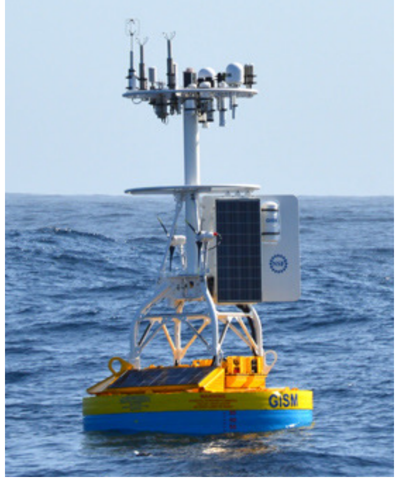
An Armada of Assets for Air-Sea Interaction Research

James Edson & Numerous Colleagues

Woods Hole Oceanographic Institution

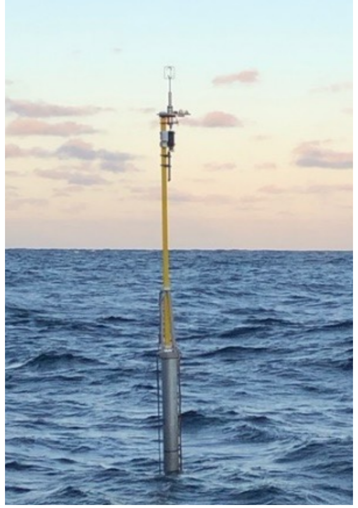
Ocean Observatories Initiative (OOI)

CLIMODE
Year long



OOI
Real-time Fluxes

SPURS
Latent Heat Flux



X-Spar
Long duration
Real-time Fluxes

Saildrone
Long duration
Mobile

OCEAN OBSERVATORIES INITIATIVE

US CLIVAR Mesoscale and Frontal-Scale
Air-Sea Interaction Workshop
March 6-8, 2023   Boulder, CO

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

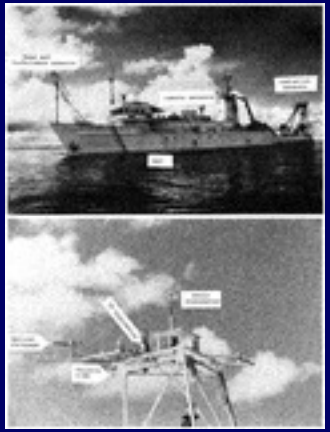
Momentum Flux: $\tau_o = \rho_a \overline{uw} = \rho_a C_D S_r \Delta U$ Drag Coefficient

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 $E = Q_E/(\rho_w L_v)$

Saildrone
Mobile Fluxes



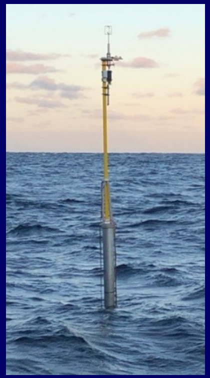
1992 TOGA COARE

2017 NASA SPURS

Air-Sea Interaction Spar (ASIS)

CLIMODE Year long

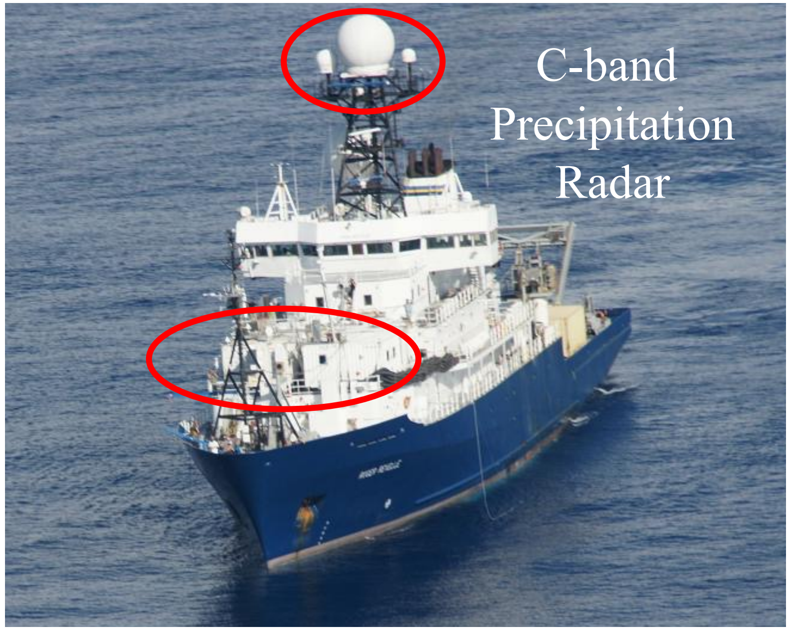
SPURS Latent Heat Flux

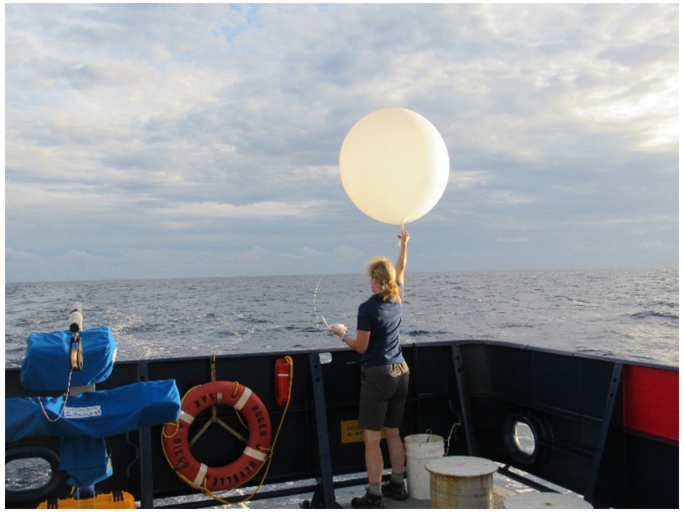


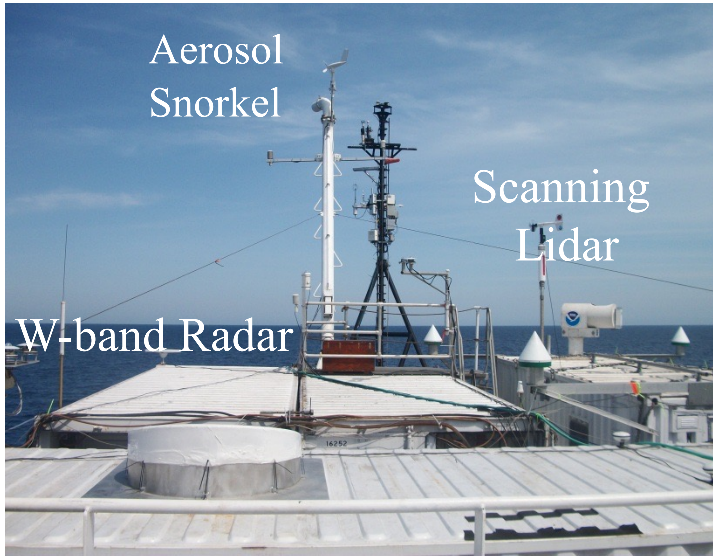
OOI, TPOS & XSpar Real-time Fluxes

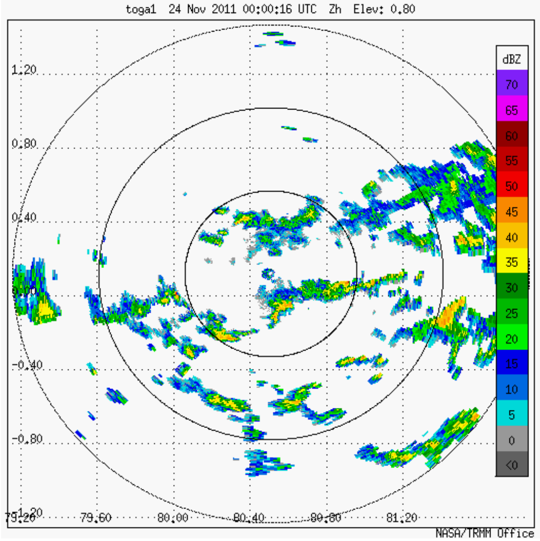
Ships

- 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.





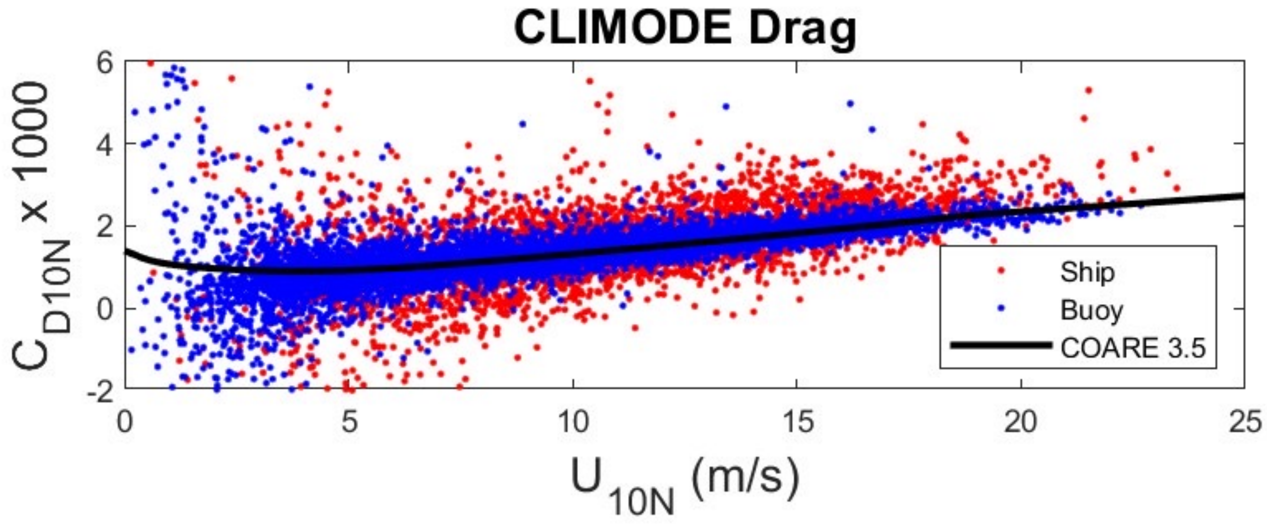


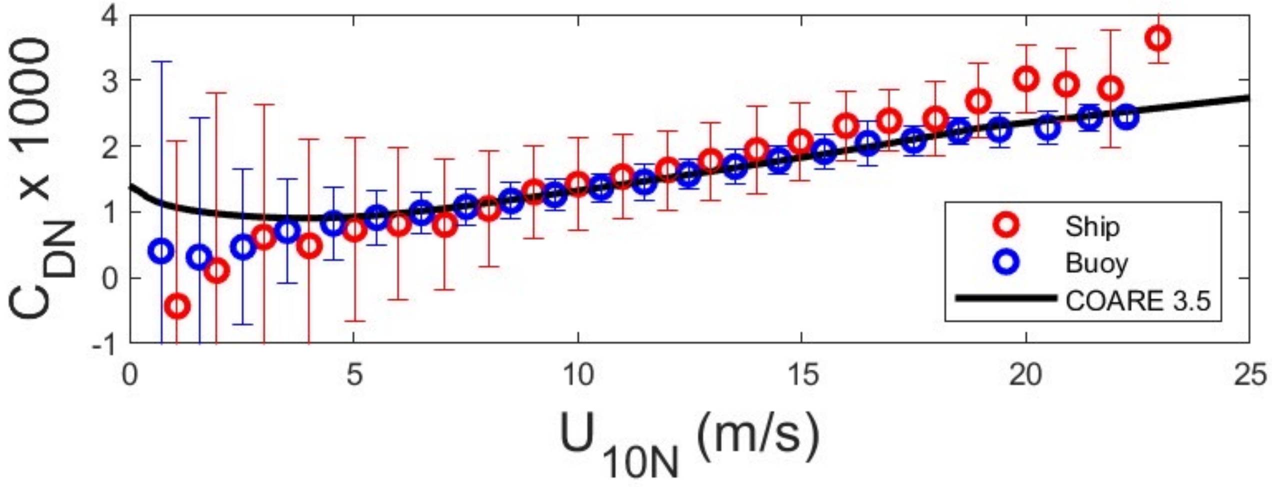


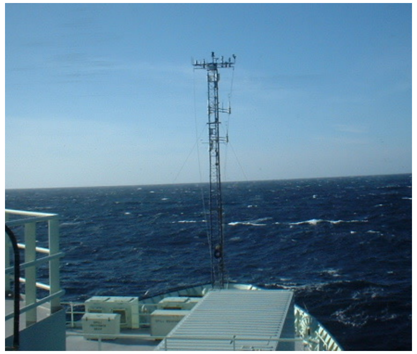
Ship Drag Coefficient – Flow Distortion

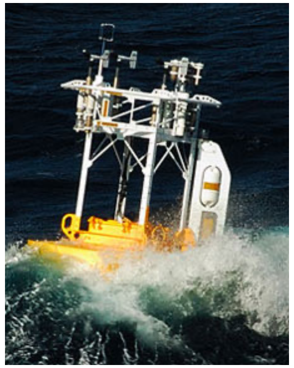
- Optimal placement of sensors based on wind tunnel results and high-resolution models.
- Empirical corrections for flow distortion on the means based on LIDAR and other measurements.
- New methodologies for reduced flow distortion such as:

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.



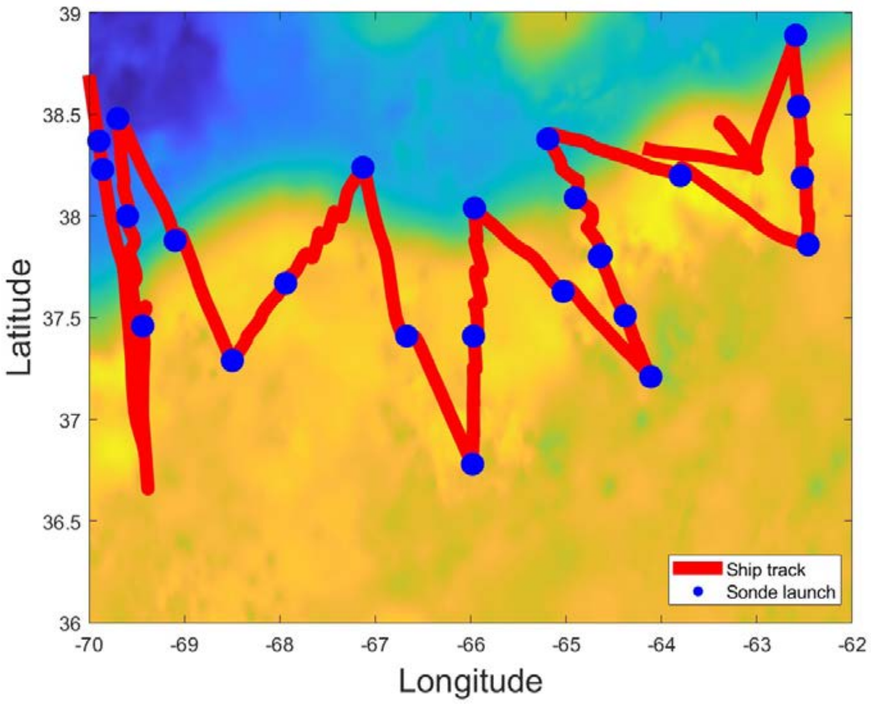




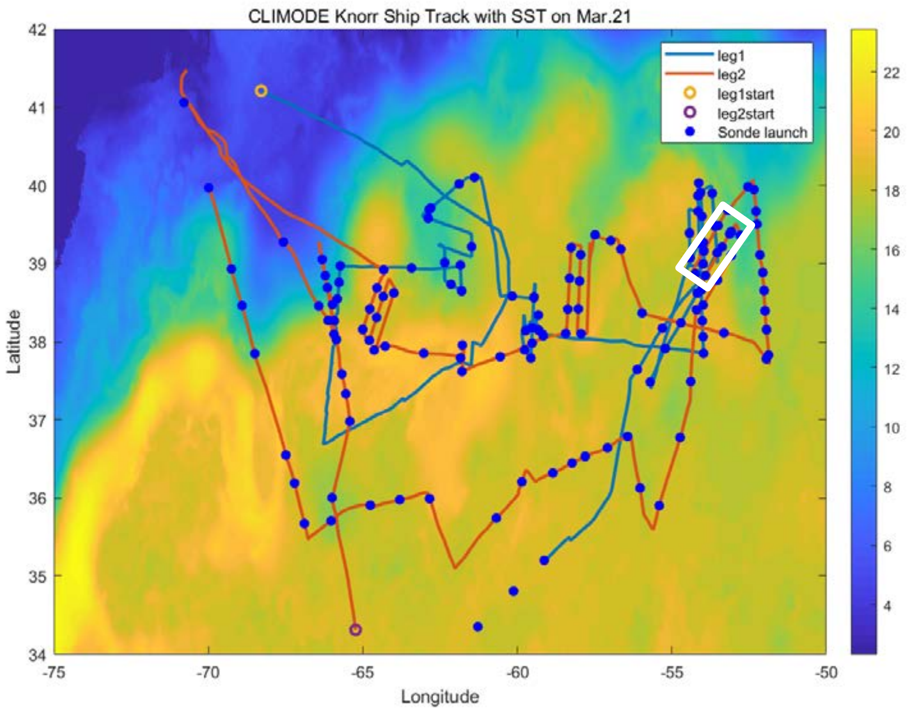


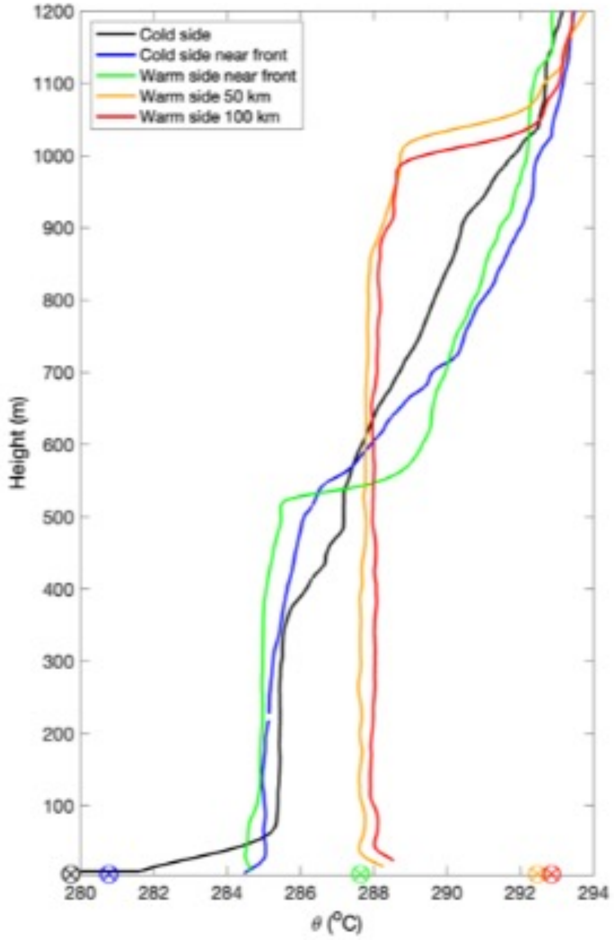
Ship Transects

CLIMODE Pilot Cruise (2006)



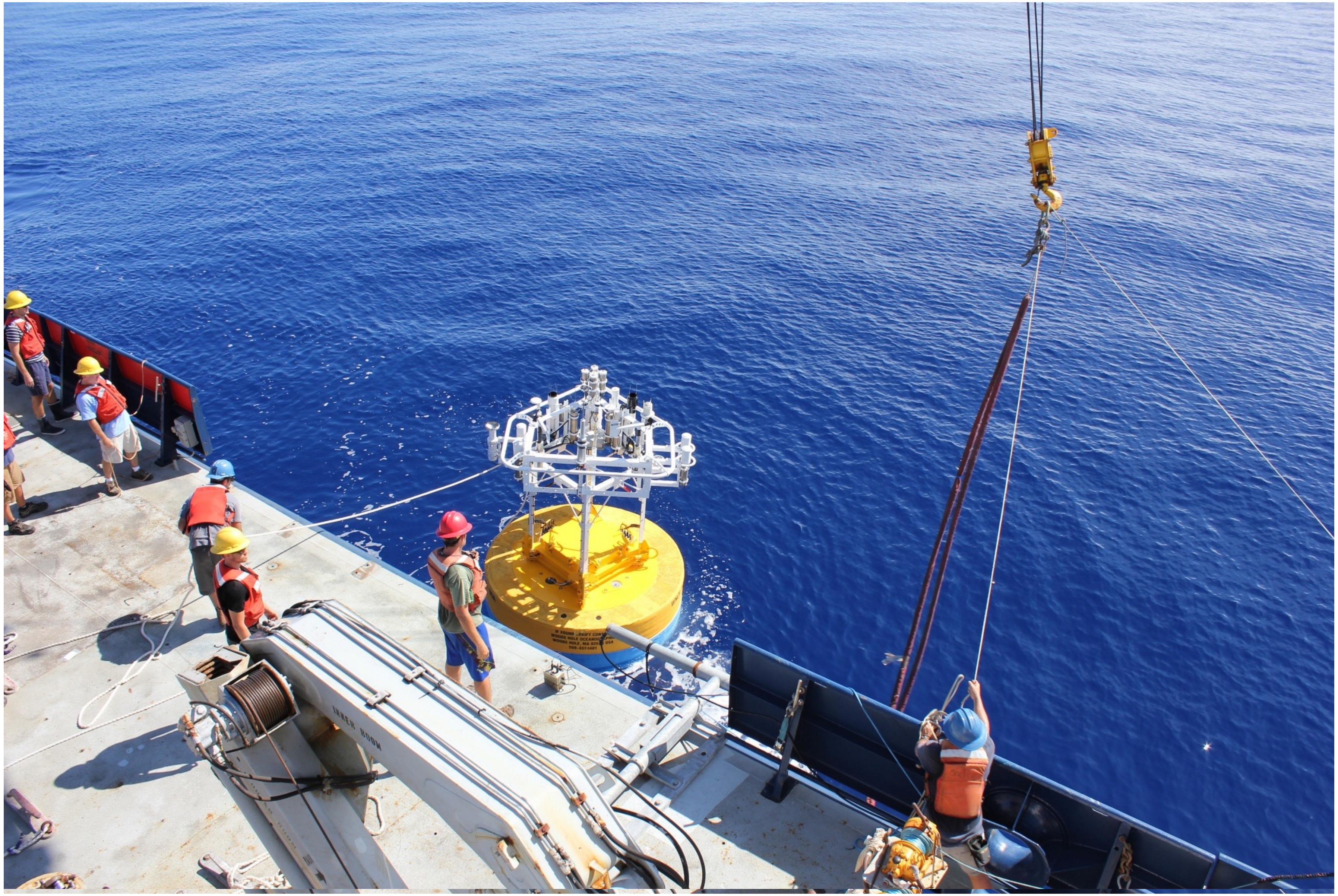
CLIMODE Main Cruise (2007)



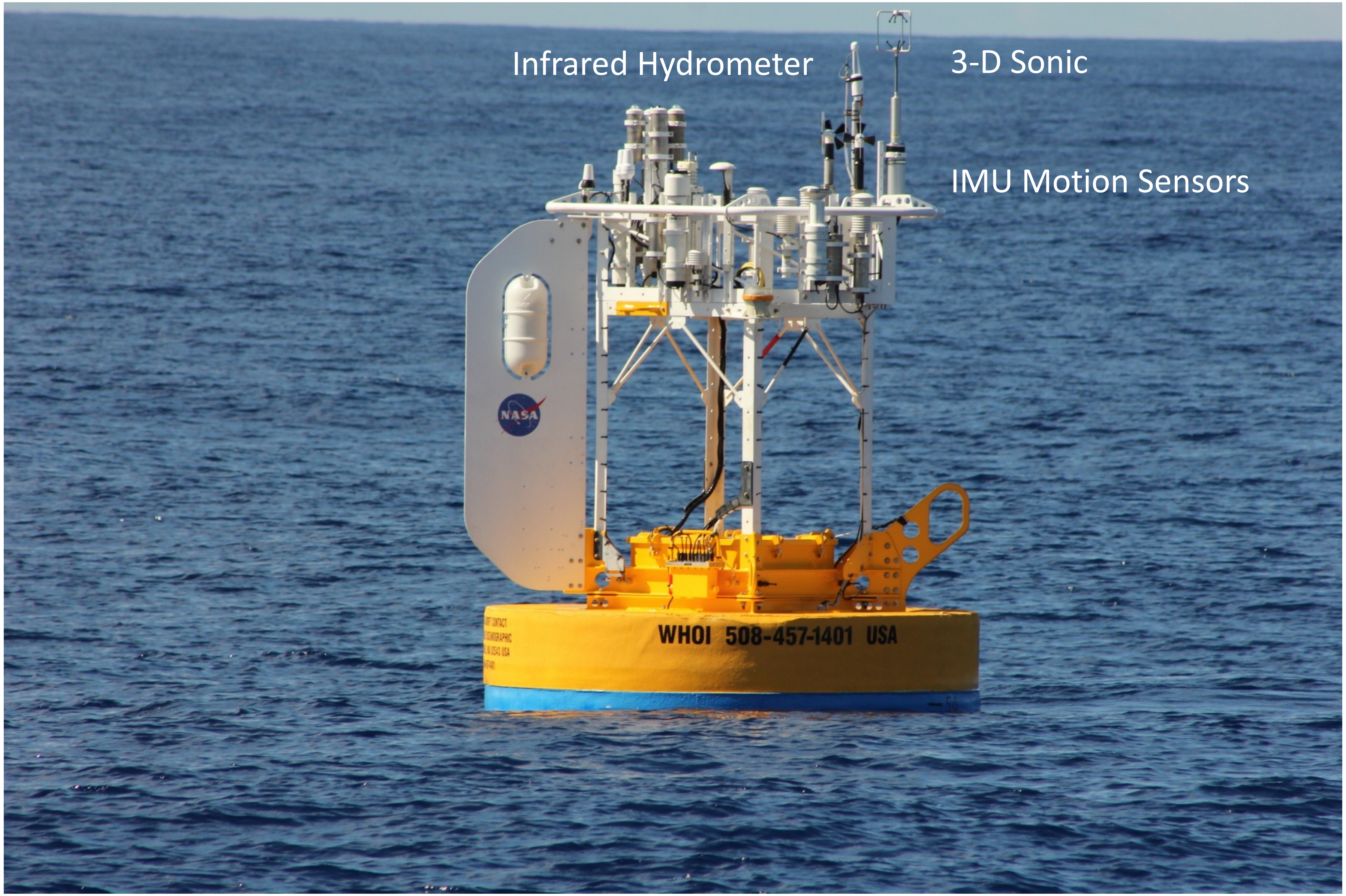


Cruise needs to be dedicated to Air-Sea Interaction

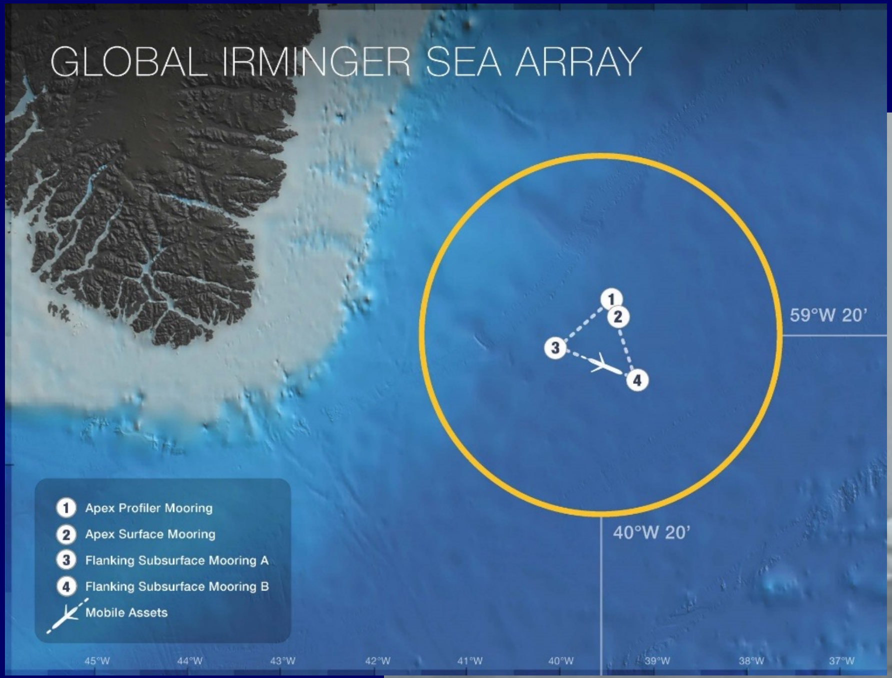
Surface Moorings from Ships



Surface Moorings



Platform Motion



Motion Correction

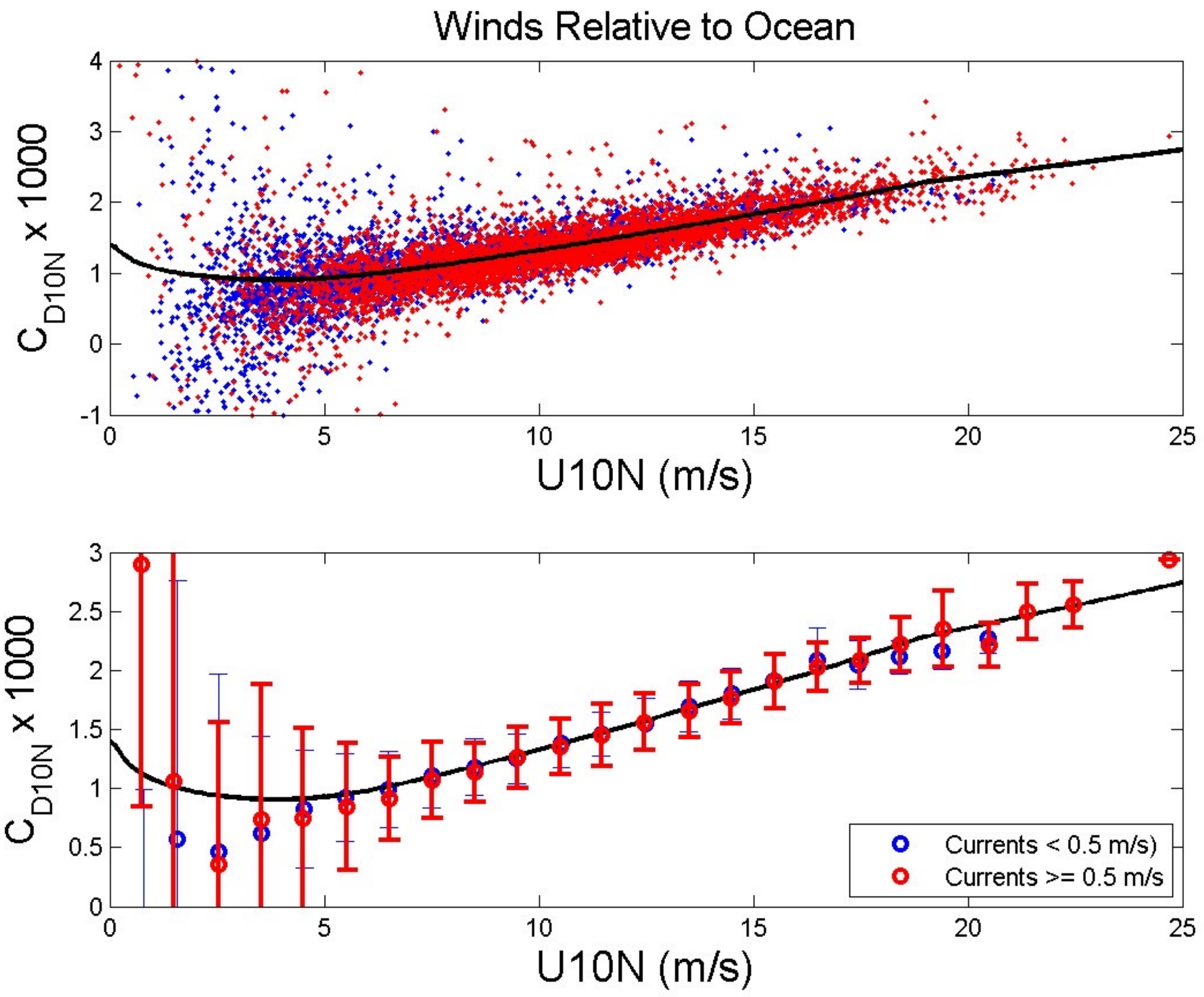
$$U_{true}^{water} = T(\phi,\theta,\psi)\left[U_{obs} + \Omega_{obs} \times R\right] + V_{hp} + V_{lp}$$

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

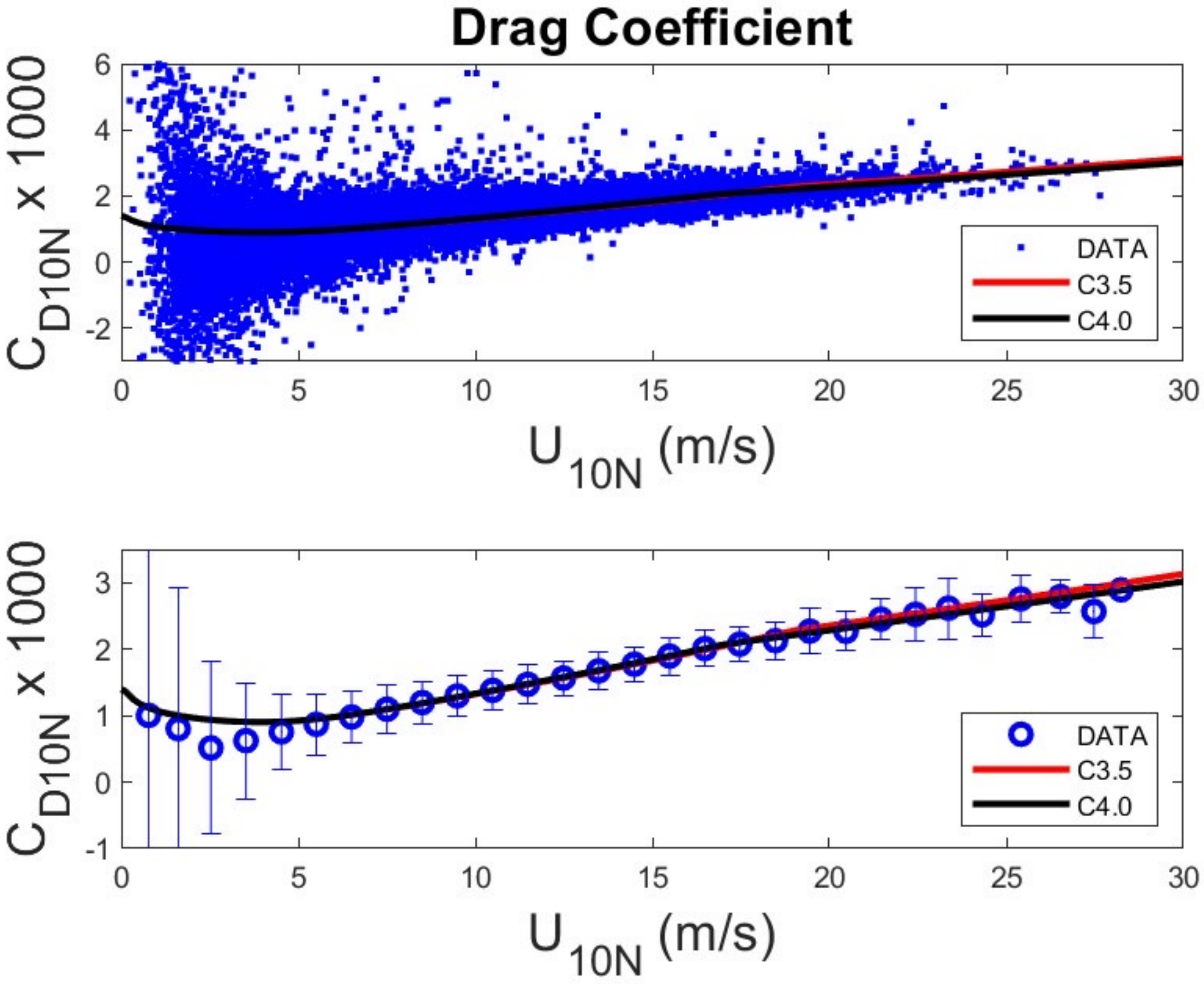
Relative Velocity

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

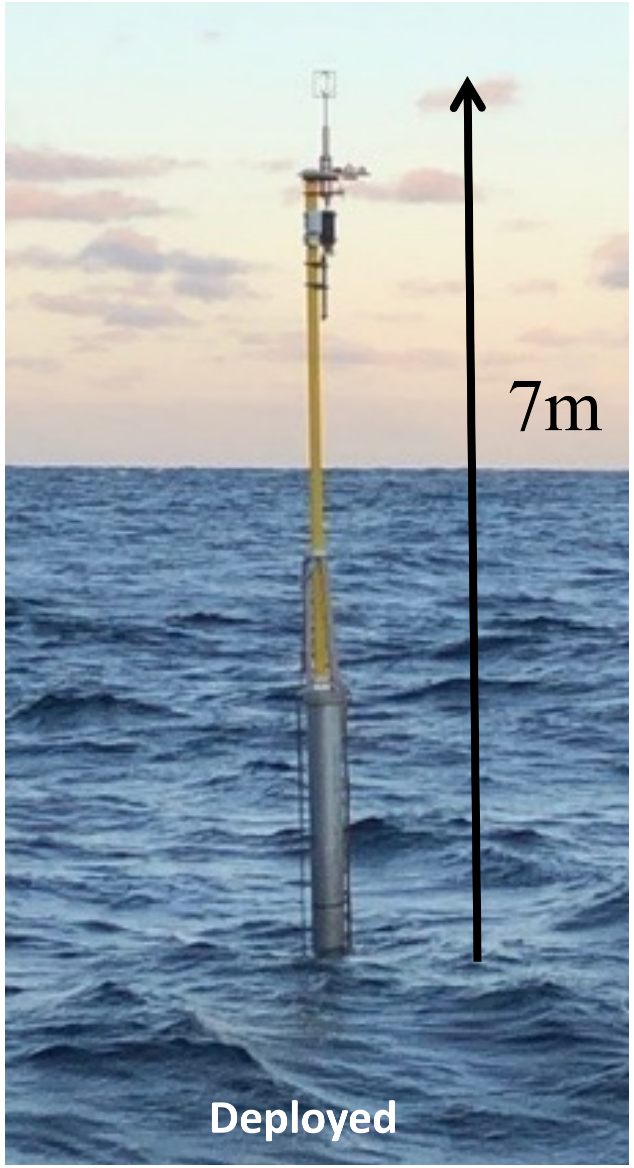


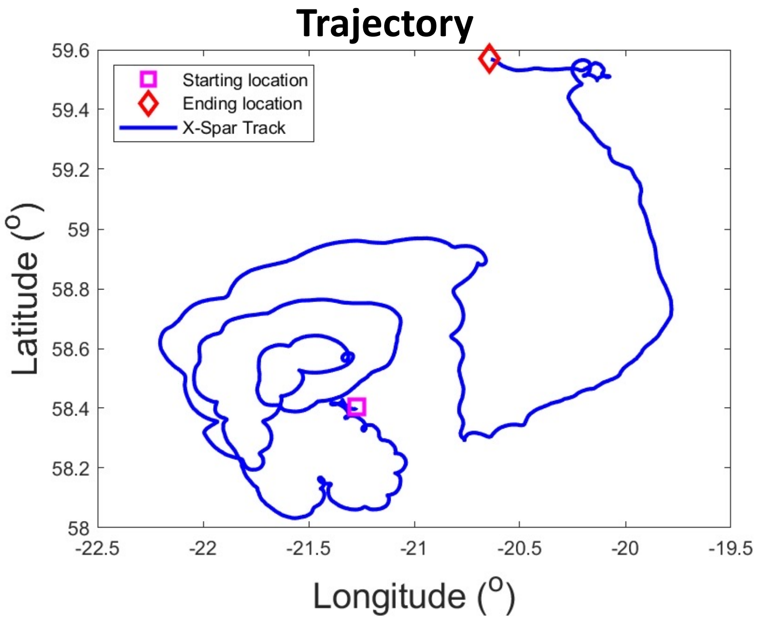
COARE: A Global Formulation using a Growing Global Array

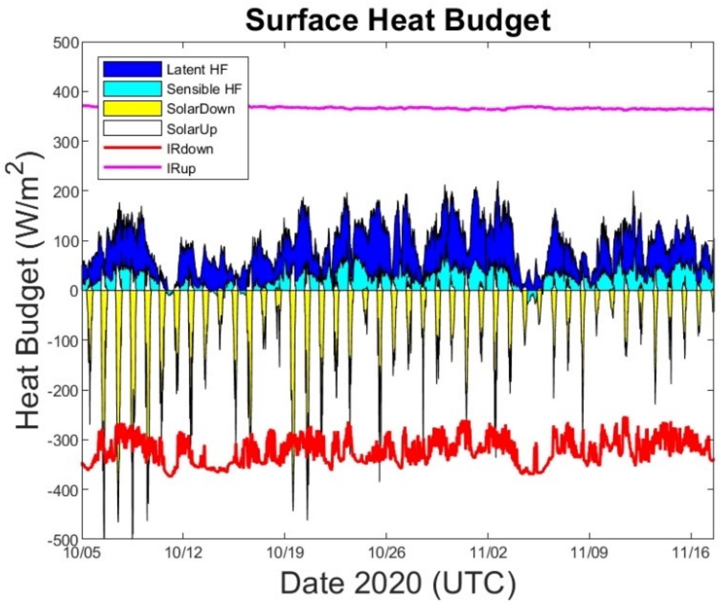
$$C_{DN} = -\frac{\overline{uw}}{U_{rN}^2 G} = \left(\frac{\kappa}{\ln(z/z_0)}\right)^2 \qquad \alpha = \frac{g z_0}{u_*^2} = f(U_{10N})$$



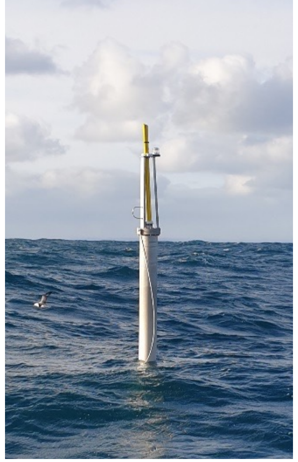
The Drifting eXpendible Spar Buoy (X-Spar)



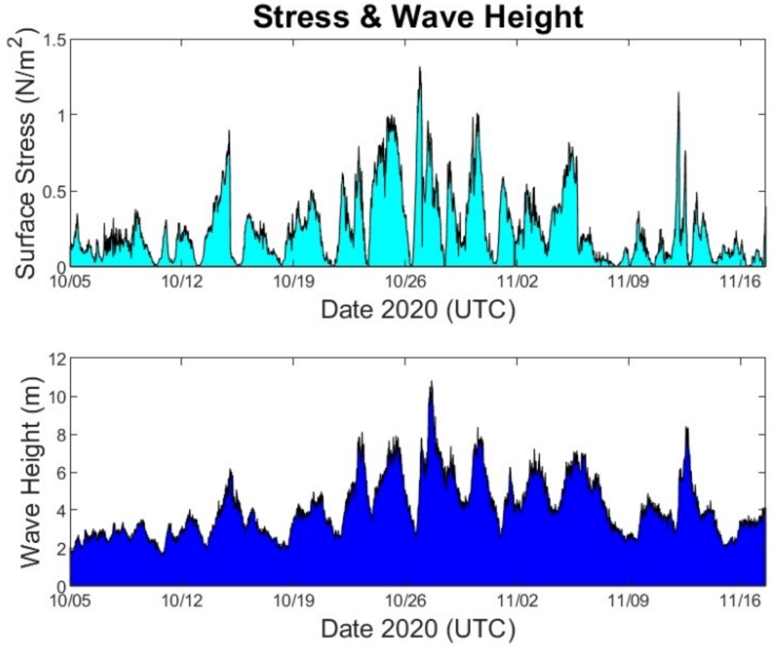




- Real-time direct covariance platform for stress and buoyancy fluxes.
- Battery pack could run DCFS for 14 months
- It could run a DCFS/IRGA for ~10 months to measure latent and sensible heat flux



Recovered



Woods Hole Oceanographic Instit

Measuring Horizontal Variability Uncrewed Surface Vessels (USV)

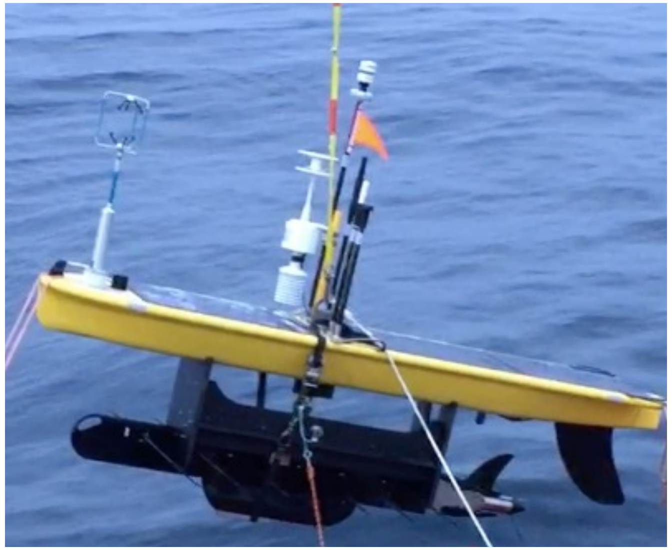
Saildrone
Wind Powered
Long Duration
Not Fast

Saildrone

JetYak
Gas Powered
Short Duration
Fast

Peter Trakovski, WHOI

Wave Rider
Wave Powered
Long Duration
Not Fast

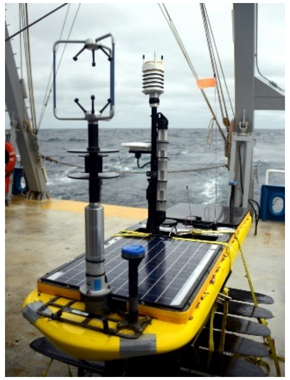


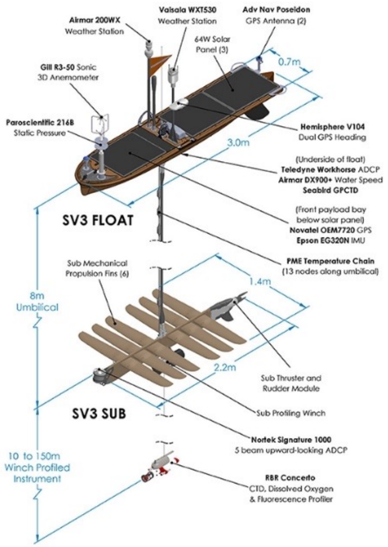
Wave Glider, UW-APL

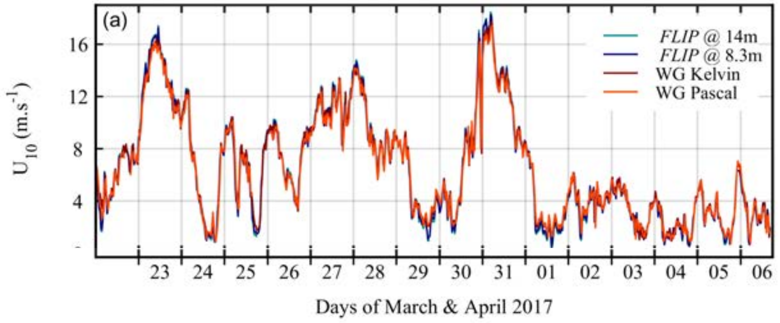
Wave Glider instrumented for air-sea interaction research

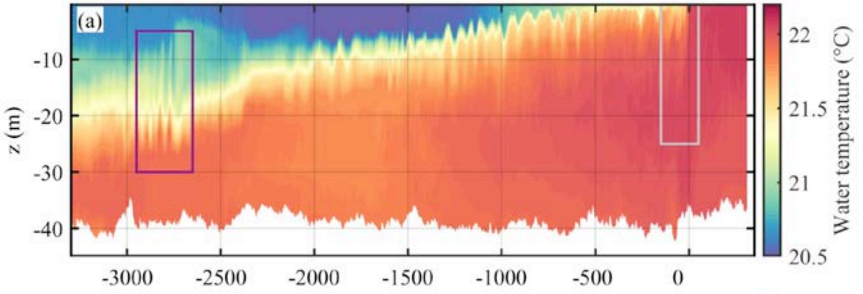
SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

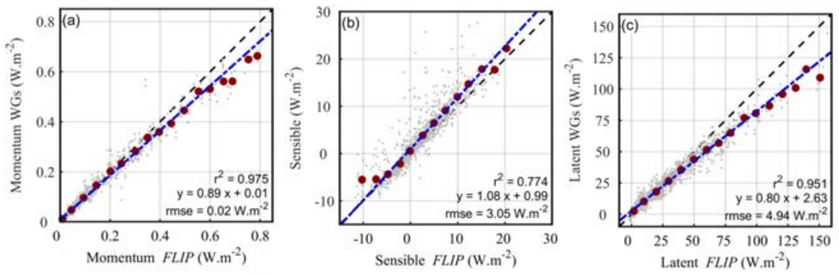
MABL, upper-ocean and surface properties characterization











Lenain et al. (2014), Grare et al. (2021), Grare et al. (2023)

Measuring Horizontal Variability Uncrewed Surface Vessels (USV)

Drix USV
iXblue/exail

Diesel Powered
~ 7-day Duration at 7 knots

Used for mapping.

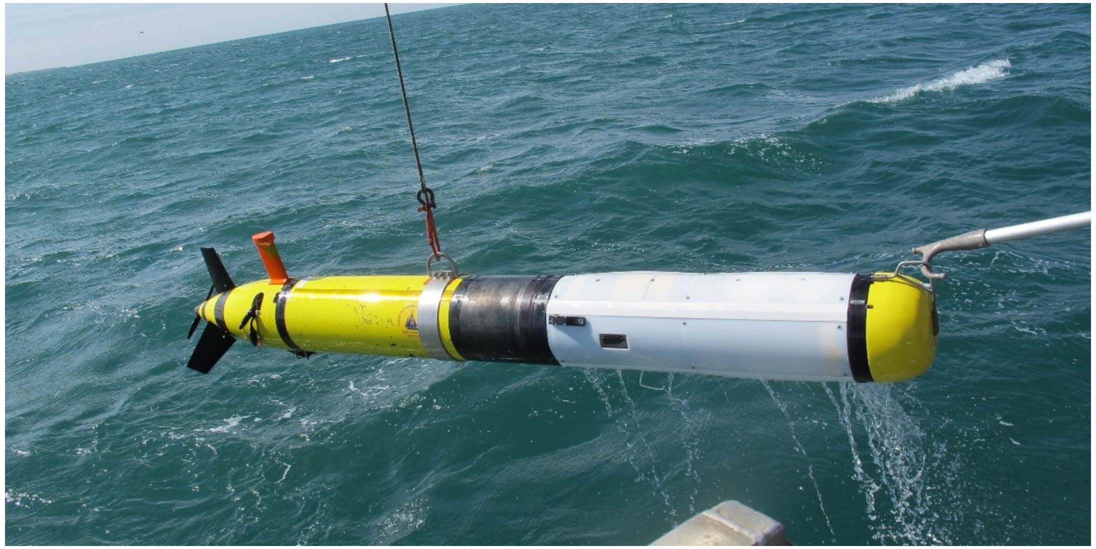
Met and other ocean sensors could be easily added.

Measuring Oceanic Variability with Autonomous Underwater Vehicles and Gliders

Slocum G3 Glider, Teledyne Webb Research
Buoyancy Driven
Long Duration
Slower speeds

REMUX AUV, WHOI
Battery Powered
Short Duration
Higher speeds

Glider, Jason Orfanon, MBL



REMUS, OSL, WHOI

Crewed Uncrewed Aerial Vehicles (UAV)

UAV, Luc Lenain, SIO/UCSD

UAV, Chris Zappa, LDEO/Columbia University

Quadcopter, Adam Shore, NOAA

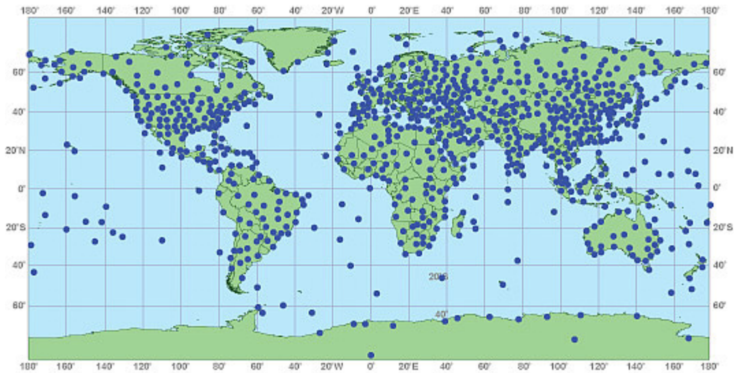
Twin Otter, NRL

Argo Floats Array

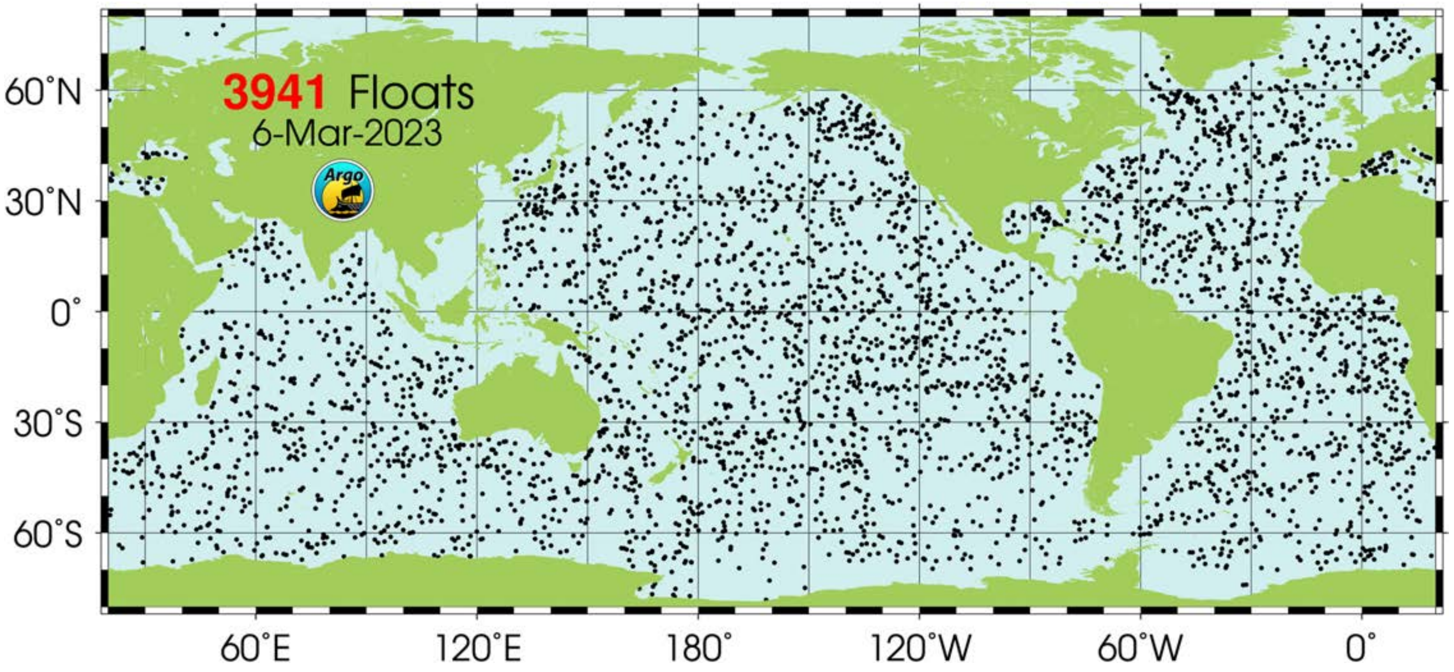
Argo by the Numbers

- 3900+ floats collecting data
- 800+ deployments total each year
- 1,964,000+ temperature and salinity profiles collected so far
- 26 countries participating
- 18 years of data collection
- 94% of Argo data is shared within 24 hours

Radiosonde/Rawinsonde Network



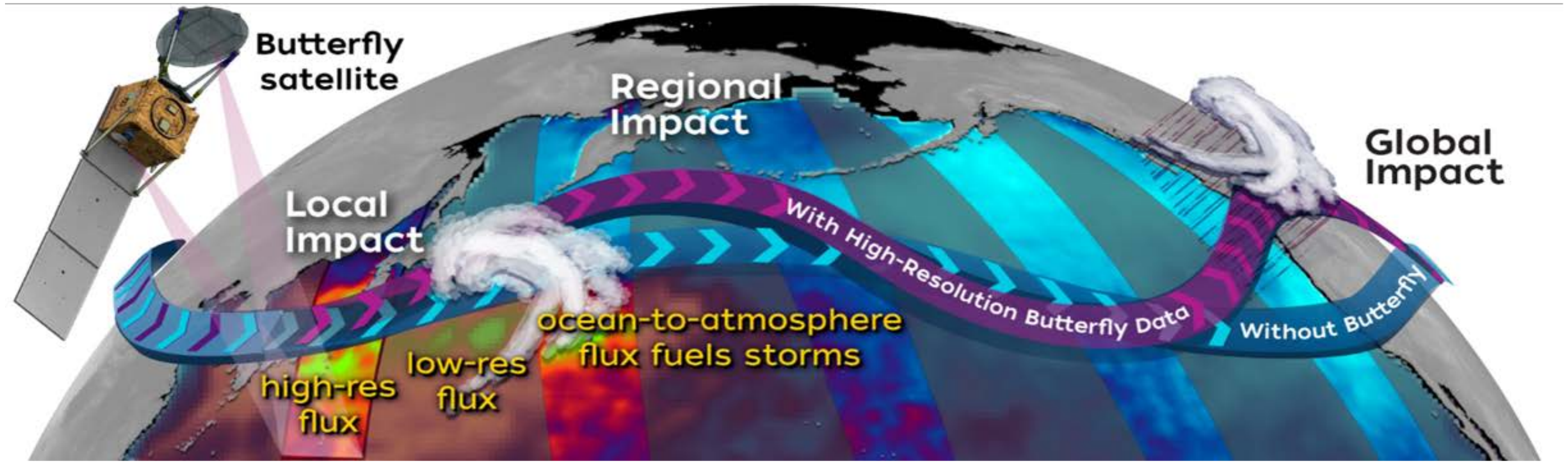
Ship deployed SOLO Floats



Air deployed ALAMO Floats

BUTTERFLY

revealing the oceans' impact on weather & climate



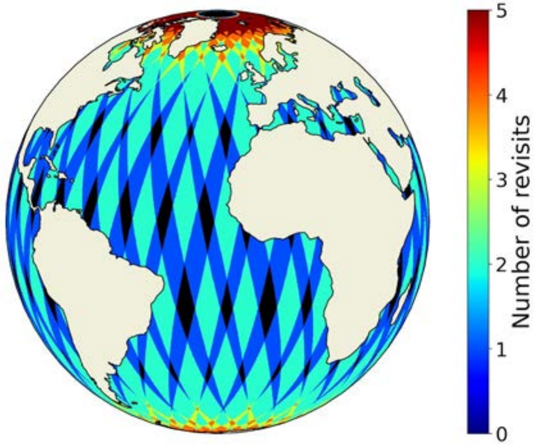
WHAT

Butterfly is the first satellite mission to **simultaneously** measure sea surface temperature, wind, & near-surface air temperature & humidity in order to estimate air-sea turbulent heat and moisture fluxes at a spatial resolution and accuracy sufficient to resolve the impact of small-scale ocean features on large-scale weather and climate.

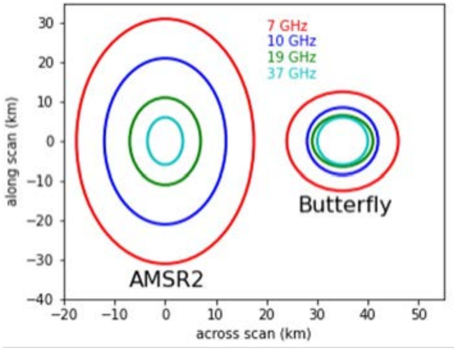
WHY

The ocean supplies the atmosphere with heat and moisture, dominating the global water and energy cycles while fueling weather and climate variability. Butterfly measures this air-sea exchange at spatial scales never before observed to unlock how the small-scale ocean "drives" the large-scale atmosphere, transforming predictability from mere days to weeks.

2-DAY COVERAGE



Mission	Details
Launch Date	4/2026
Length (minimum)	18-months
Orbit	>80° inclination
Swath Width	640 km
Resampled Footprint	20 km



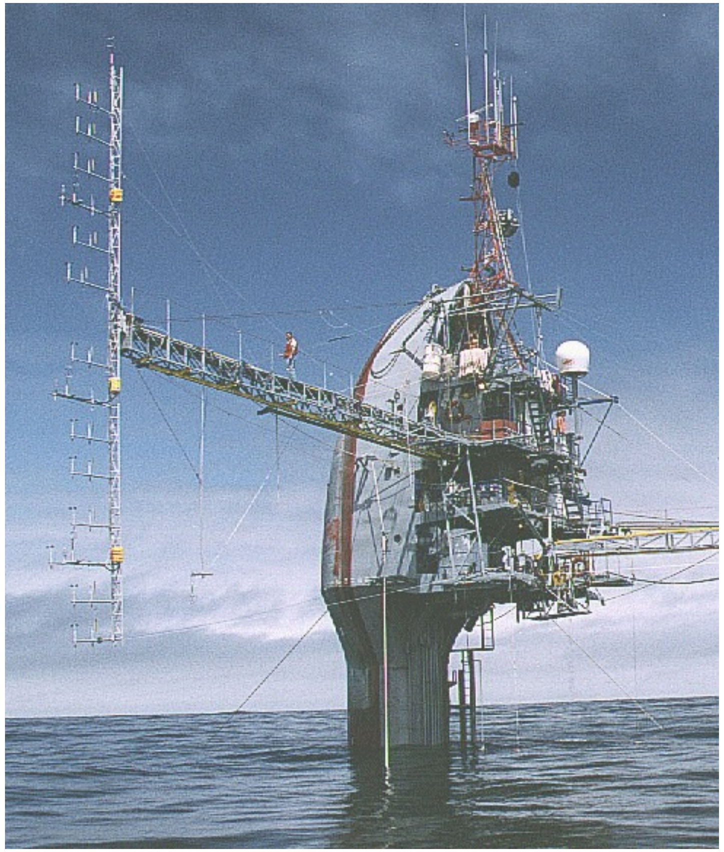
HOW

Butterfly's passive microwave instrument is specially designed to measure air-sea turbulent heat and moisture flux at <25-km resolution.

Marine Atmospheric Boundary Layer Vertical Structure

- A few towers have been used to investigate flux-profile relationships in the marine boundary layer.

R/P FLIP

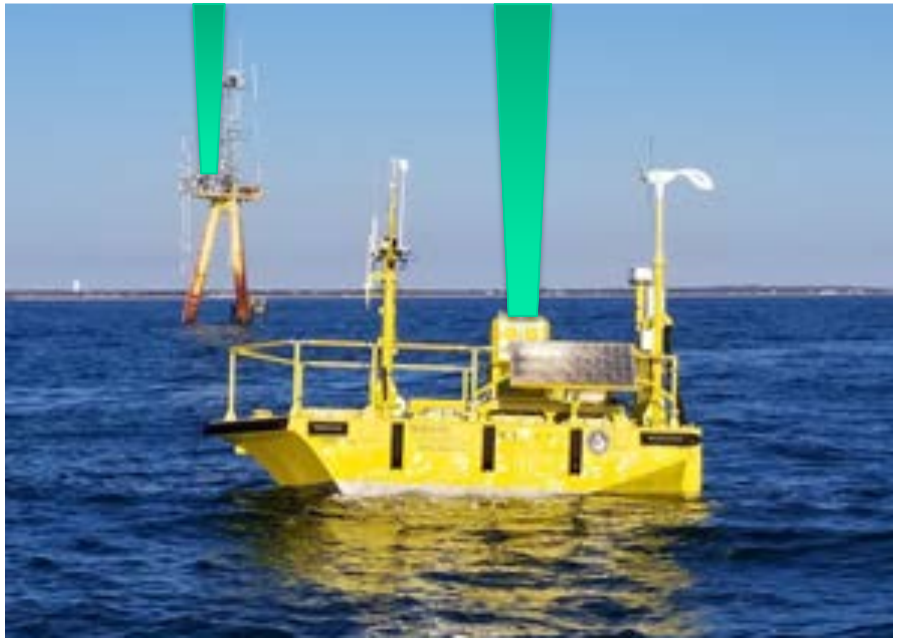


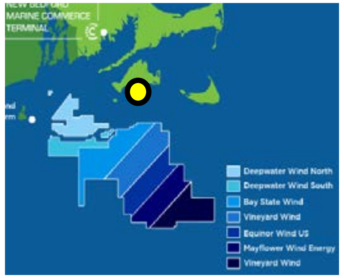
RASEX Tower

ASIT/MVCO

Can we go higher?

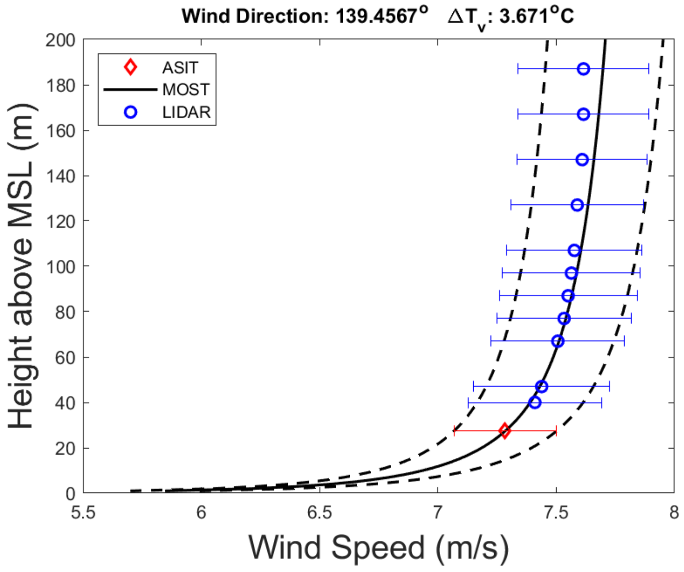
- Lidar buoys are now being used to measure wind mean profiles and to provide some estimates of turbulent-intensity primarily in wind farm applications.



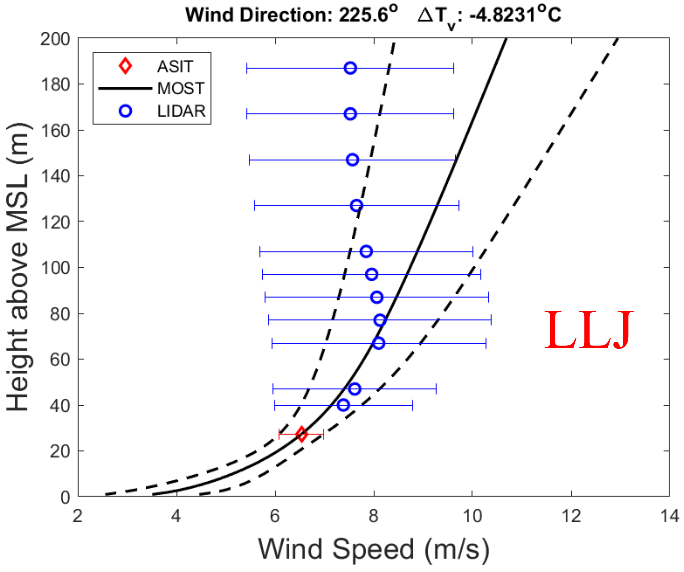


Measured vs Modeled Wind Profiles

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



Convectively Unstable



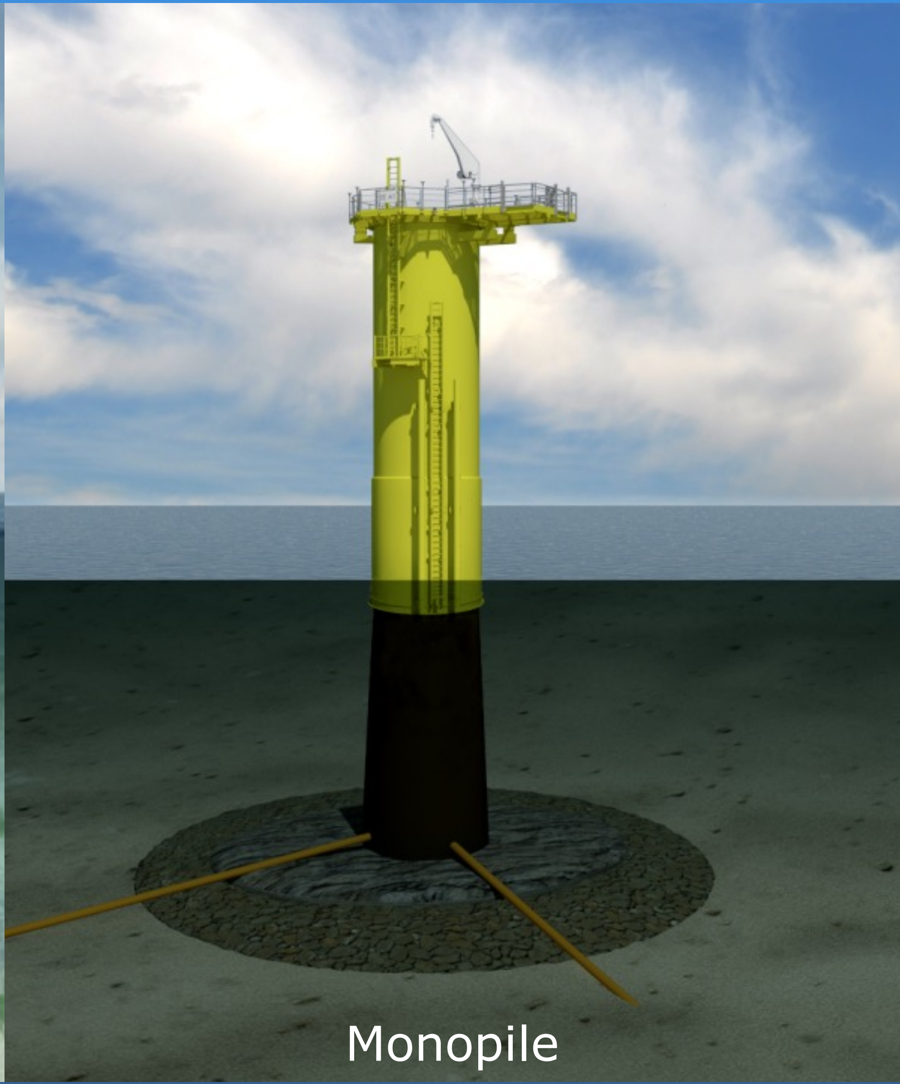
Stably Stratified

Onshore Flow

Can we go higher using structures developed by offshore wind projects?

Gravity Based (GBF)

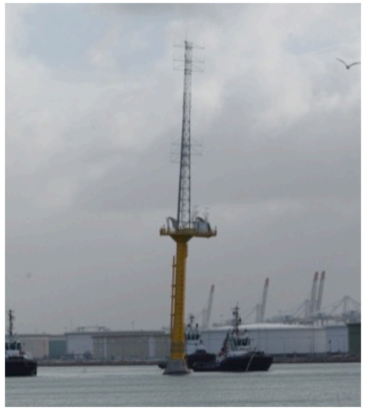
Jacket

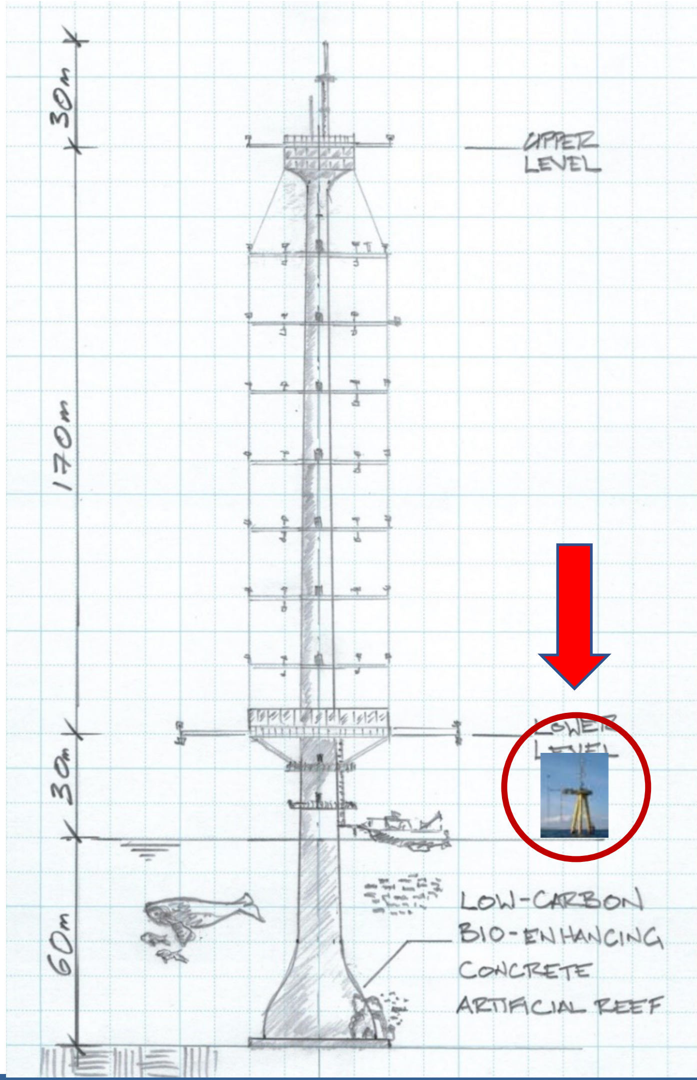


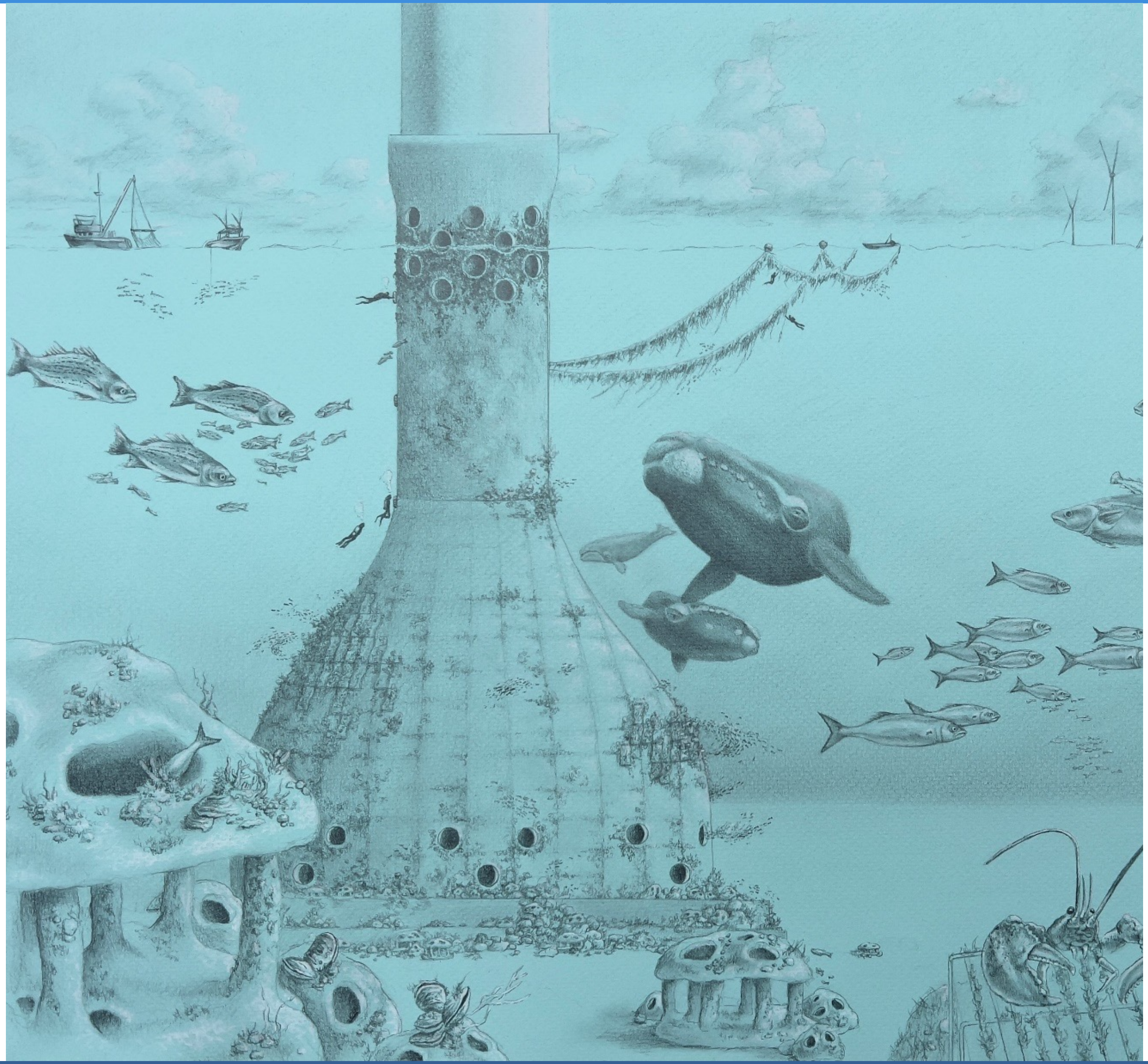
Monopile

Tufts UNIVERSITY

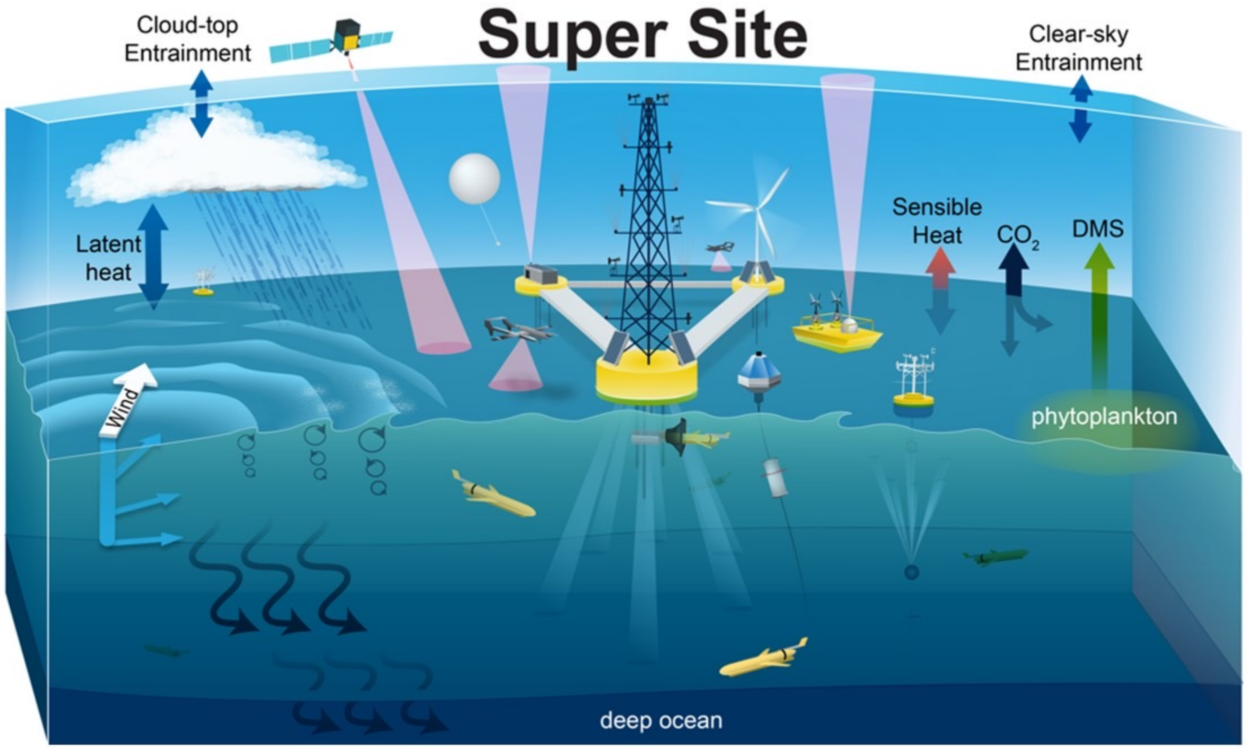
Yes! Engineer have designed a 200m Air Sea Interaction Tower using a Base Designed for Offshore Turbines





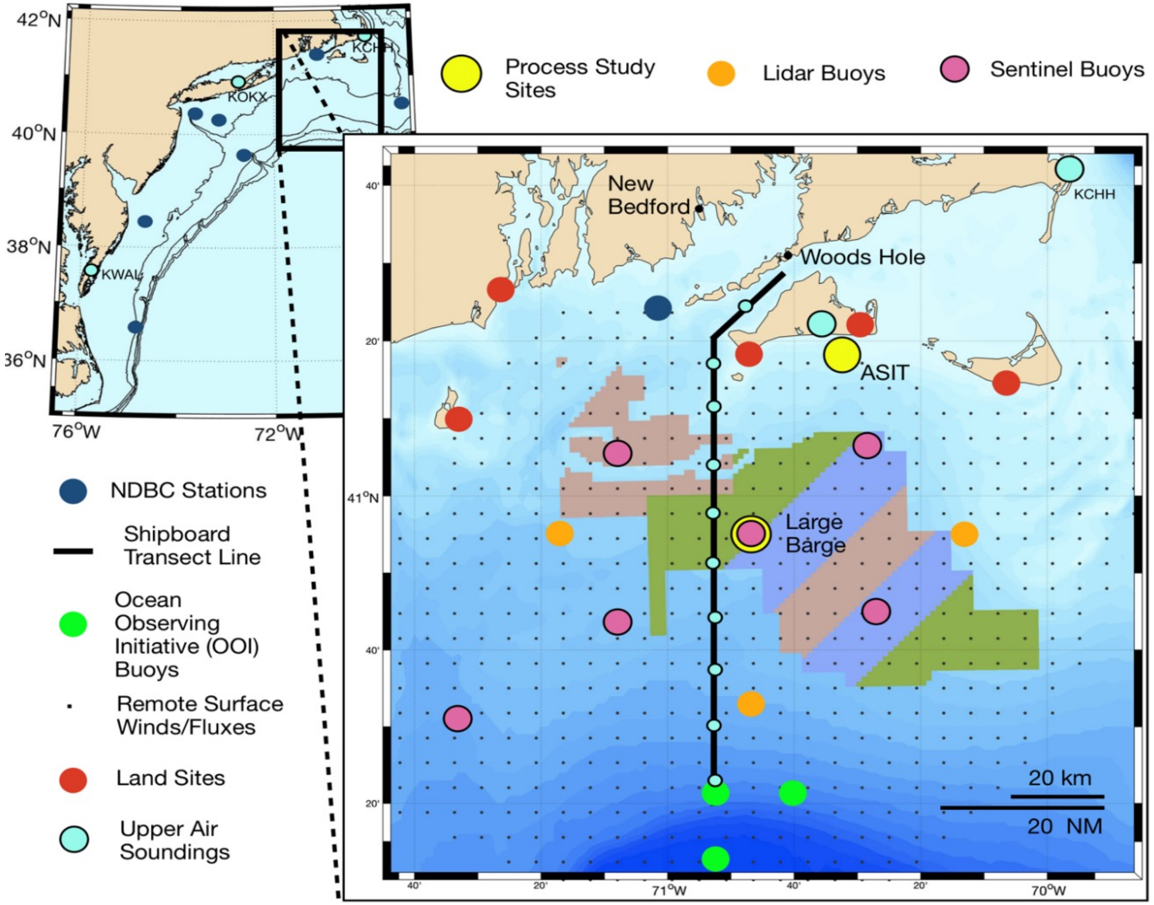


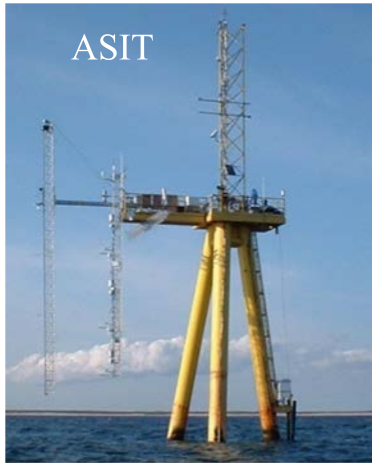
The Future of Ocean and Atmospheric Science

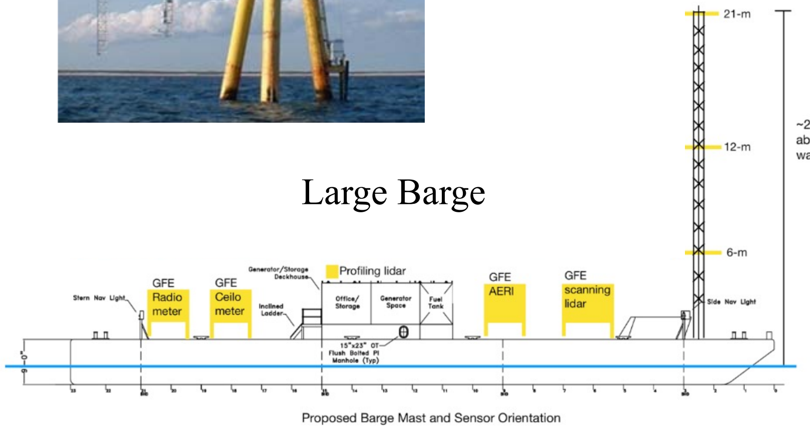


- An ocean laboratory to gather data essential for marine weather and climate forecasts.
- Super Sites have become feasible through technology developed by the offshore wind industry.

An Observational Array for Offshore Wind – Ocean Test Bed (OTB)





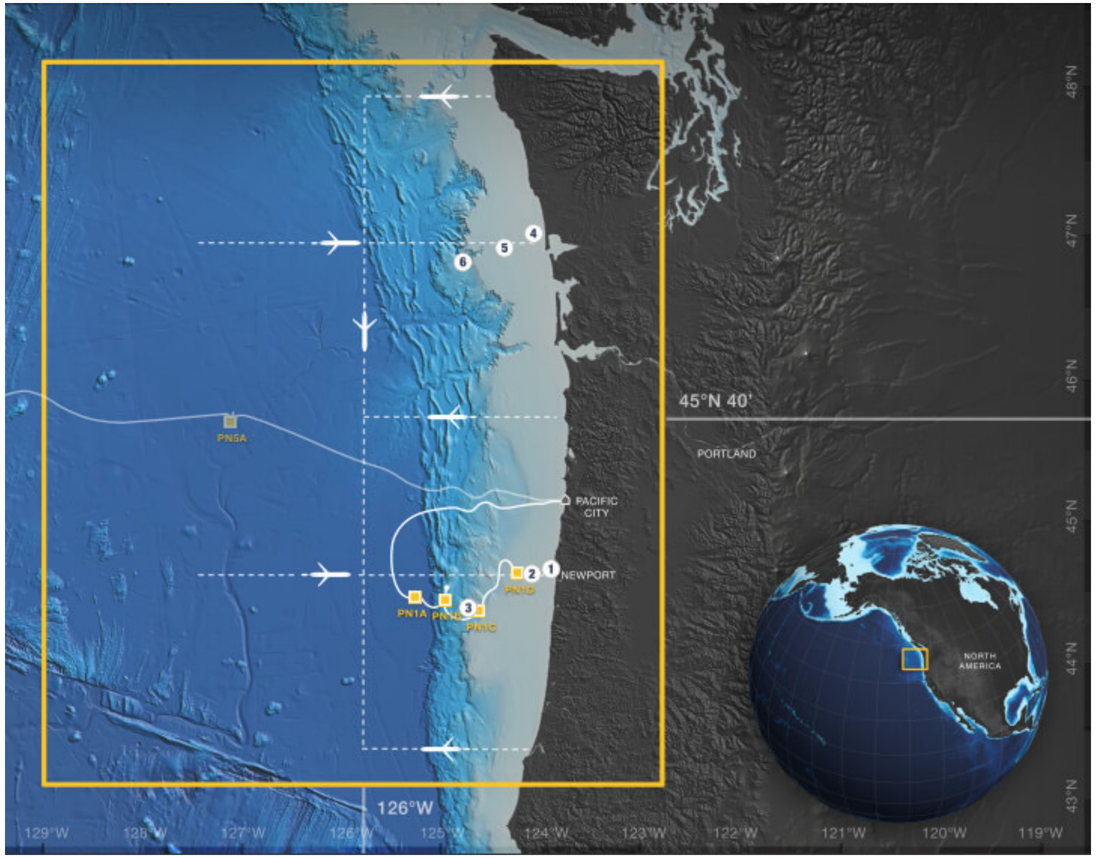


Woods Hole Oceanographic Institution

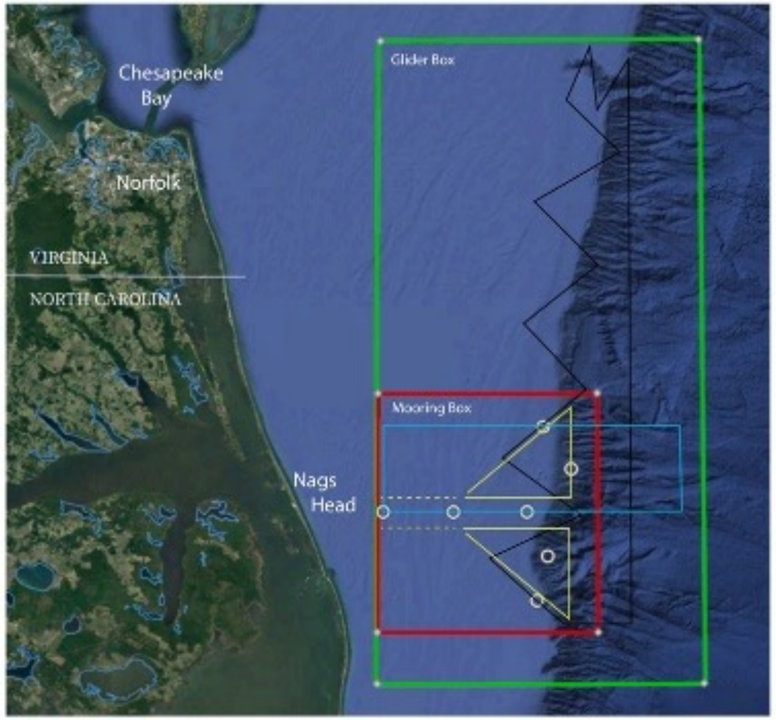
An Observational Array for Mesoscale and Frontal Scale Air-Sea Interaction

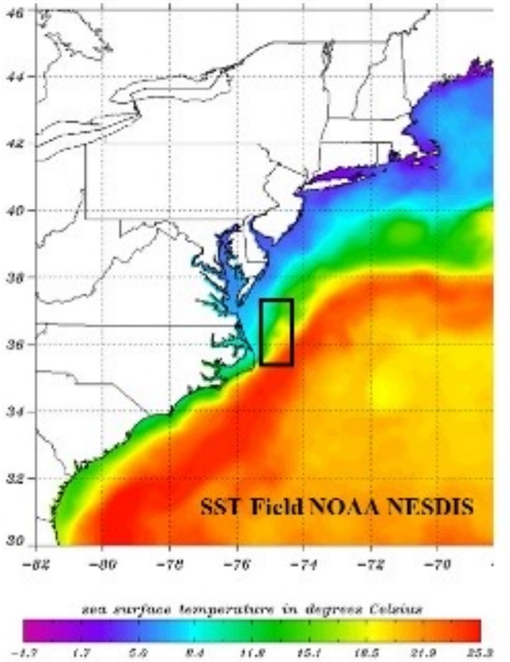
Ocean Observatories Initiative (OOI)

OOI Coastal Endurance Array

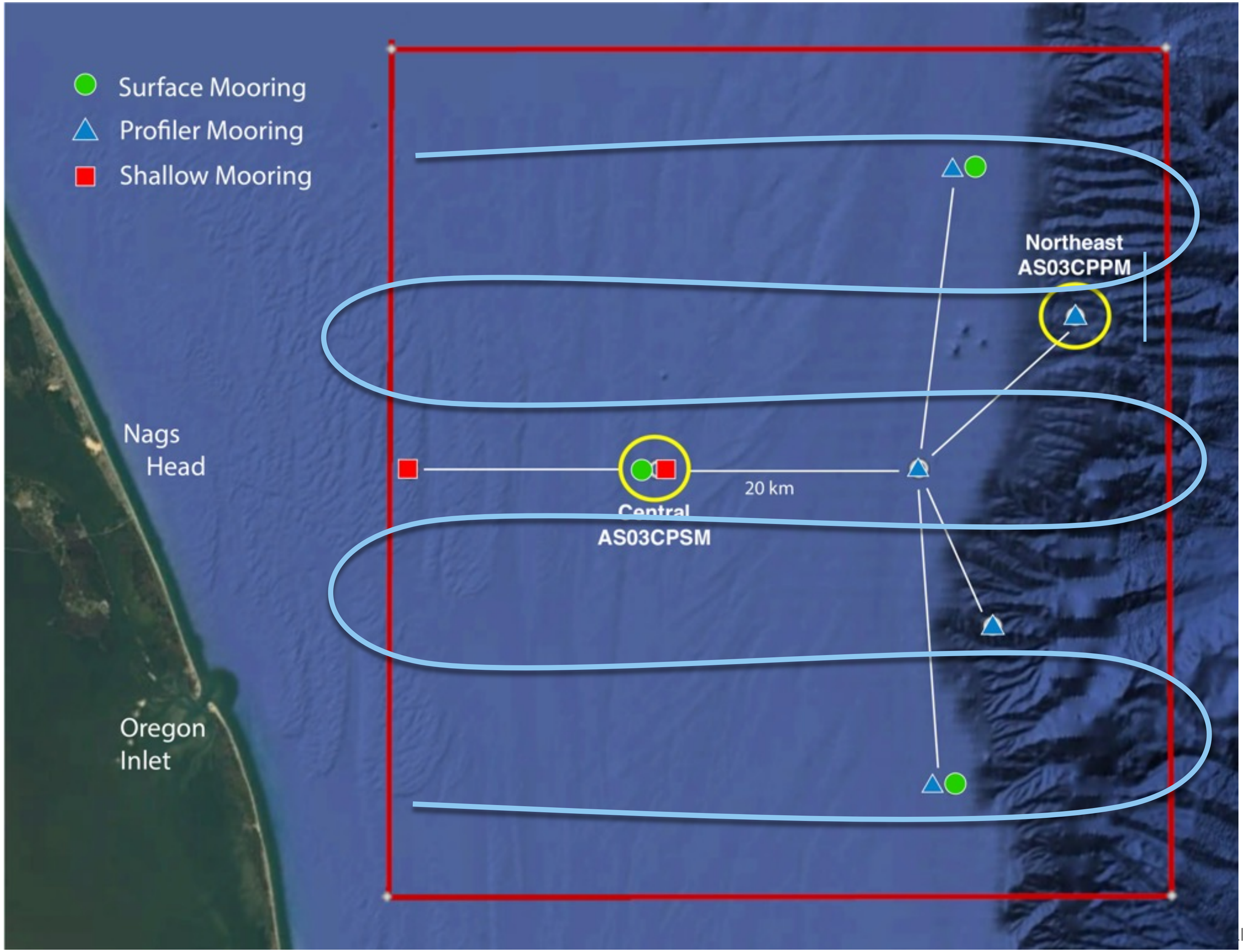


OOI Coastal Pioneer Relocation





An Observational Array for Mesoscale and Frontal Scale Air-Sea Interaction



THANK YOU