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

Momentum Flux: \( \tau_o = \rho \overline{uw} = \rho_\alpha C_D S_f \Delta U \)

Sensible Heat Flux: \( Q_H = \rho c_p \overline{wT} = \rho_\alpha c_p C_H S_f \Delta \Theta \)

Latent Heat Flux: \( Q_E = \rho_\alpha L_v \overline{wq} = \rho_\alpha L_v C_E S_f \Delta Q \)

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

1992 TOGA COARE
2017 NASA SPURS
Air-Sea Interaction Spar (ASIS)
CLIMODE Year long
SPURS Latent Heat Flux
OOI, TPOS & XSpar Real-time Fluxes

Saildrone Mobile 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:

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

- Infrared Hydrometer
- 3-D Sonic
- IMU Motion Sensors
Platform Motion
Motion Correction

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

- 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

\[ C_{DN}(z/z_o) = \frac{-uw}{\Delta U_N G} = \left( \frac{\kappa}{\ln(z/z_o)} \right)^2 \]
COARE: A Global Formulation using a Growing Global Array

\[ C_{DN} = -\frac{\bar{u}w}{U_{10N}^2} G = \left( \frac{\kappa}{\ln(z/z_0)} \right)^2 \alpha = \frac{g z_0}{u^2} = f(U_{10N}) \]
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

Deployed

7m

Recovered

Woods Hole Oceanographic Institute
Measuring Horizontal Variability Uncrewed Surface Vessels (USV)

Saildrone
Wind Powered
Long Duration
Not Fast

JetYak
Gas Powered
Short Duration
Fast

Wave Rider
Wave Powered
Long Duration
Not Fast

Saildrone

Peter Trakovski, WHOI

Wave Glider, UW-APL
Wave Glider instrumented for air-sea interaction research

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

Photo credit: Jason Orfanon, Image courtesy of MBL
Crewed Uncrewed Aerial Vehicles (UAV)

UAV, Luc Lenain, SIO/UCSD

Quadcopter, Adam Shore, NOAA

UAV, Chris Zappa, LDEO/Columbia University

Twin Otter, NRL
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
**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.

---

**HOW**

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

---

**2-DAY COVERAGE**

<table>
<thead>
<tr>
<th>Mission Details</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Launch Date</strong></td>
<td>4/2026</td>
</tr>
<tr>
<td><strong>Length (minimum)</strong></td>
<td>18-months</td>
</tr>
<tr>
<td><strong>Orbit</strong></td>
<td>&gt;80° inclination</td>
</tr>
<tr>
<td><strong>Swath Width</strong></td>
<td>640 km</td>
</tr>
<tr>
<td><strong>Resampled Footprint</strong></td>
<td>20 km</td>
</tr>
</tbody>
</table>
Marine Atmospheric Boundary Layer Vertical Structure

• A few towers have been used to investigate flux-profile relationships in the marine boundary layer.
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:  \[ U(z) = U(z_o) + \frac{u_s}{k} \left[ \ln \left( \frac{z}{z_o} \right) - \psi_m \left( \frac{z}{L} \right) \right] \]
Can we go higher using structures developed by offshore wind projects?

Gravity Based (GBF)  
Jacket  
Monopile
Yes! Engineers have designed a 200m Air Sea Interaction Tower using a Base Designed for Offshore Turbines.
• 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)

Soundings
Lidar Buoy
Sentinel Buoys
Large Barge
ASIT
AUV
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