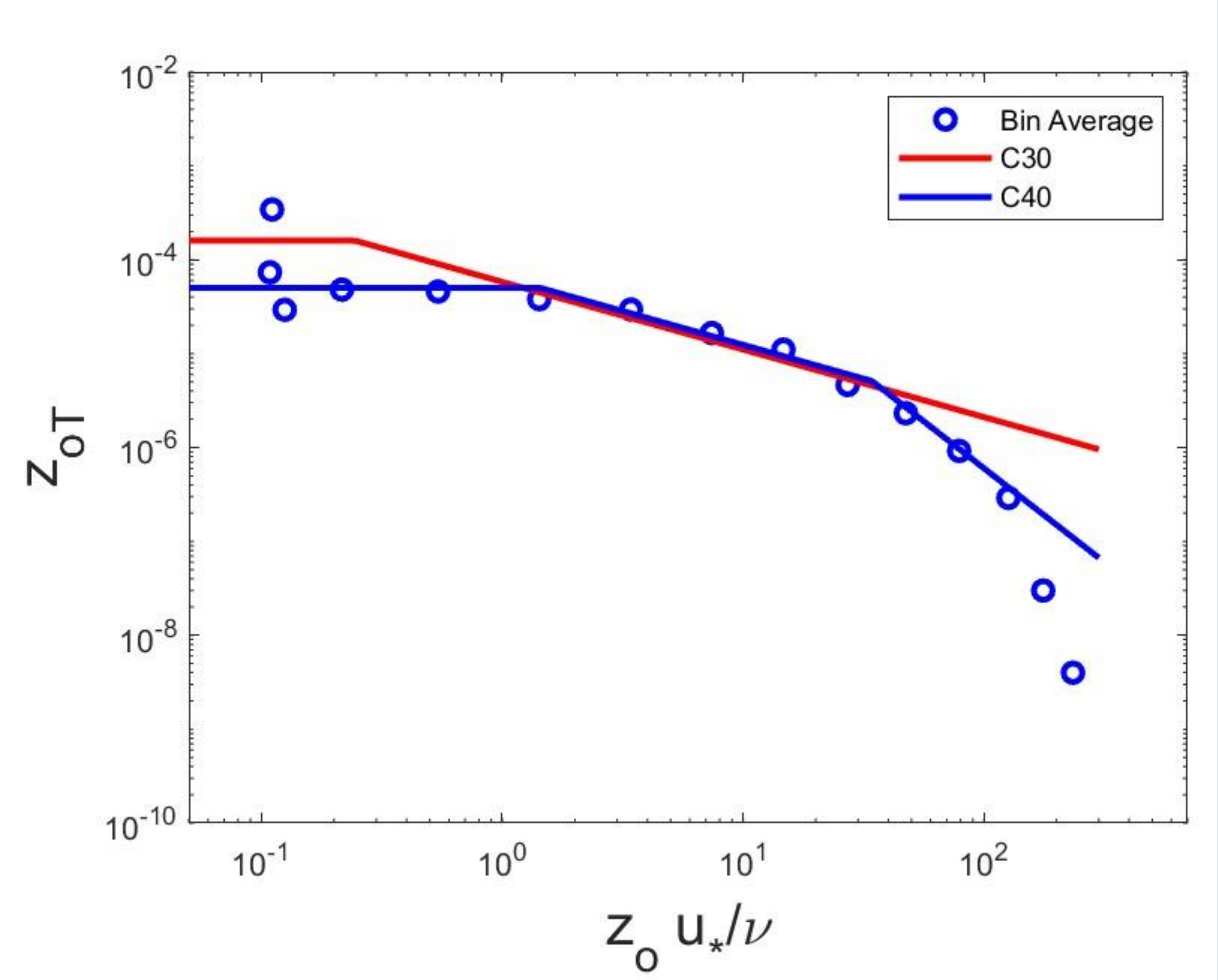


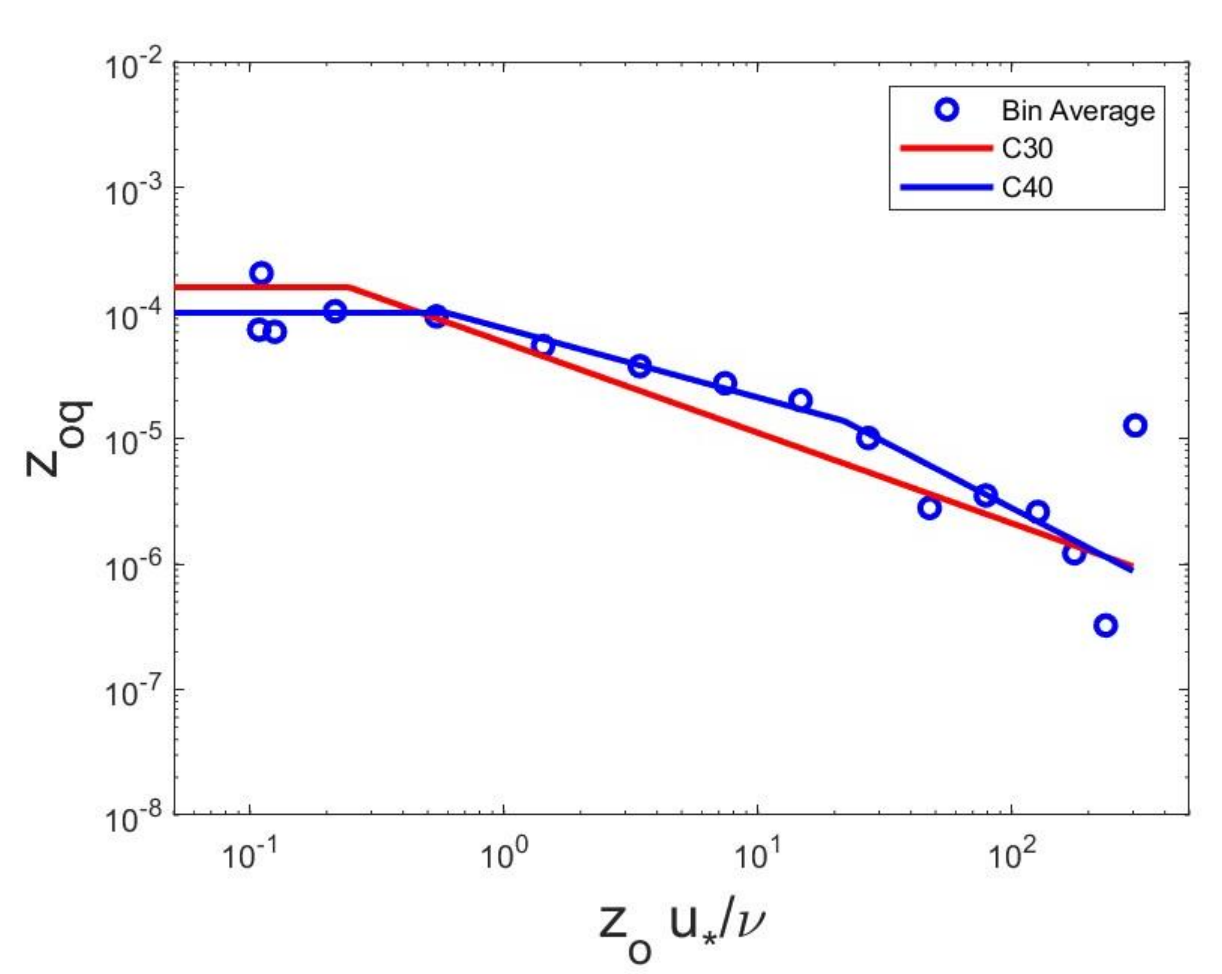


$$C_{EN} = -\frac{\overline{wq}}{\Delta Q \, \Delta U_N G} = C_{DN}^{1/2}\left(\frac{\kappa}{\ln(z/z_{oq})}\right)$$

$$z_{oq} = \mathrm{f}\left(\frac{z_o u_*}{\nu}\right)$$

Ship & Buoy-based Dalton Numbers





$$z_{oT} = \mathrm{f}\left(\frac{z_o u_*}{\nu}\right)$$

$$z_{oq} = \mathrm{f}\left(\frac{z_o u_*}{\nu}\right)$$

A NEW PLATFORM

2020 Hurricane Season

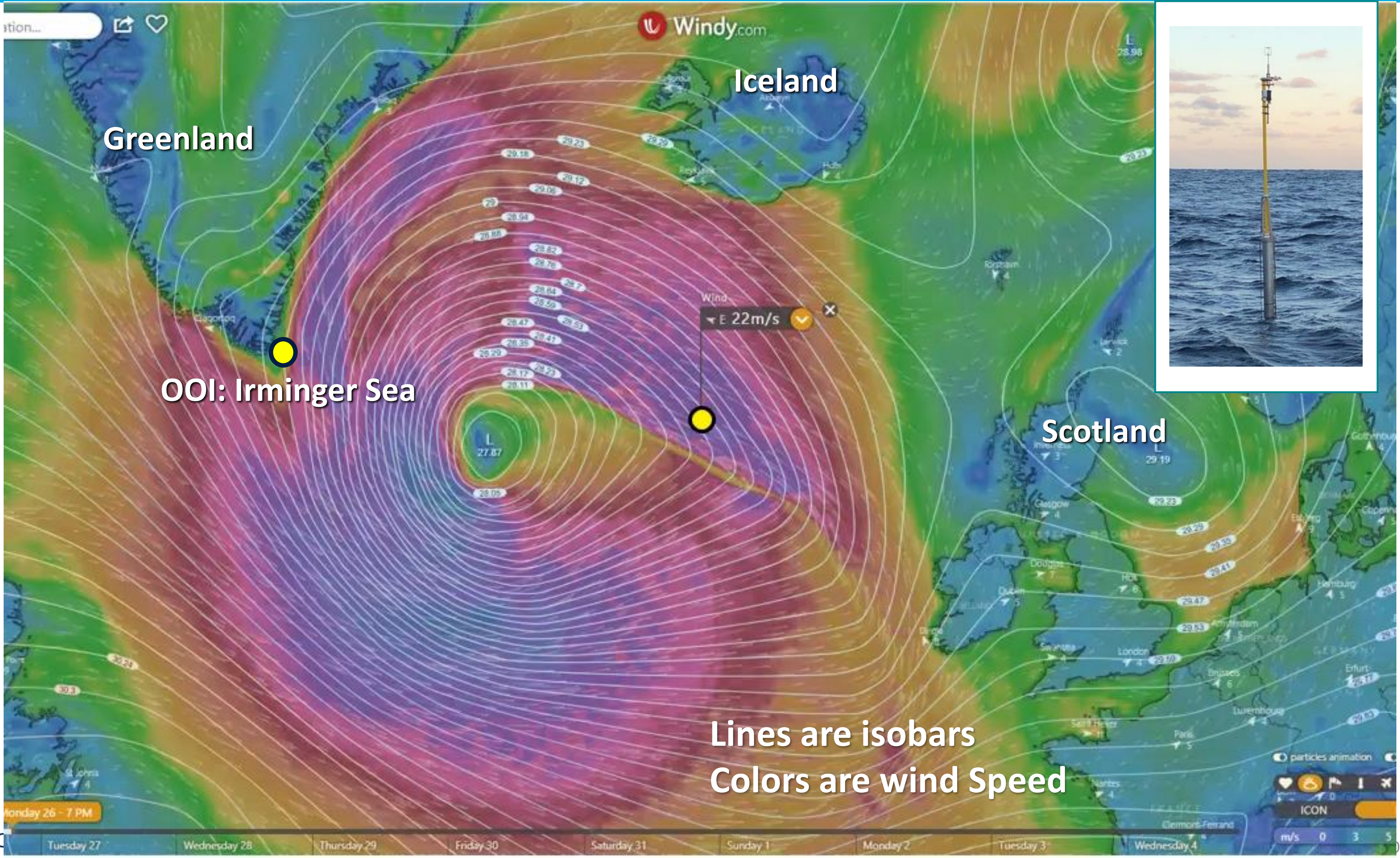
Very Active Hurricane Season

- 30 Named Storms from Arthur to Iota
- 14 Hurricanes
- 7 Major Hurricanes
- 11 Storms made landfall
- 6 as Hurricanes

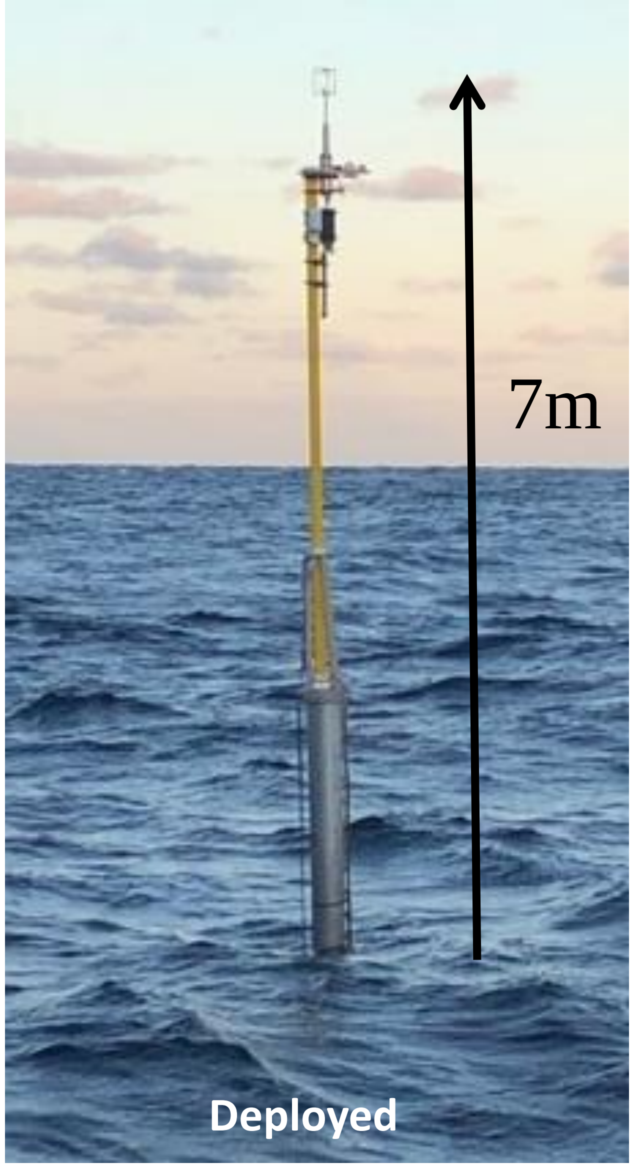
Epsilon

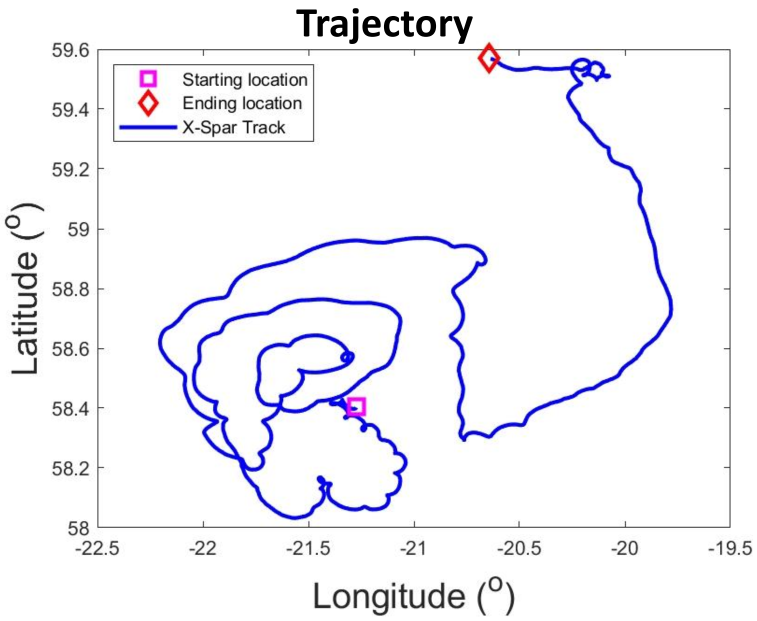
WHOI Science + Engineering = X-Spar

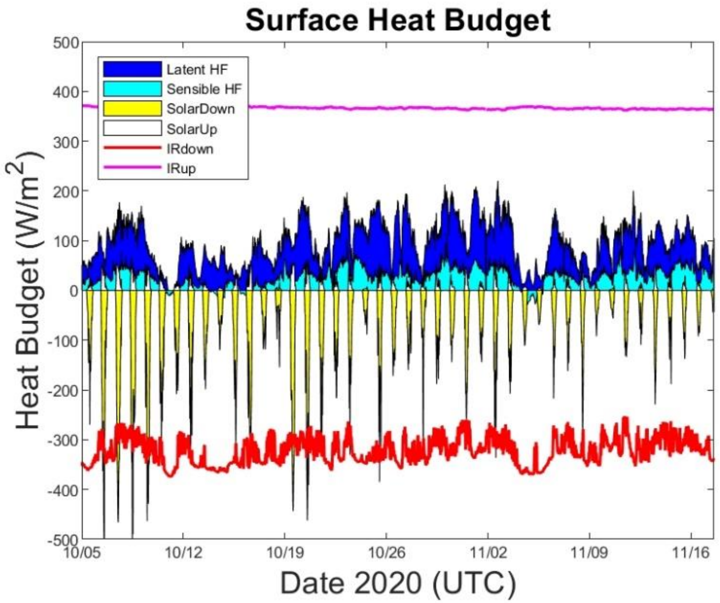
Through the Eye of Epsilon



The Drifting eXpendible Spar Buoy (X-Spar)

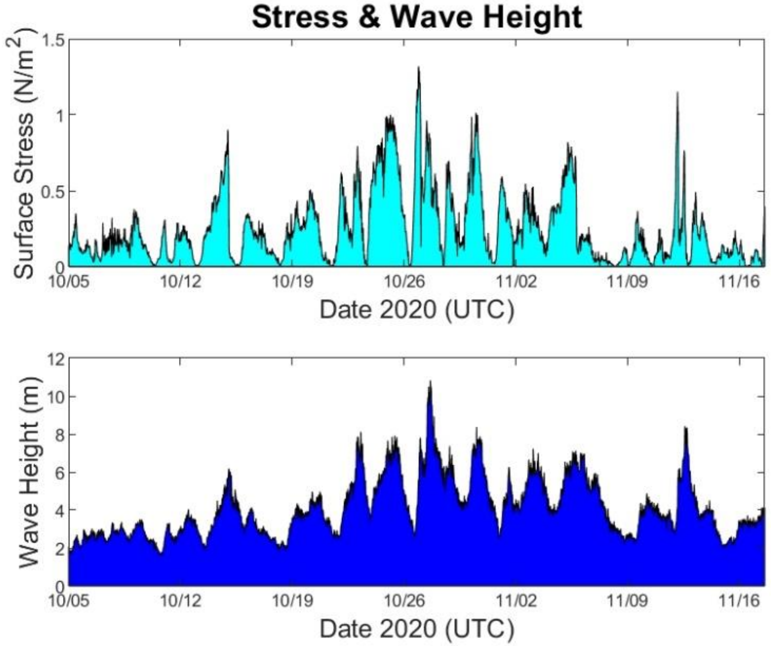






- Real-time direct covariance platform for stress and buoyancy fluxes.
- Battery pack could run DCFS for 14 months
- It could run a DCFS/IRGA for ~10 months to measure latent and sensible heat flux

Recovered



Woods Hole Oceanographic Instit

Summary

- Marine physicists have made significant progress in recent decades in our ability to directly measure surface fluxes from research vessels, moored buoys and, most recently, mobile platfroms.
- These platforms utilize Direct Covariance Flux Systems (DCFS) to remove platform motion from the measured wind speeds to measure the flux directly.
- Over the past decade or so, researchers have begun to collect long time series, O(year), of momentum and buoyancy fluxes from surface moorings that experience less flow distortion over a wider range of conditions.
- The accuracy of the COARE transfer coefficients continues to improve over a wind range of wind speeds.
- Understanding the relationship of the transfer coefficients to wave driven processes at low winds and their behavior at high to extreme winds remain major objectives.
- This includes sensors to measure latent heat fluxes on research moorings and some mobile platforms to improve the heat flux parameterizations at all wind speed.
- Recent result suggest that he heat and moisture coefficients are different, which will impact model output and global budgets.

THANK YOU

Relative Velocity

$$C_{DN}(z/z_o) = \frac{-\overline{uw}}{\Delta U_N G} = \left(\frac{\kappa}{\ln(z/z_o)}\right)^2$$