Ship-based UAV measurements of the marine atmospheric boundary layer in the equatorial Pacific

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AGOR / UAS Scientific Demonstration Integration during the EquatorMix experiment

UNOLS FIC meeting – SIO, March 5 2013
Background - Air-sea interaction measurements from Unmanned Aerial Vehicles (UAV)

- Coupling of atmospheric and oceanic boundary layers plays important role in **local and global fluxes of mass, momentum, and energy**
- Air-sea fluxes are poorly understood, especially in **high wind and wave** environments (e.g., high latitude, extreme conditions, remote locations)

- Aircraft provide an **efficient** way to measure small to mesoscale processes over **large spatial** ranges
- To measure these surface processes, need to be close to the surface (<30 m)
- Transition to **smaller, lighter, safer** platforms, that can deployed from research vessels: Unmanned Aerial Vehicles (UAVs)
**Boeing-Insitu ScanEagle UAV**

- 2 – 3 kg payload, >11 hrs endurance
- Pneumatic launch, vertical line recovery
- Capable of ship-launch and recovery

![SkyHook recovery system](image)

- Wingtip hook mechanism
- 3.1 m
- 5 m
- 11 m
Coincident remote sensing and measurements of energy and momentum fluxes
### "Flux" payload

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-port turbulence/gust probe</td>
<td>Winds, momentum fluxes, other fluxes</td>
</tr>
<tr>
<td></td>
<td>(vertical wind est. accuracy 2.6 cm/s)</td>
</tr>
<tr>
<td>Laser altimeter</td>
<td>Surface waves, a/c control</td>
</tr>
<tr>
<td>Humidity/temperature</td>
<td>H/T profiles and bulk fluxes</td>
</tr>
<tr>
<td>SST sensor</td>
<td>SST, frontal processes</td>
</tr>
<tr>
<td>Fast response optical temp.</td>
<td>T, sensible heat flux</td>
</tr>
<tr>
<td>sensor</td>
<td></td>
</tr>
<tr>
<td>Krypton hygrometer</td>
<td>H₂O covariance fluxes</td>
</tr>
<tr>
<td>DAQ system</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>DGPS</td>
<td>georeferencing, winds, a/c control</td>
</tr>
<tr>
<td>IMU – LN200</td>
<td>georeferencing, winds</td>
</tr>
</tbody>
</table>

- Relative vertical wind spectra, comparison with CSAT3 sonic anemometers
- Instruments mounted on pickup truck

![SIO ScanEagle UAS for air-sea interaction research](image)
**SIO ScanEagle UAS for air-sea interaction research**

### “Imaging” payload

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lidar</td>
<td>Surface waves, a/c control</td>
</tr>
<tr>
<td>Digital Video Camera</td>
<td>Ocean surface processes, wave kinematics and breaking</td>
</tr>
<tr>
<td>SST sensor</td>
<td>SST, frontal processes</td>
</tr>
<tr>
<td>Humidity/Temperature</td>
<td>H/T profiles and bulk fluxes</td>
</tr>
<tr>
<td>FLIR A325 LWIR Camera</td>
<td>SST, fronts, ocean surface processes</td>
</tr>
<tr>
<td>DAQ system</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>DGPS</td>
<td>georeferencing, winds, a/c control</td>
</tr>
</tbody>
</table>

### “Radiometric” payload

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity/Temperature</td>
<td>H/T profiles and bulk fluxes</td>
</tr>
<tr>
<td>Radiometers</td>
<td>SST, radiation budget</td>
</tr>
<tr>
<td>SST sensor</td>
<td>SST</td>
</tr>
<tr>
<td>Digital Video Camera</td>
<td>Ocean surface processes, wave kinematics and breaking</td>
</tr>
<tr>
<td>DAQ system</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>DGPS</td>
<td>georeferencing, winds, a/c control</td>
</tr>
</tbody>
</table>
Deployment of instrumented ScanEagle UAVs from the R/V Revelle during the Papeete to Nuku Hiva, Tahiti cruise (4 - 22 Oct., 2012; Jerome Smith, Chief Scientist)

ScanEagles will extend the capabilities of the research vessel by measuring air-sea fluxes, marine atmospheric boundary layer (MABL) variables, and surface signatures of ocean boundary layer (OBL) processes.

A. Air-sea Fluxes and the Marine Atmospheric Boundary Layer
- Measure momentum, heat, and moisture fluxes, atmospheric soundings, and surface wave measurements
- Measure spatial decorrelation scales of the air-sea fluxes and related MABL variables relative to the research vessel.

B. Atmospheric Convection & Precipitation
- Measure horizontal entrainment velocities approaching the perimeter of convective cells
- Correlation of recently precipitated pools of cooler fresher water at the surface with the convective activity

C. The Diurnal Surface Layer
- Coordinated flights with fast CTD profiling the DSL (air-sea fluxes, waves, met.)

D. Surface Wave Processes and Mixing
Coordinated effort with other assets, researchers

50kHz HDSS (Pinkel/Smith, SIO)

Fast CTD (Pinkel/Smith, SIO)

Wind Doppler profiler (Melville, SIO)

Eddy flux system & Array of scanning laser altimeters (Melville, SIO)

“PADS” sonar (J. Smith, SIO)
R/V Revelle UAV launch and recovery equipment
Movie: 20121008RecoveryLong.mov
At-sea recovery “as seen from the ScanEagle”
Ship-based UAV operations

Inside the Ground Control Station:

- Tracking antenna (100 km line-of-sight)
- UAV pilot workstations
- Scientific payload monitoring workstation

Night operations

Ground Control Station (GCS)

ScanEagle
Real-time Google Earth plotting sample:
11-hr “Flux” payload flight

Plot any variable as color along the flight track
Use for “on-the-fly” flight mission planning
UAV profiles of wind, temperature, water vapor

Vertical profiles upwind of the Revelle, during one 11-hr flight (taking off in the middle of the night)
Sample low-altitude (32-m) time series

Positive correlation between vertical wind and water vapor, temperature
Sample low-altitude (32-m) flux calculations

- Integrated cospectra (high to low freq), “ogives”
- Asymptote at low frequency to covariance (with scalings noted)

- In agreement with bulk fluxes from ship-based observations
- Next step: resolve limitations of ship and UAV measurements

\[ \tau_x = \rho \langle u'w' \rangle \]

\[ Q_L = L_v \langle q'w' \rangle \]

\[ Q_S = \rho C_p \langle \theta'_v w' \rangle \]
Sample imagery, stacked ScanEagle flight

- **Visible and infrared** imagery captured by Imaging payload (300 m AGL)
- During *vertically-stacked formation* – Flux payload UAV (30 m) in field of view
- Permits analyses of surface fluxes in the context of surface kinematics

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**Visible**

100 m

**Infrared**

whitecap

10-m wind = 9 m/s

100 m
Summary: UAV-based atmospheric, oceanic measurements from research vessels

- Developed systems for measurement of **momentum**, **energy fluxes** within atmospheric boundary layer from UAVs
- Permit coincident remote sensing measurements of surface (imagery, IR, lidar)

- Advantages over manned aircraft experiments:
  - Introduces **no significant human risk** during low-altitude flights
  - Long endurance (> 11 hours)
  - No transit time (already on-site right after take off)

- First direct air-sea flux measurements from a ship-launched UAV during EquatorMix off R/V Revelle
- 71 flight-hours were accumulated over 12 days.

Outlook: the future of ship-launched UAVs for atmospheric, oceanographic research

- Greatly **extend the scientific reach** of a research vessel
- Low-altitude flights permit **safe** air-sea flux measurements over **large spatial scales**, over long science missions
- Extends reach of small research aircraft beyond coastal waters, with **no transit times**
- **Real-time data** monitoring allows for **real-time mission planning**
- Can combine with **simultaneous surface and subsurface** ship measurements

Next deployment? July 2013 on R/V Knorr, as part as a large field effort that also includes wave gliders, underwater gliders, research aircraft, mooring and drifter deployments.