Development and testing of instrumentation for ship-based UAV measurements of ocean surface processes and the marine atmospheric boundary layer

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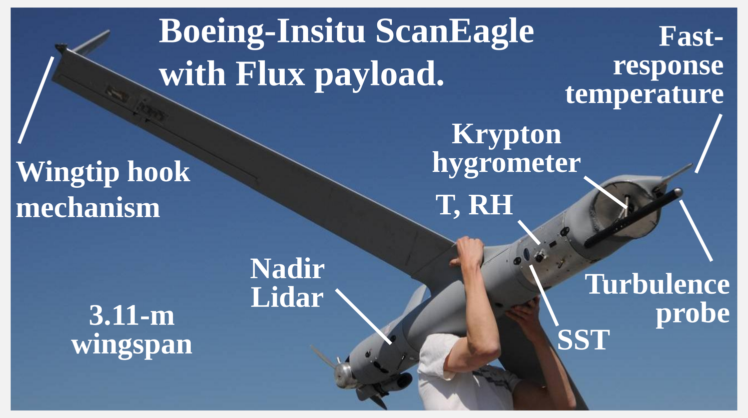
1. Introduction

We have developed instrumentation packages for Unmanned Aerial Vehicles (UAVs) to directly measure air-sea momentum transfer, latent, sensible, and radiative heat fluxes, and surface topography.

The low altitude required for accurate air-sea flux measurements is below the typical safety limit of manned research aircraft; however, with advances in laser altimeters, small aircraft flight control, and real-time differential GPS (DGPS), it is within the capability of the UAV. Ship-launched UAVs can greatly increase the range of atmospheric and oceanographic measurements well beyond the immediate vicinity of the vessel, and enable investigation of spatial variability.



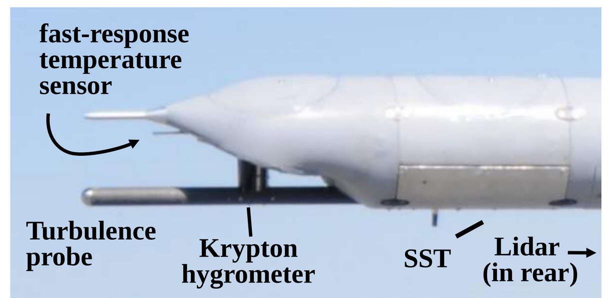
Accurate air-sea measurements will lead to more robust models to relate near-surface atmospheric profiles to surface fluxes. These relationships are essential for improving ocean-atmosphere coupled models for scales ranging from local weather to extreme weather events to global climate.

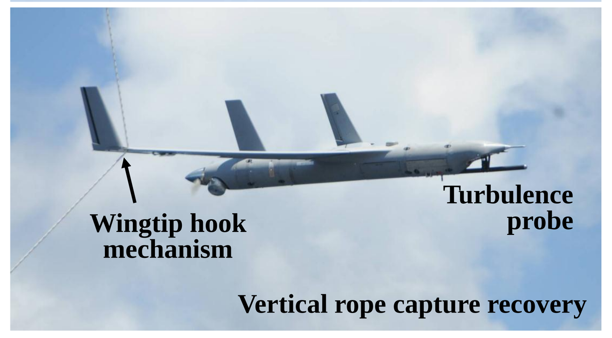
2. ScanEagle scientific payloads

- Integrated into **Boeing-Insitu ScanEagle** platform:
  - 3.11-m wingspan, 22.0-kg maximum takeoff weight
  - 2 – 3 kg payload, >11-hr endurance, on-board generator to power electronics
  - Pneumatic launch, vertical line recovery (both at-sea capable)

"FLUX" Payload

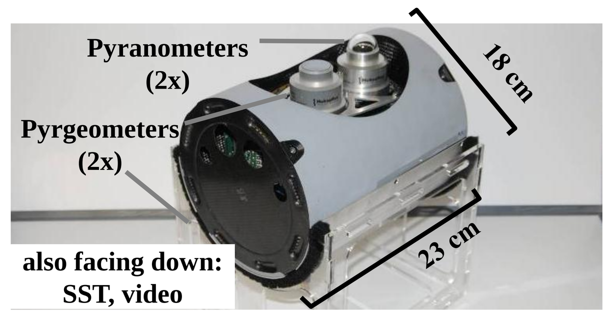
9-port turbulence probe	Winds, momentum fluxes, other fluxes
Laser altimeter (Measurement Devices Ltd.)	Surface waves, a/c control
Humidity/temperature (Vaisala)	H/T profiles and bulk fluxes
SST sensor (Everest Sci.)	SST, frontal processes
Fast-response optical temperature sensor (Opsens)	T, sensible heat flux
Krypton hygrometer (Campbell)	Water vapor, latent heat flux
DAQ system (NI, Kontron)	Data acquisition
DGPS (NovAtel)	Georeferencing, winds
LN200 IMU (Northrop Grumman)	Georeferencing, winds





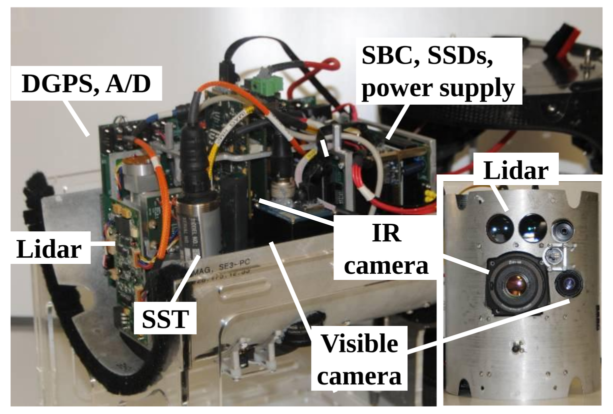
"RADIOMETRIC" Payload

Humidity/temperature (Vaisala)	H/T profiles and bulk fluxes
Radiometers (Hukseflux)	radiation budget, SST
SST sensor (Everest Sci.)	SST
DAQ system (NI, Kontron)	Data acquisition
DGPS (NovAtel)	Georeferencing



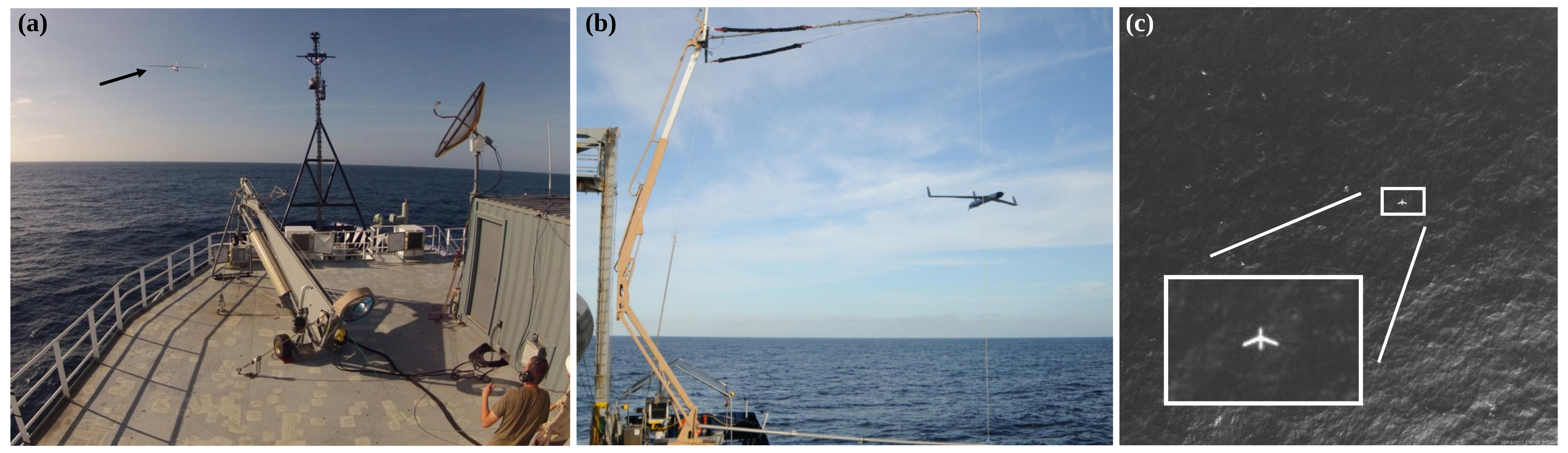
"IMAGING" Payload

Laser altimeter (Measurement Devices Ltd.)	Surface waves, a/c control
Digital video camera (Prosilica)	Ocean surface processes, wave kinematics and breaking
SST sensor (Everest Sci.)	SST, frontal processes
Humidity/temperature (Vaisala)	H/T profiles and bulk fluxes
FLIR A325 LWIR camera	SST, fronts, ocean surface processes
DAQ system (NI, Kontron)	Data acquisition
DGPS (NovAtel)	Georeferencing

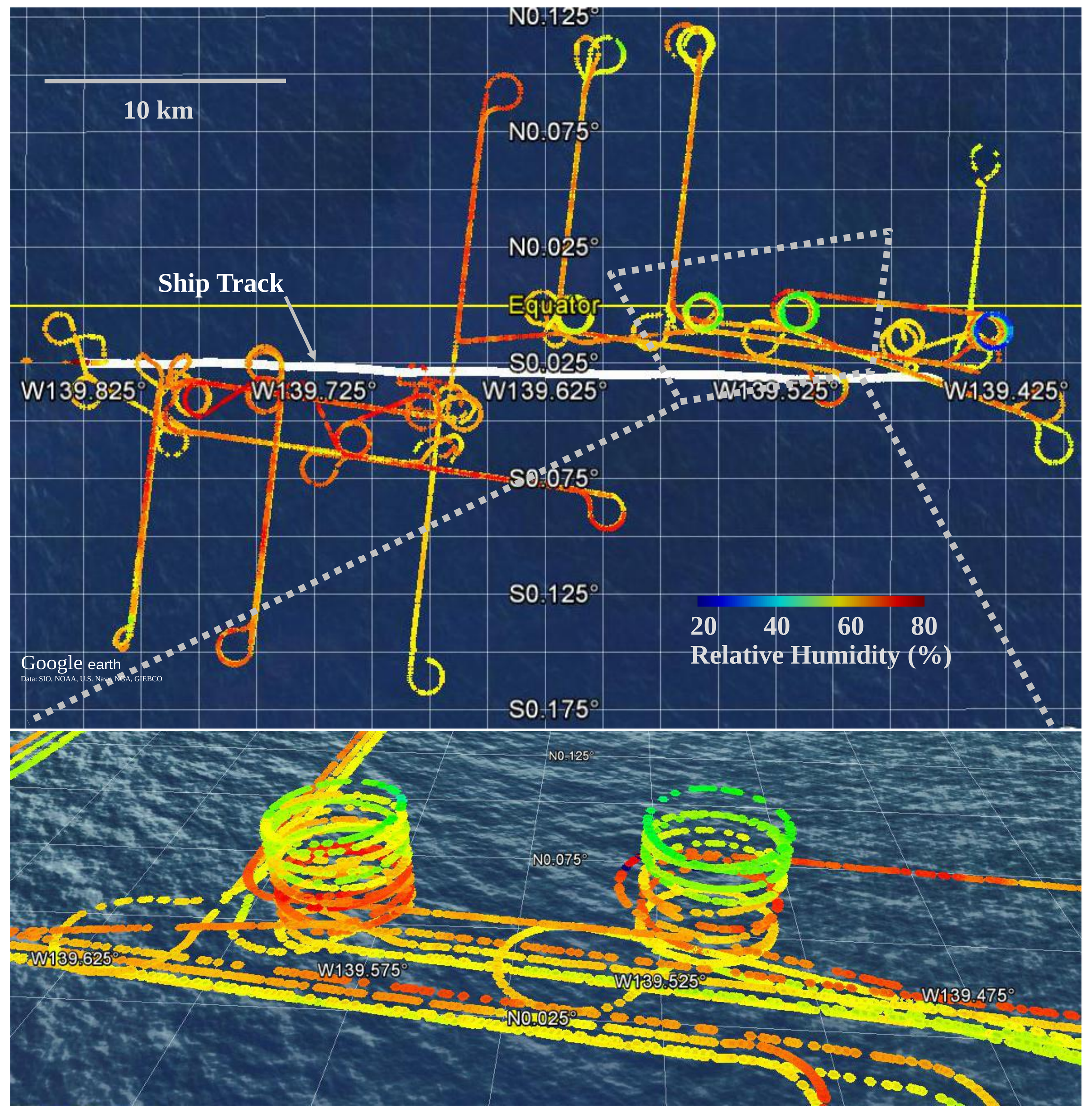


3. ScanEagle flights from the R/V *Roger Revelle*, October 2012

- Equatorial Pacific Ocean (0°N, 140°W); 11 flights in 10 days, 70 flight hours.
- Included two 11-hr back-to-back flights of the Flux payload UAV, capturing day-to-night and night-to-day transitions.
- Demonstrated **vertically-stacked formation flying**, with the upper (300 m) imaging UAV maintaining the low-level (30 m) flux-measuring UAV in the field of view of its cameras.
- **Real-time graphical monitoring** of atmospheric data permitted real-time mission planning to explore areas of interest.

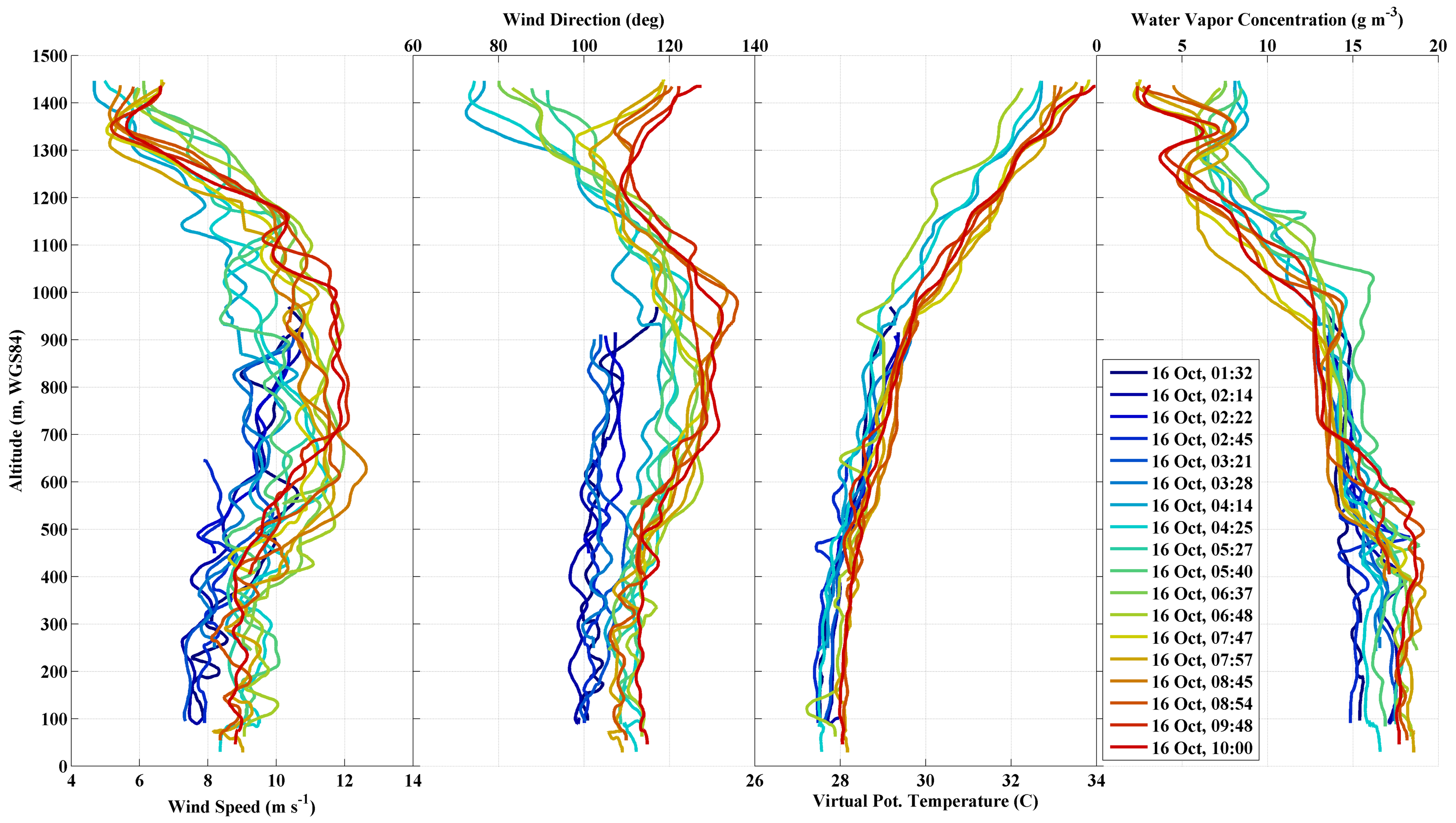


↑ ScanEagle (a) launch and (b) recovery from the R/V *Roger Revelle*. (c) Image of lower UAV (Flux payload) acquired by upper UAV (Imaging payload) while in **vertically-stacked formation**.



⟵ ScanEagle flight track from 11-hr flight, 0049 to 1143 hrs (Local Time), 19 Oct. 2012. Included **helical soundings** 100' to 4700' approx. every hour, and constant altitude up-/down-/crosswind **10-km straight-and-level legs down to 30 m**. Shown is an example of the 1-Hz real-time atmospheric data, in this case relative humidity.

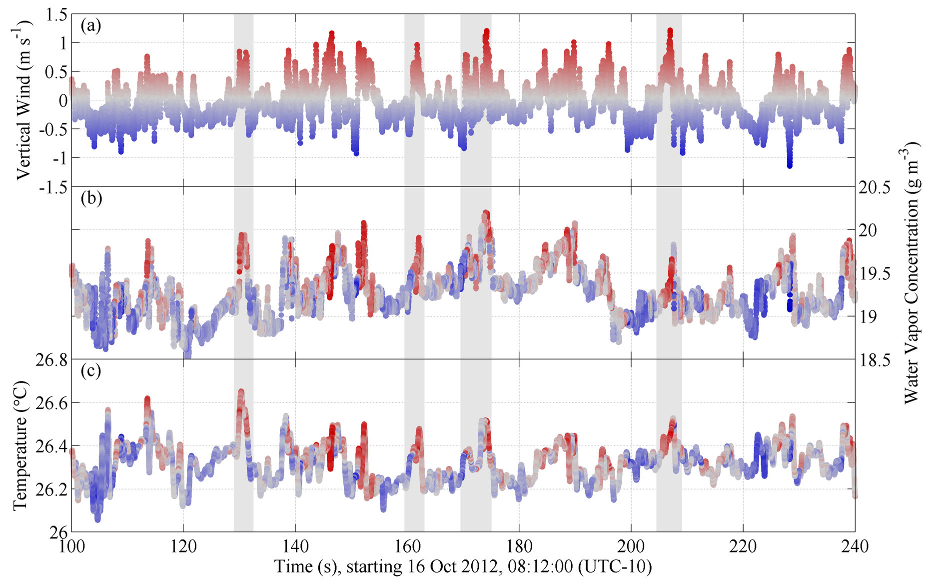
↓Sample **vertical profiles** of wind, temperature, and water vapor through an 11-hr flight of the Flux payload. Profile start times (Local Time, UTC-10) are given.



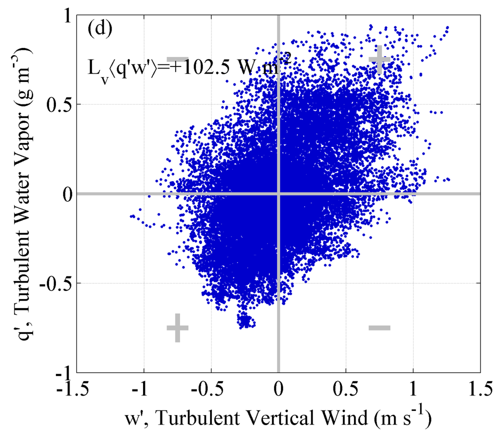
4. Air-sea fluxes measured during low-altitude flight

- 10-km straight-and-level flights from the R/V *Roger Revelle* (0°N, 140°W), 30 to 70 m altitude.
- Use covariance of vertical wind (w) with fluctuations in horizontal wind (u'), moisture (q'), and virtual potential temperature (θ_v') to calculate momentum, sensible and latent heat fluxes.

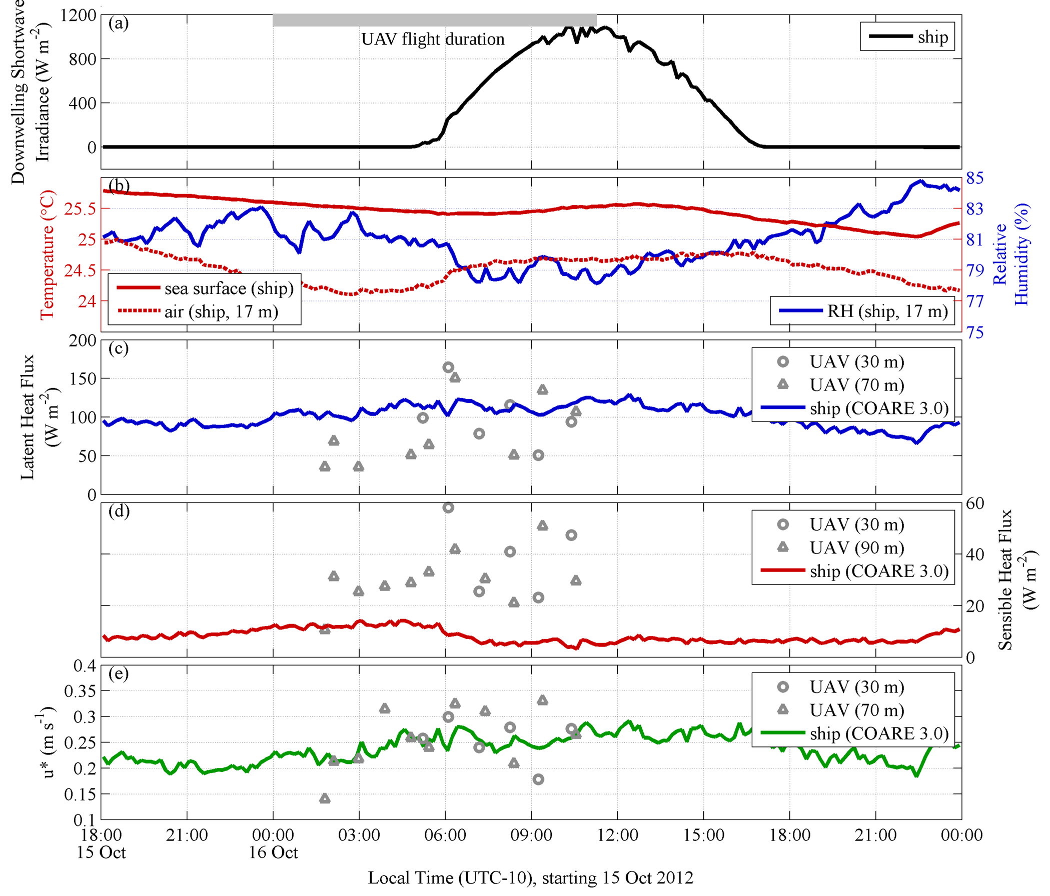
↓ Sample time series from 30-m UAV flights. Note the coincidence peaks in vertical wind, water vapor, and temperature.



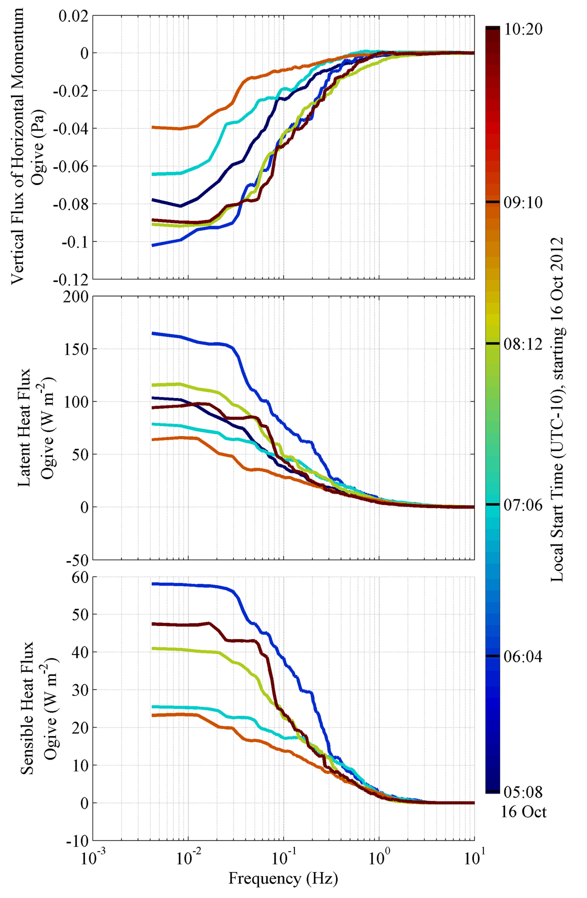
↓ Scatter plot of turbulent water vapor vs. vertical wind.



↓ Preliminary atmospheric and surface measurements from shipboard instruments (lines) and UAV Flux payload (markers) during an 11-hr flight. The UAV flux calculations are made using integrated cospectra from 240-s (~5 – 7-km) segments. $U_{10} \approx 7 - 8$ m s^{-1}.



↓ Sample **integrated cospectra** ("ogives") from 30-m flights showing (a) momentum flux ($\rho\langle u'w'\rangle$; wind stress), (b) latent heat flux ($L_v\langle q'w'\rangle$), and (d) sensible heat flux ($\rho C_p\langle\theta_v'w'\rangle$). Low frequencies asymptote to the final flux estimate. 240-s (~5 – 7-km) segments are used.



5. Summary

- We have developed instrument packages for UAVs to measure meteorological variables, surface wave fields, and air-sea interaction, including momentum, energy, heat, and moisture fluxes. Instrumentation has been **calibrated and tested with ground vehicle platforms** and with **engineering flight tests over land and water** (*Reineman et al., accepted by J. Atmos. and Oceanic Technol.*).
- Measurements taken **at low altitude** (and with **no human risk**) within the boundary layer permit accurate determination of atmospheric state near the sea surface, and of surface stress and its relationship to the wave field, including spatial evolution. With **vertically-stacked flight**, there are coincident measurements of surface wave field kinematics and topography.
- Demonstrated **scientific missions with ship-launched UAVs**, showing the potential to greatly extend the reach of atmospheric and oceanographic research beyond the vicinity of the vessel.
- Interactions between the atmosphere and ocean occur at small scales but have significant impacts on global circulation and climate variability. Accurate in situ measurements in near-surface environments are essential for **improving numerical model parameterizations** and **validating satellite flux products** for global coverage.