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

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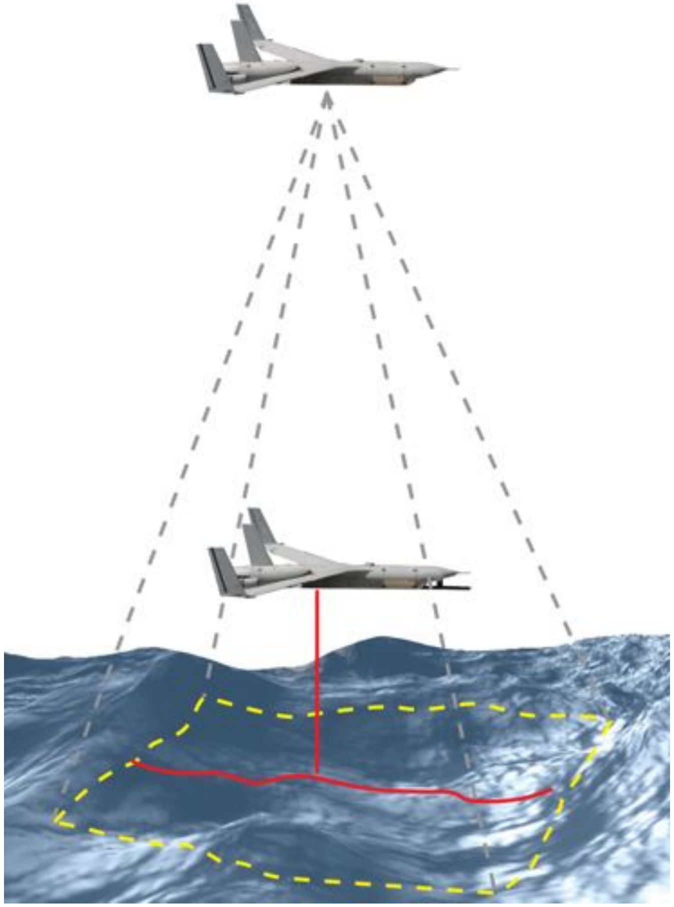
Flight support: Lorenz Eber, Cyrus Roohi (NSWCDD)

AGOR / UAS Scientific Demonstration Integration during the EquatorMix experiment

UNOLS SCOAR meeting – WHOI, June 27 2013



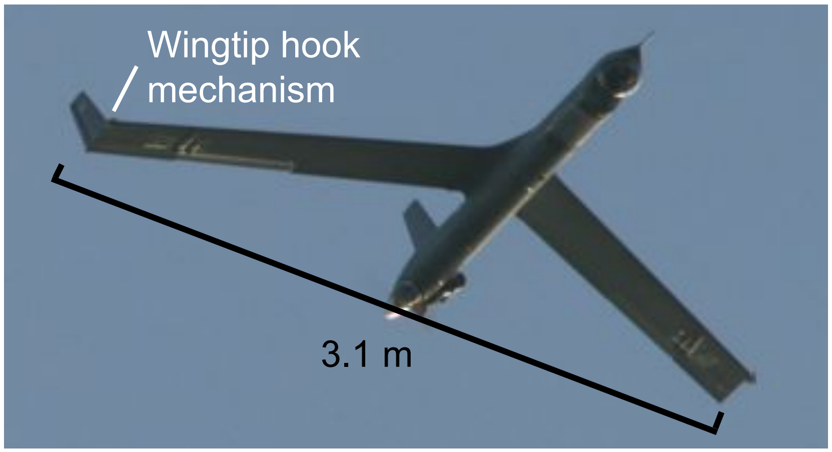
Background - Air-sea interaction measurements from Unmanned Aerial Vehicles (UAV)

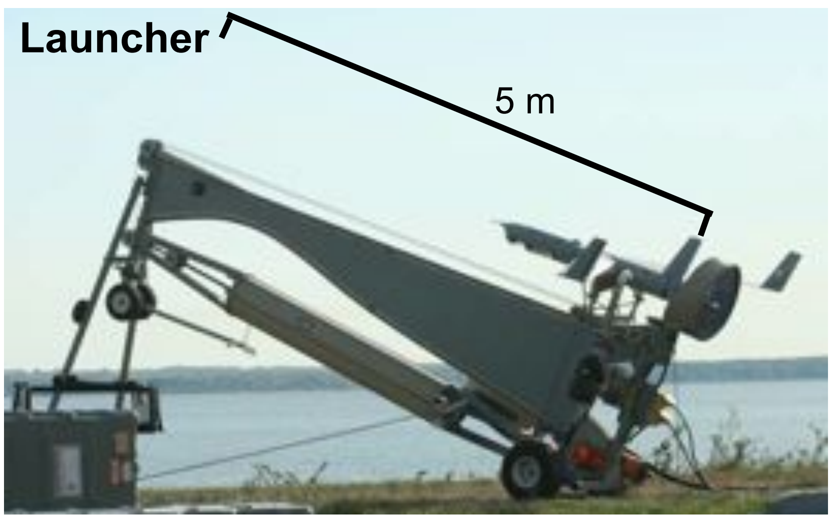
- Coupling of atmospheric and oceanic boundary layers plays important role in **local and global fluxes** of **mass, momentum, and energy**
- Air-sea fluxes are poorly understood, especially in **high wind and wave** environments (e.g., high latitude, extreme conditions, remote locations)

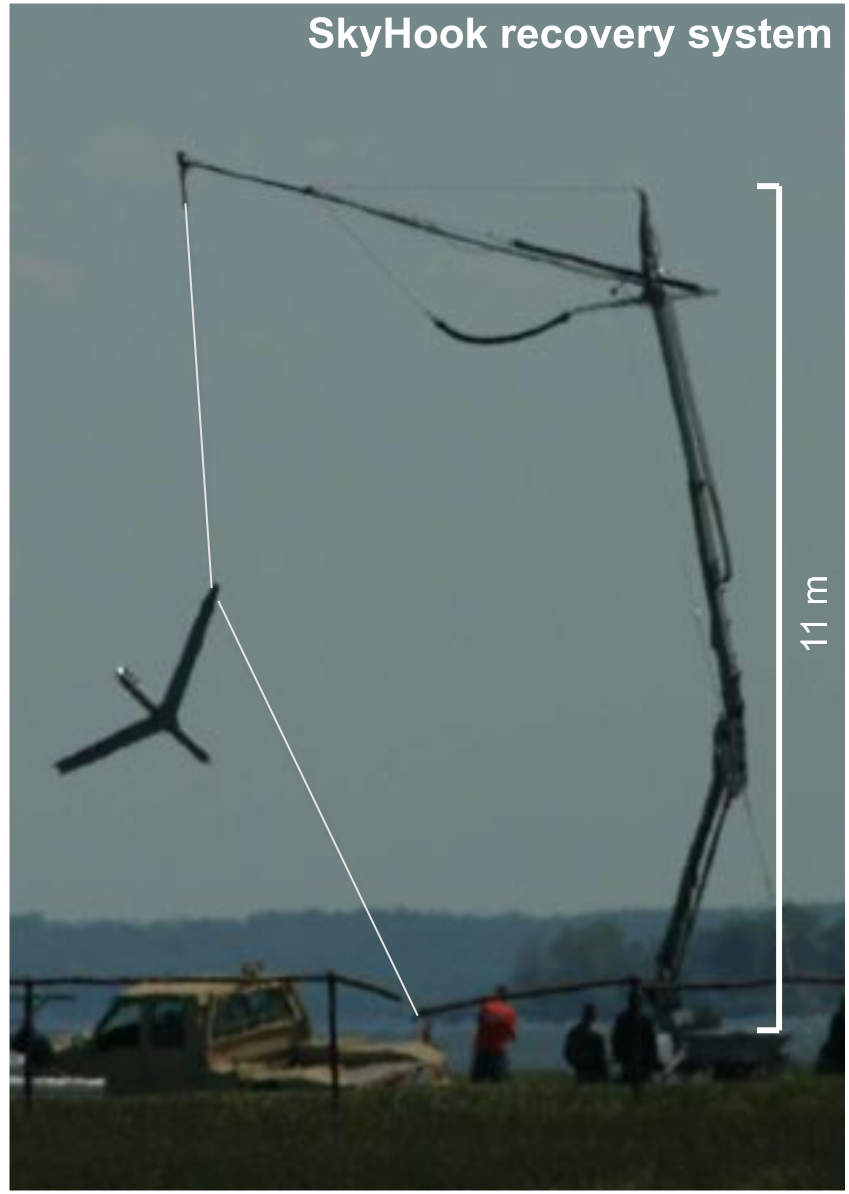
- Aircraft provide an **efficient** way to measure small to mesoscale processes over **large spatial** ranges
- To measure these surface processes, need to be close to the surface (<30 m)
- Transition to **smaller, lighter, *safer*** platforms, that can deployed from research vessels: Unmanned Aerial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

Boeing-Insitu ScanEagle UAV

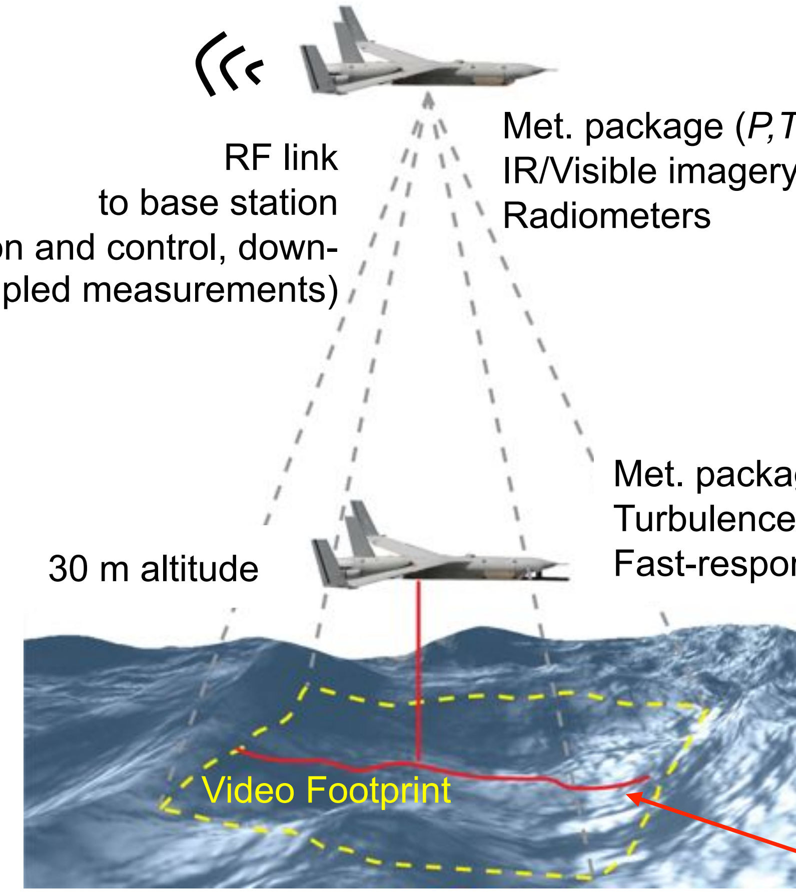
- 2 – 3 kg payload, >11 hrs endurance
- Pneumatic launch, vertical line recovery
- Capable of ship-launch and recovery







Flight configuration: “stacked" UAV

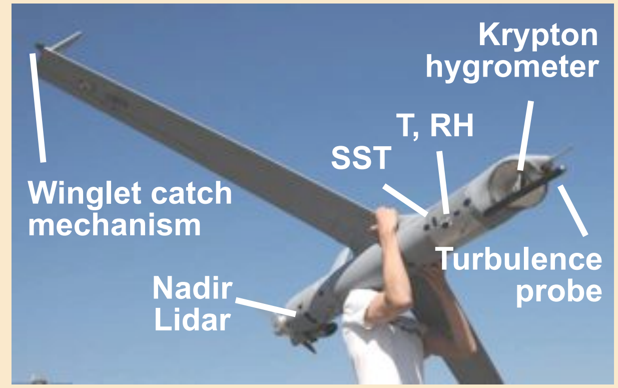


Coincident remote sensing and measurements of energy and momentum fluxes

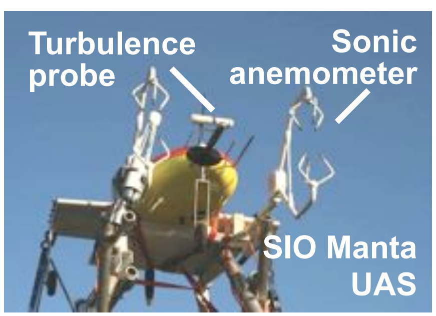
SIO ScanEagle UAS for air-sea interaction research

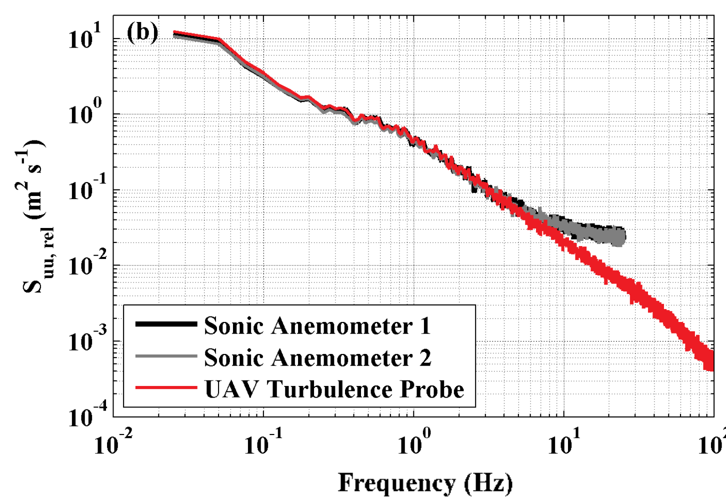
"Flux" payload

Instrumentation	Measurement
9-port turbulence/gust probe	Winds, momentum fluxes, other fluxes (vertical wind est. accuracy 2.6 cm/s)
Laser altimeter	Surface waves, a/c control
Humidity/temperature	H/T profiles and bulk fluxes
SST sensor	SST, frontal processes
Fast response optical temp. sensor	T, sensible heat flux
Krypton hygrometer	H_2O covariance fluxes
DAQ system	Data acquisition
DGPS	georeferencing, winds, a/c control
IMU – LN200	georeferencing, winds



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





SIO ScanEagle UAS for air-sea interaction research

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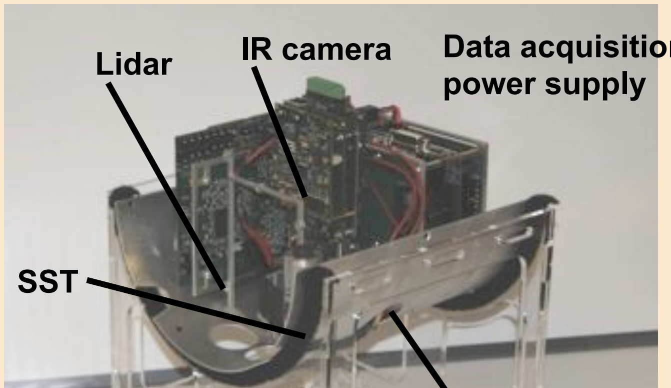
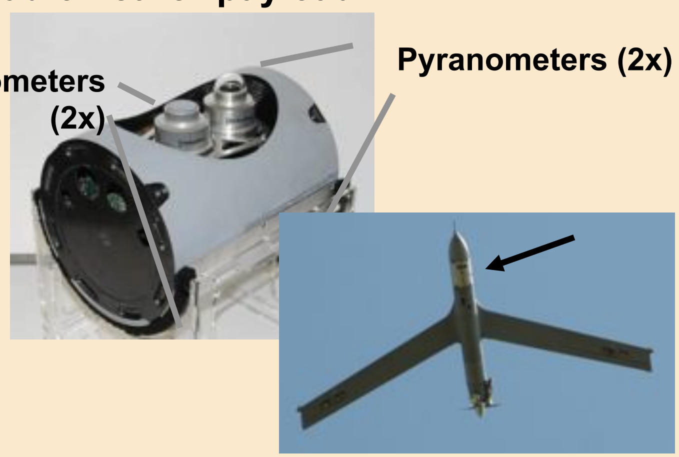
“Imaging" payload



Instrumentation	Measurement
Laser Altimeter	Surface waves, a/c control
Digital Video Camera	Ocean surface processes, wave kinematics and breaking
SST sensor	SST,frontal processes
Humidity/Temperature	H/T profiles and bulk fluxes
FLIR A325 LWIR Camera	SST, fronts, ocean surface processes
DAQ system	Data acquisition
DGPS	georeferencing, winds, a/c control

“Radiometric" payload



Instrumentation	Measurement
Humidity/Temperature	H/T profiles and bulk fluxes
Radiometers	SST, radiation budget
SST sensor	SST
Digital Video Camera	Ocean surface processes, wave kinematics and breaking
DAQ system	Data acquisition
DGPS	georeferencing, winds, a/c control

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EquatorMix experiment overview

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

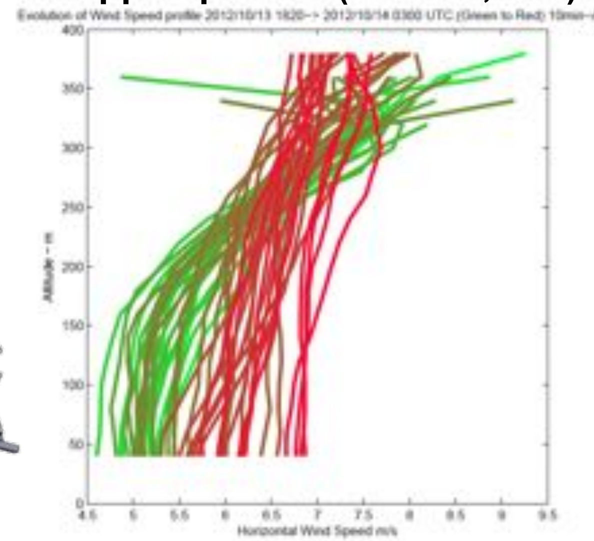
C. The Diurnal Surface Layer

- Coordinated flights with fast CTD profiling the DSL (air-sea fluxes, waves, met.)

D. Surface Wave Processes and Mixing

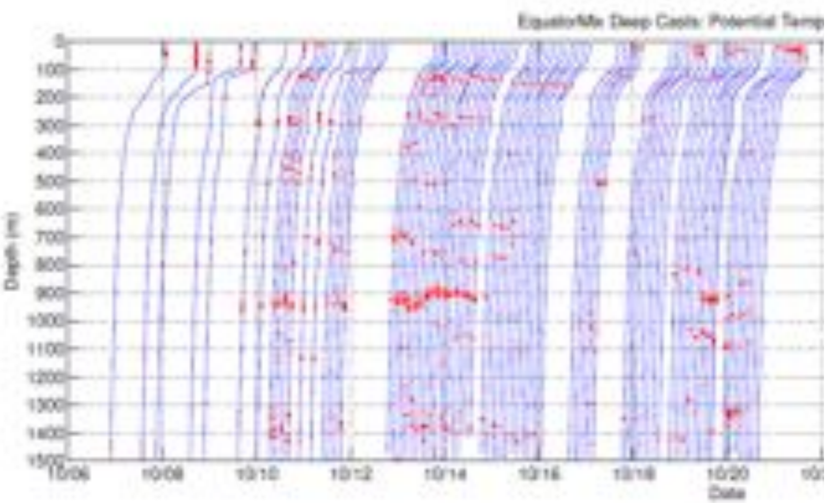
Coordinated effort with other assets, researchers

Wind Doppler profiler (Melville, SIO)

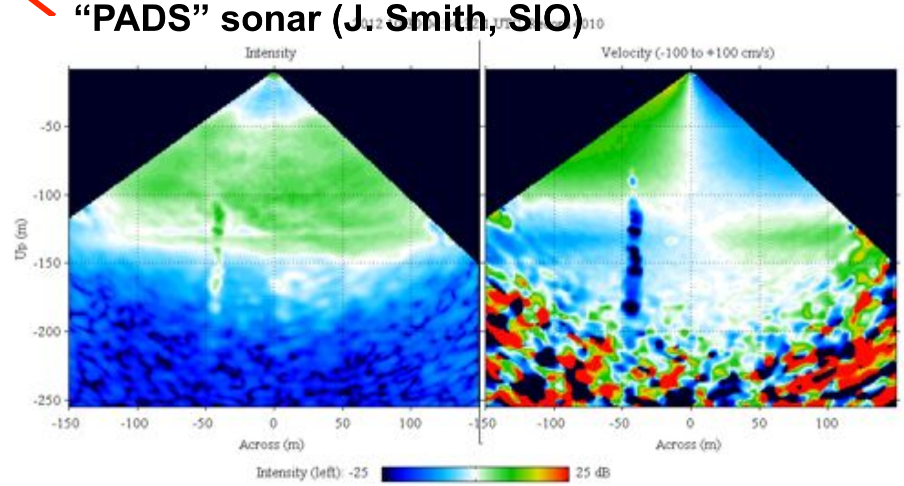


Eddy flux system &
Array of scanning laser
altimeters (Melville, SIO)

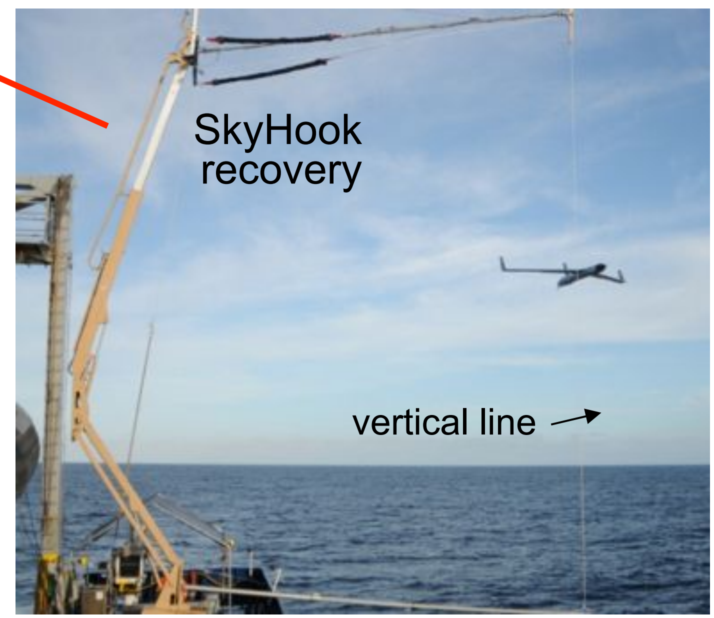
Fast CTD
(Pinkel/Smith, SIO)



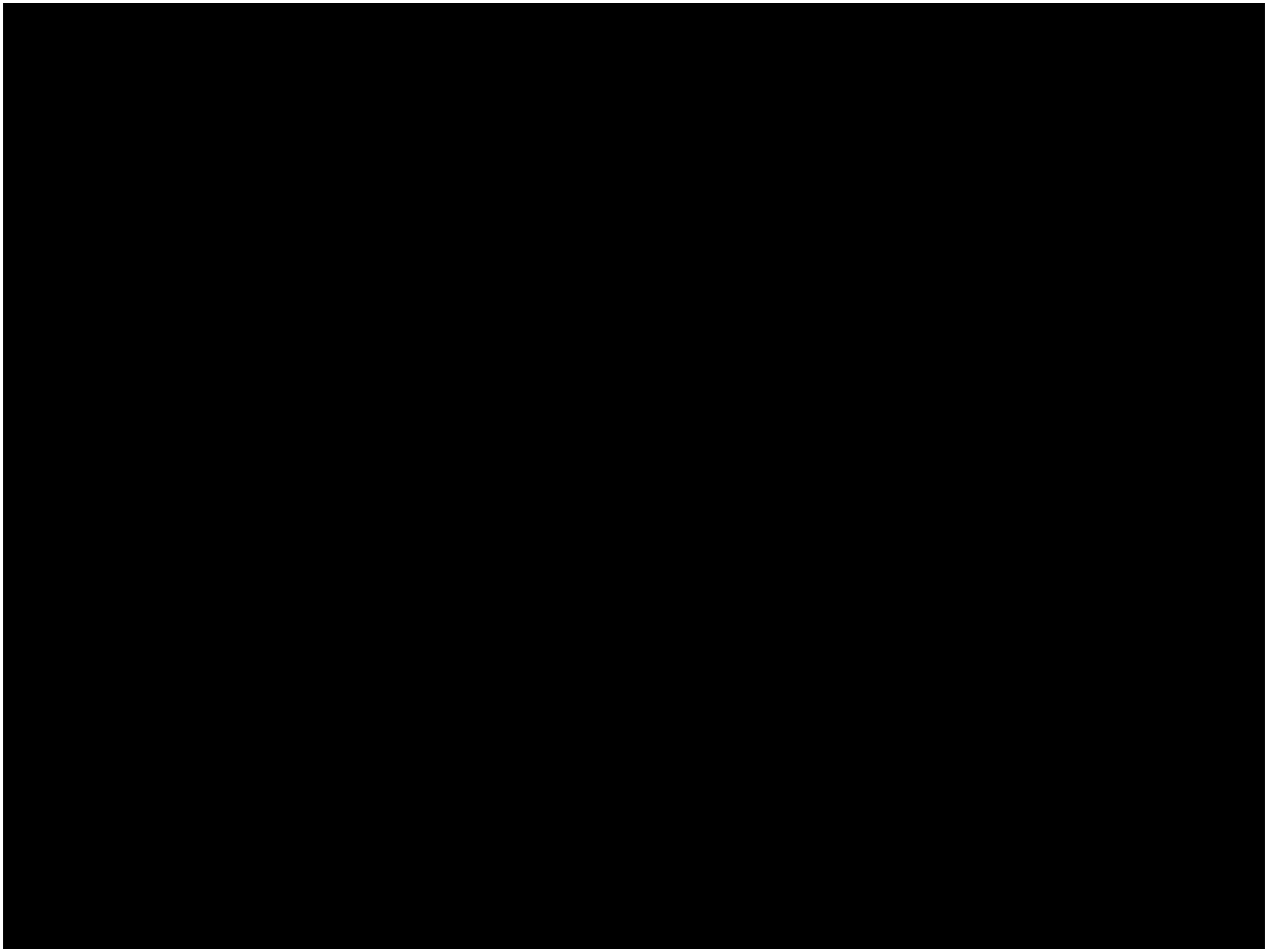
“PADS” sonar (J. Smith, SIO)



R/V Revelle UAV launch and recovery equipment



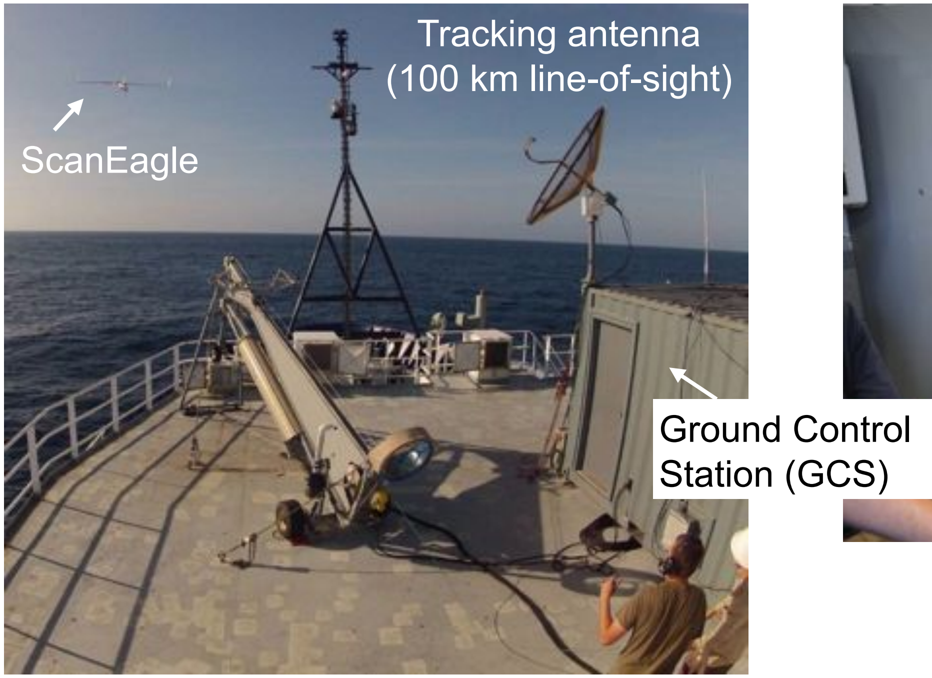
Movie: EquatorMixSEVideo.mov



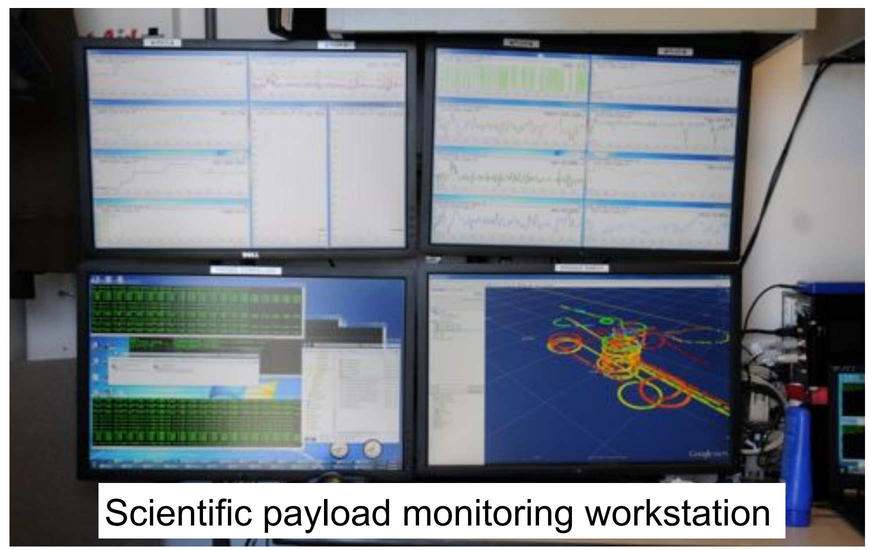
Movie: 20121008RecoveryLong.mov
At-sea recovery "as seen from the ScanEagle"


Photo composite: San Nguyen

Ship-based UAV operations



Inside the Ground Control Station:



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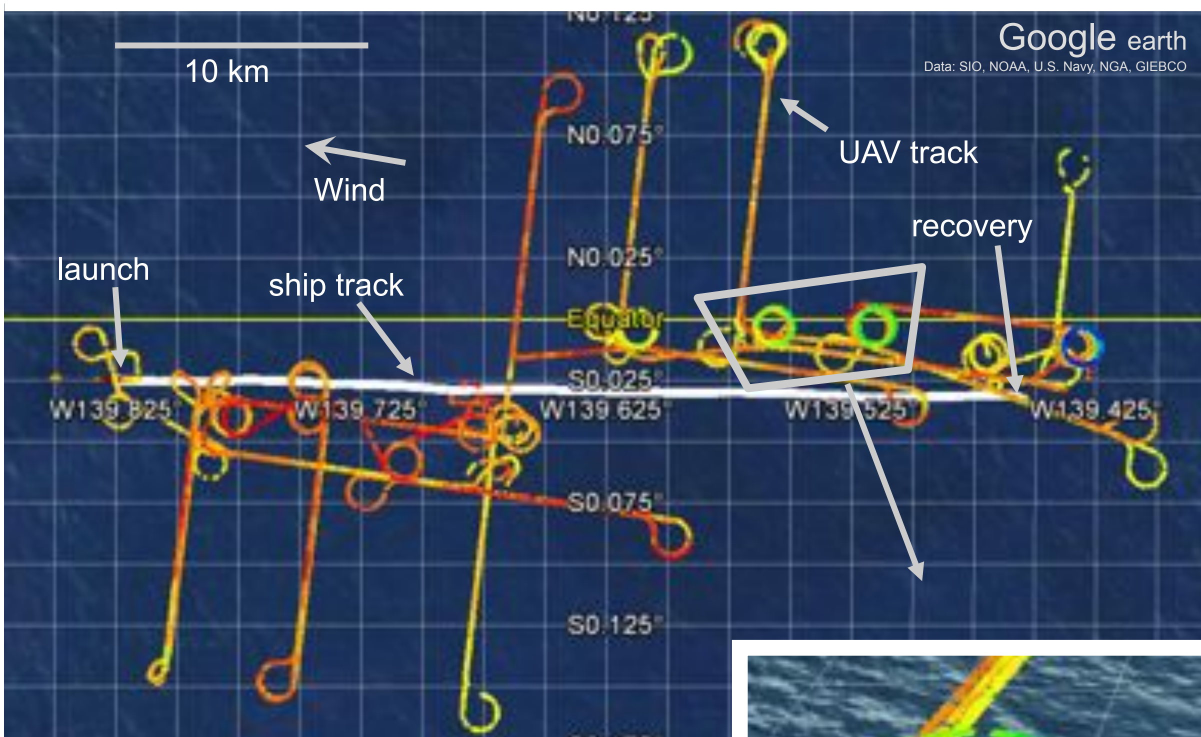
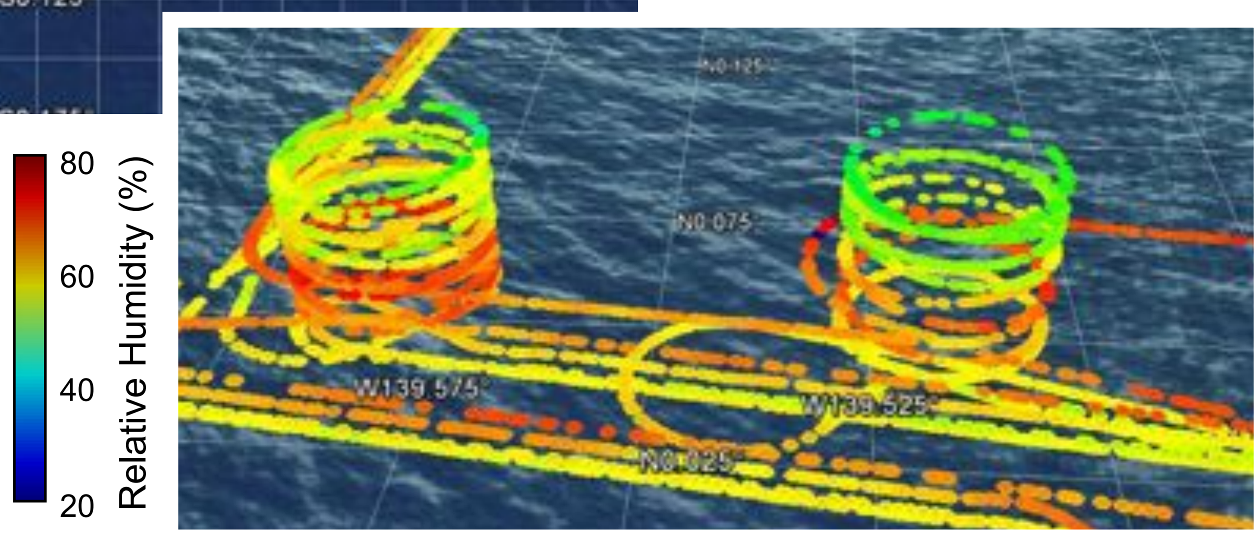
Real-time Google Earth plotting sample: 11-hr "Flux" payload flight



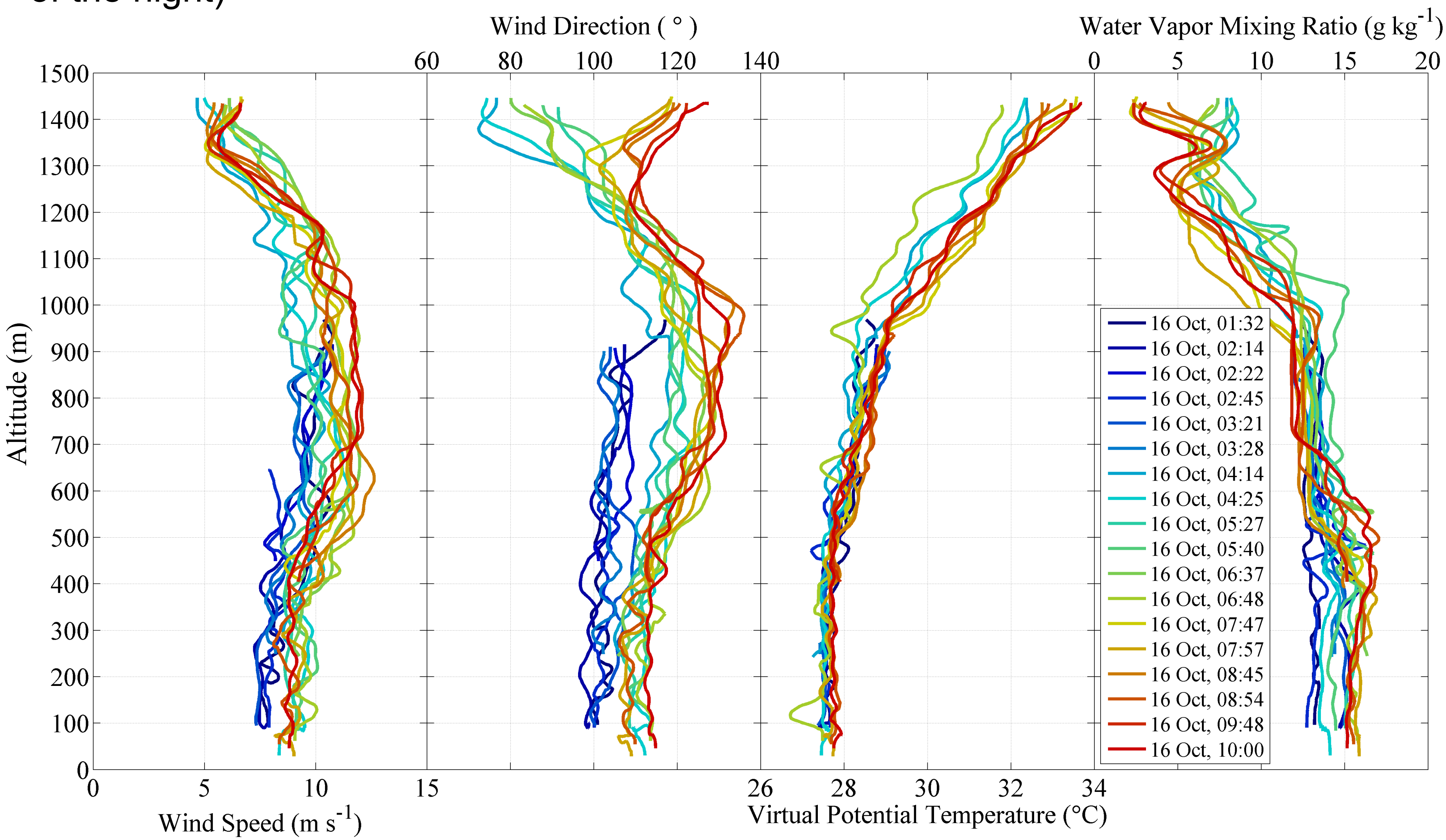
Plot any variable as color along the flight track

Use for "on-the-fly" flight mission planning



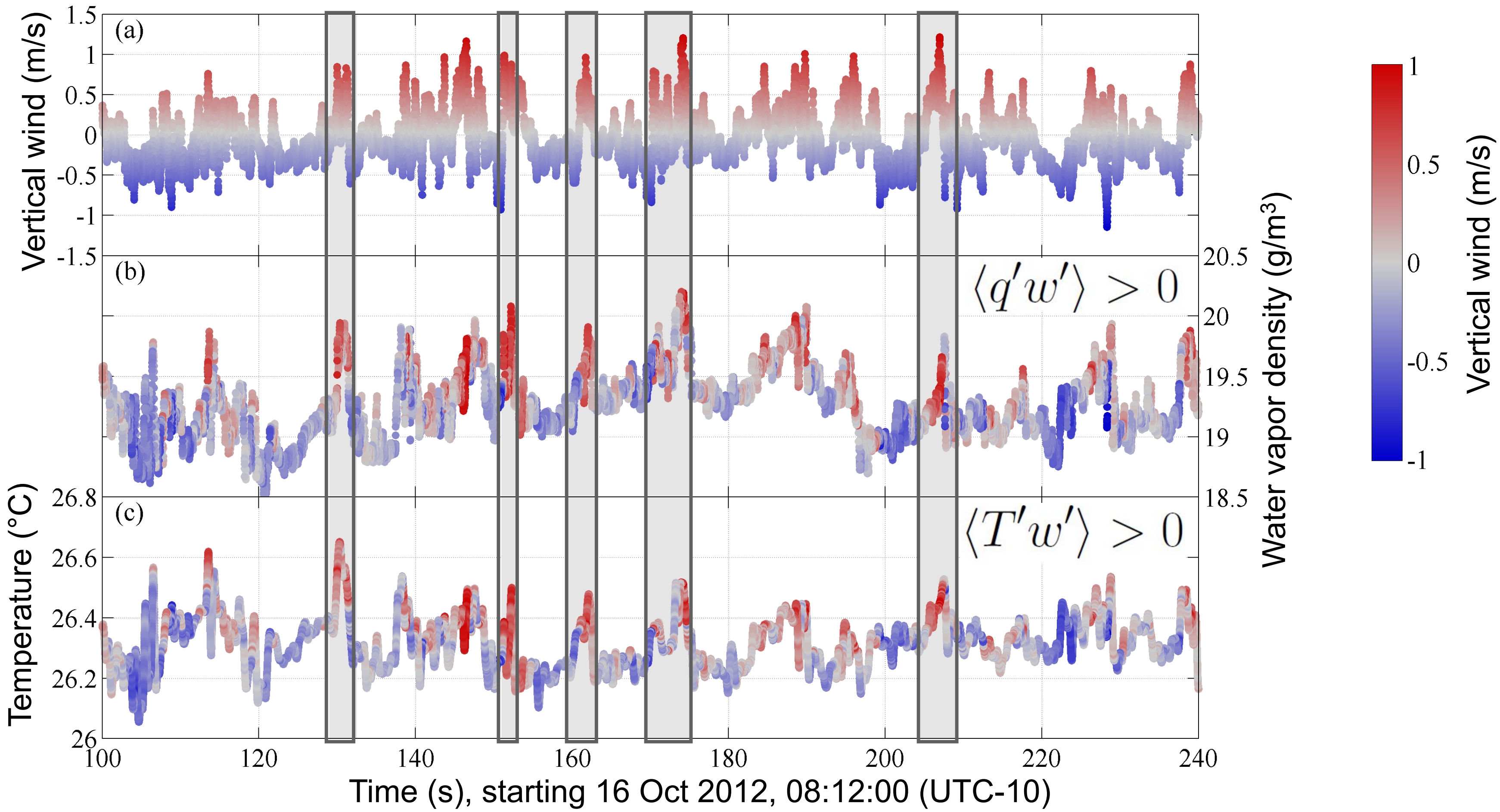
UAV profiles of wind, temperature, water vapor

Vertical profiles upwind of the *Revelle*, during one 11-hr flight (taking off in the middle of the night)



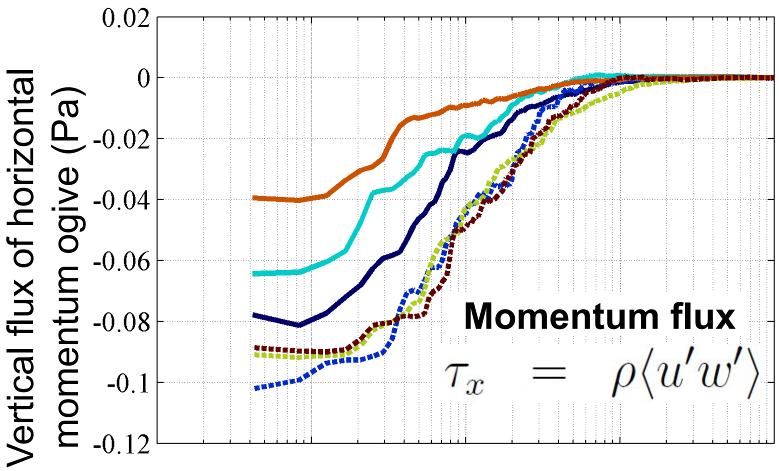
Sample low-altitude (32-m) time series

Positive correlation between vertical wind and water vapor, temperature

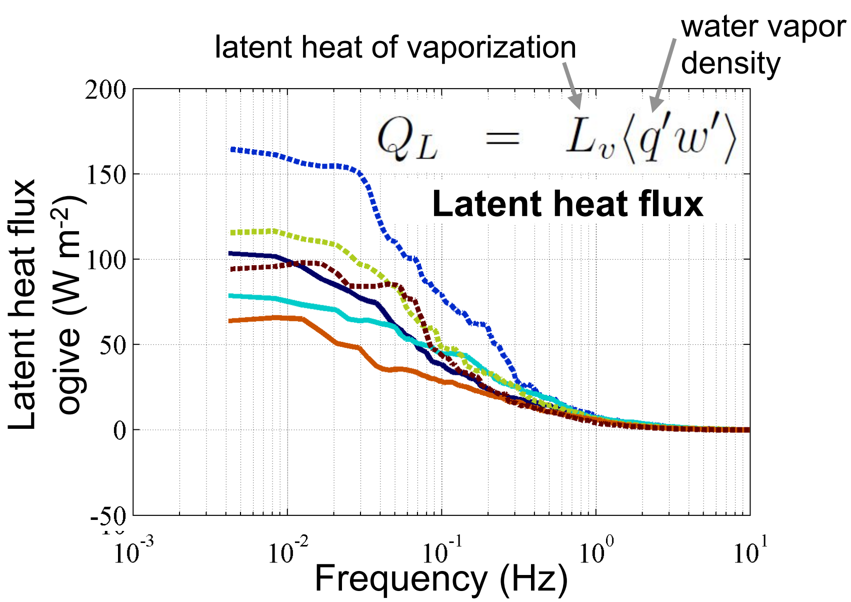


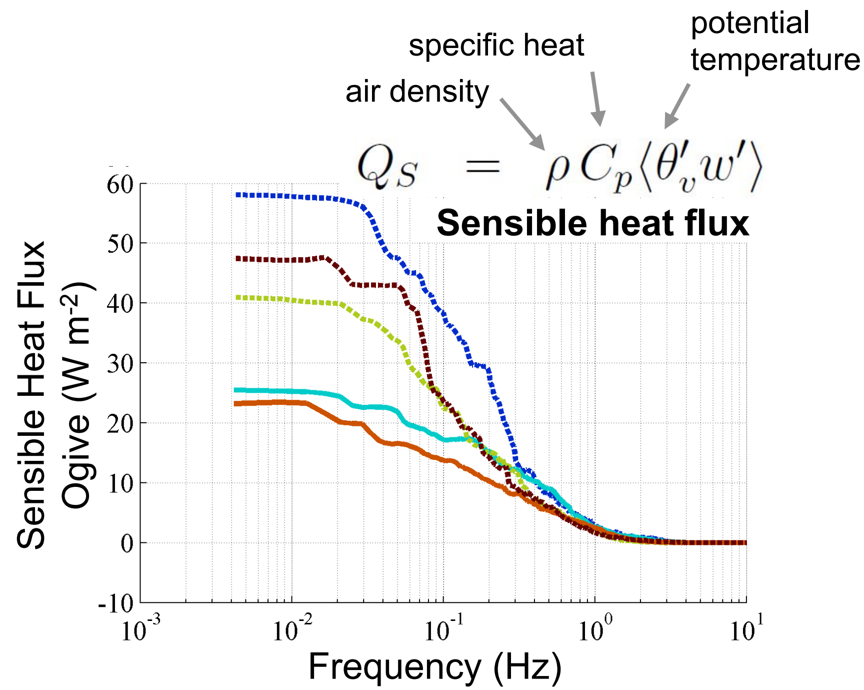
Sample low-altitude (32-m) flux calculations

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



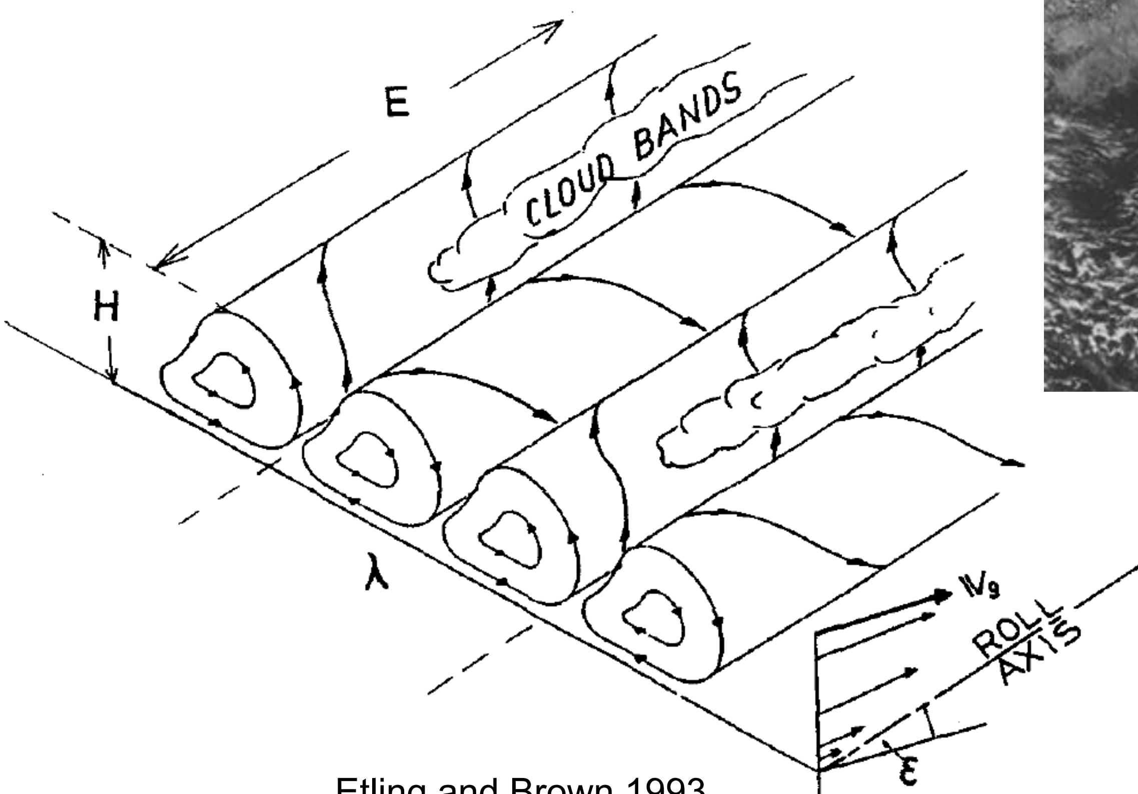
- In agreement with bulk fluxes from ship-based observations
- Next step: resolve limitations of ship and UAV measurements



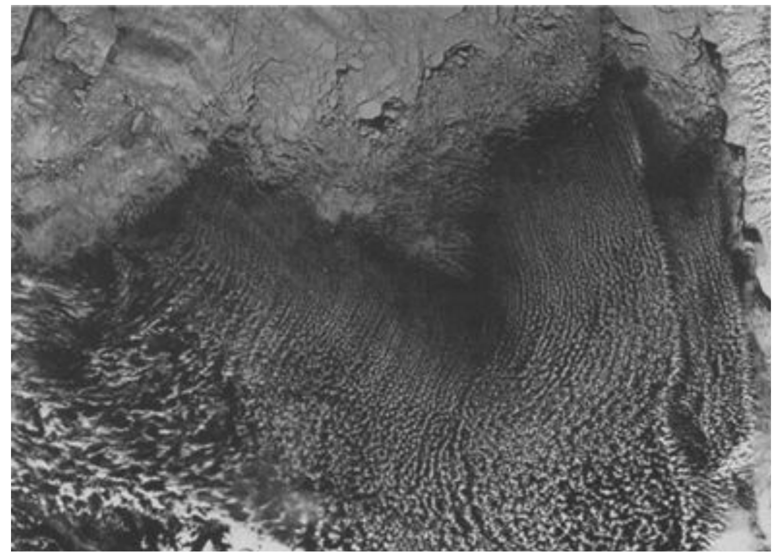


Planetary boundary layer rolls

- Large-scale (O(1 km)) persistent, coherent structures
- Often visible as "cloud streets" in satellite imagery
- Can account for large fraction of fluxes



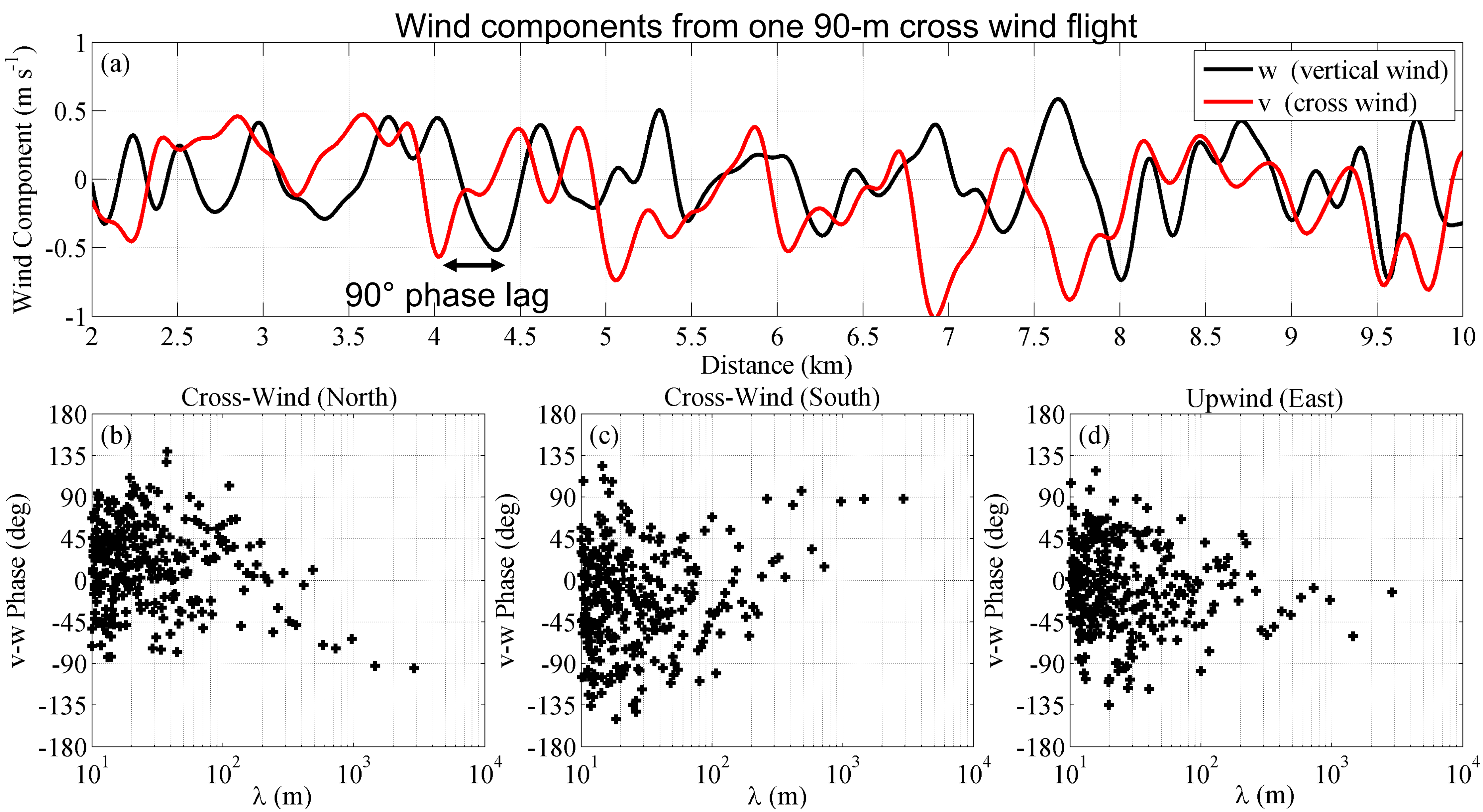
Etling and Brown 1993



Etling and Brown 1993

Planetary boundary layer rolls

- Low-pass filtered (5-s cutoff) show 90-degree phase lag
- Implies UAV flew across roll structures



Sample imagery, stacked ScanEagle flight

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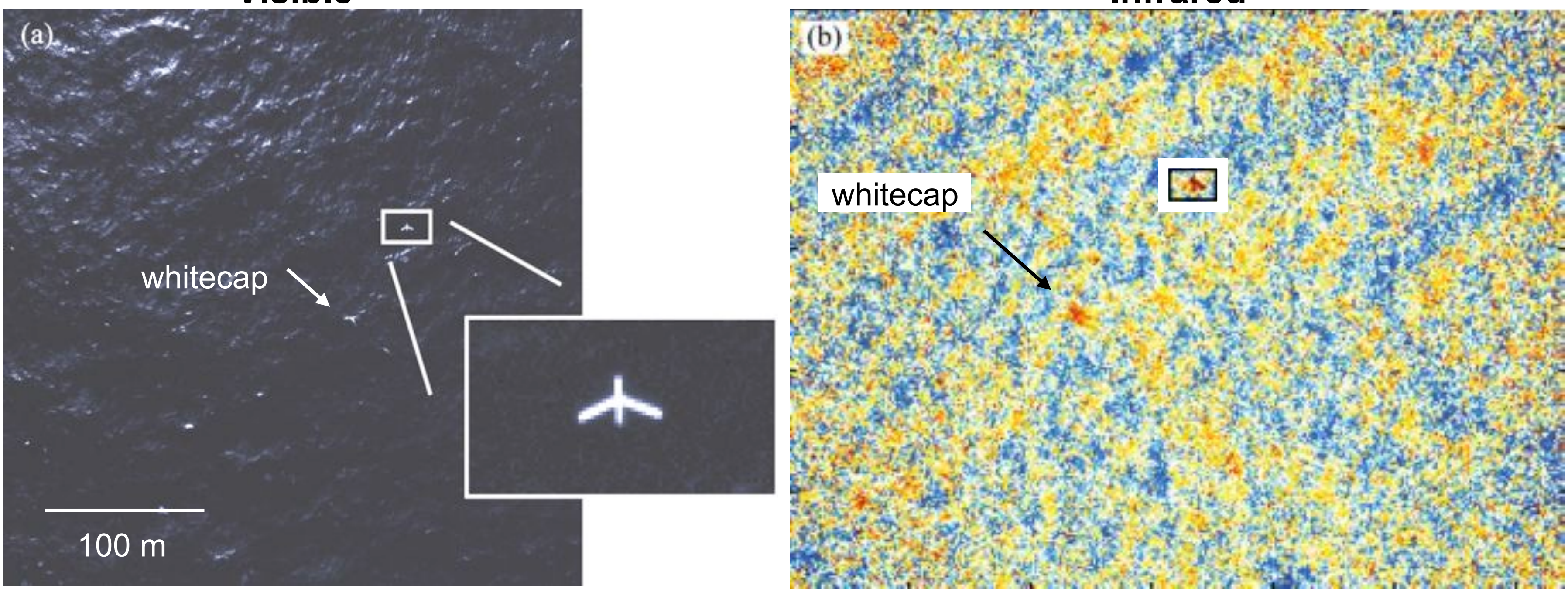
- **Visible and infrared** imagery captured by Imaging payload (300 m AGL)
- During **vertically-stacked formation** – Flux payload UAV (30 m) in field of view
- Permits **analyses of surface fluxes in the context of surface kinematics**

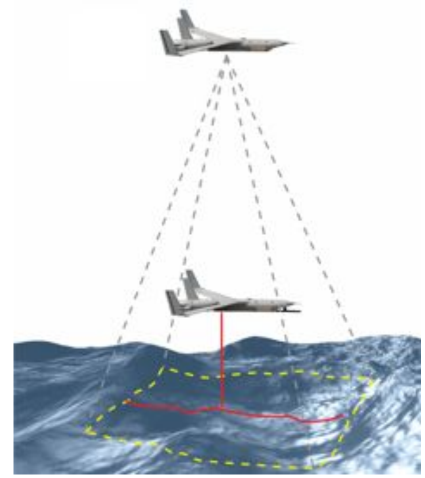
Visible **Infrared**



100 m

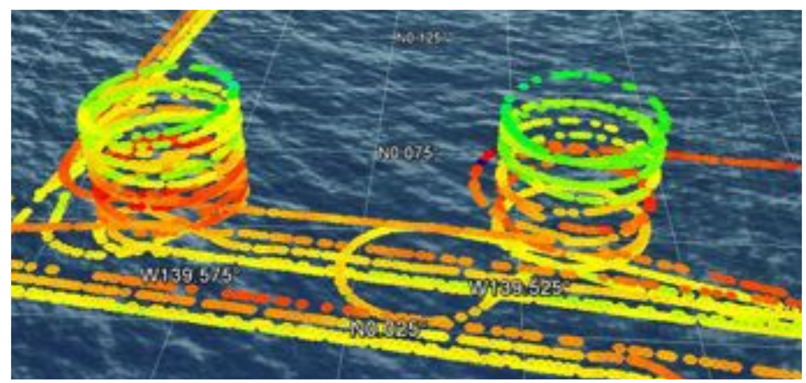
10-m wind = 9 m/s

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.

Reineman, B. D., L. Lenain, N. M. Statom, W. K. Melville, 2013. Development and testing of instrumentation for UAV-based flux measurements within terrestrial and marine atmospheric boundary layers. J. Atmos. Oceanic Technol., In press

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

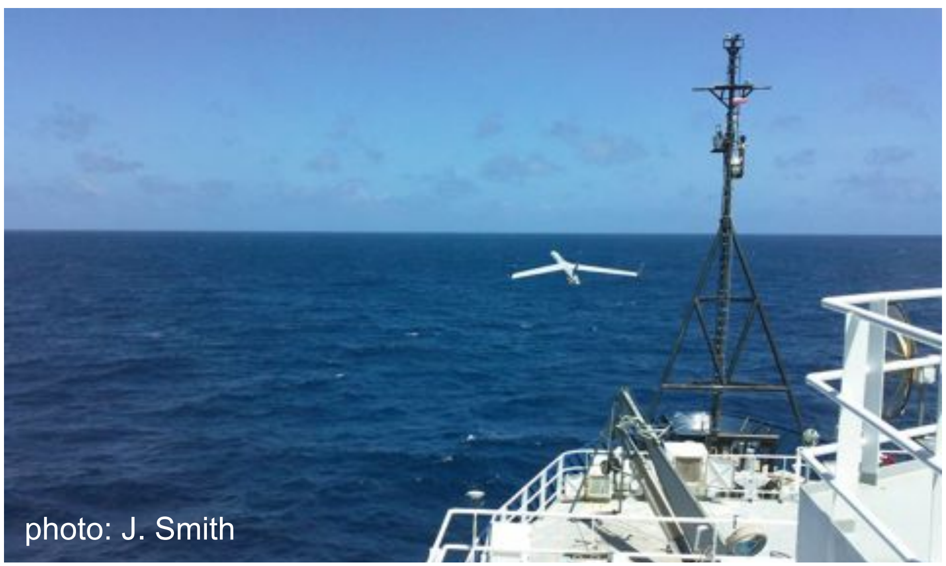


photo: J. Smith


photo: ScanEagle

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

Trident Warrior 2013 (TW13), R/V Knorr July 13-18 2013

- Employ unmanned systems in forward operating areas: demonstration experiment aboard R/V *Knorr*

- Autonomous vehicles:

  Instrumented wavegliders (SPAWAR), SLOCUM (OSU,NRL), ScanEagles (SIO/NSWCDD),

  met. and wave buoys (NPS, SIO), profiling balloon and kite radiosondes (NPS)

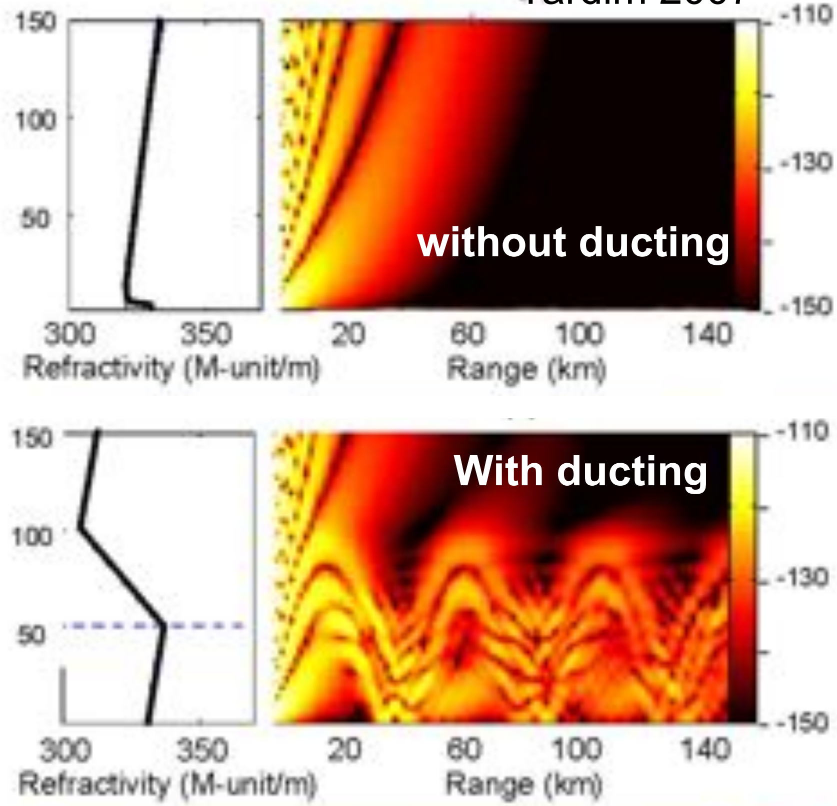
- Science objectives, measurements:
  - Time-varying 3D structure of MABL (vert. profiles wind, temp, humidity)
  - Response of MABL to SST, subsurface structure, and visa versa
  - **Real-time data assimilation** of measurements into Coupled Ocean/Atmosphere Prediction System (COAMPS) (NPS, NRL)
  - Electromagnetic propagation monitoring, model evaluation (SPAWAR, SIO)

Skyhook and launcher installation today/tomorrow on R/V Knorr!

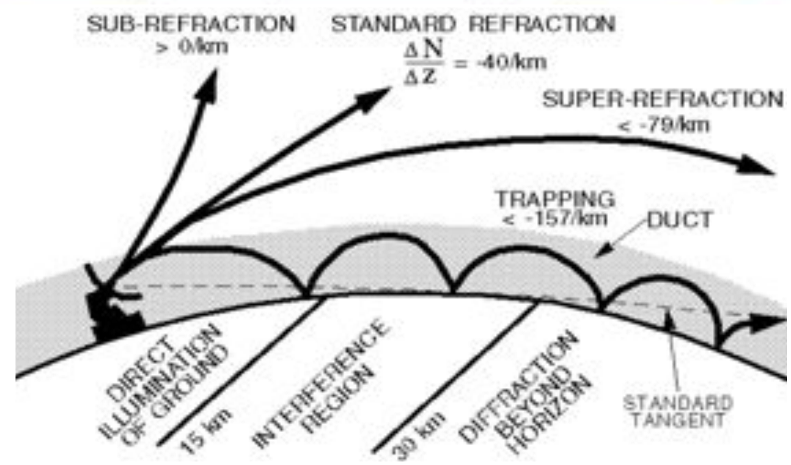
EM propagation in evaporation ducts

- "Inversions" in the M-profile:
  - blind zones, Height errors (3D radar)
  - "Clutter rings," lower signal to noise
- EM waves "trapped" in evaporation duct

Yardim 2007

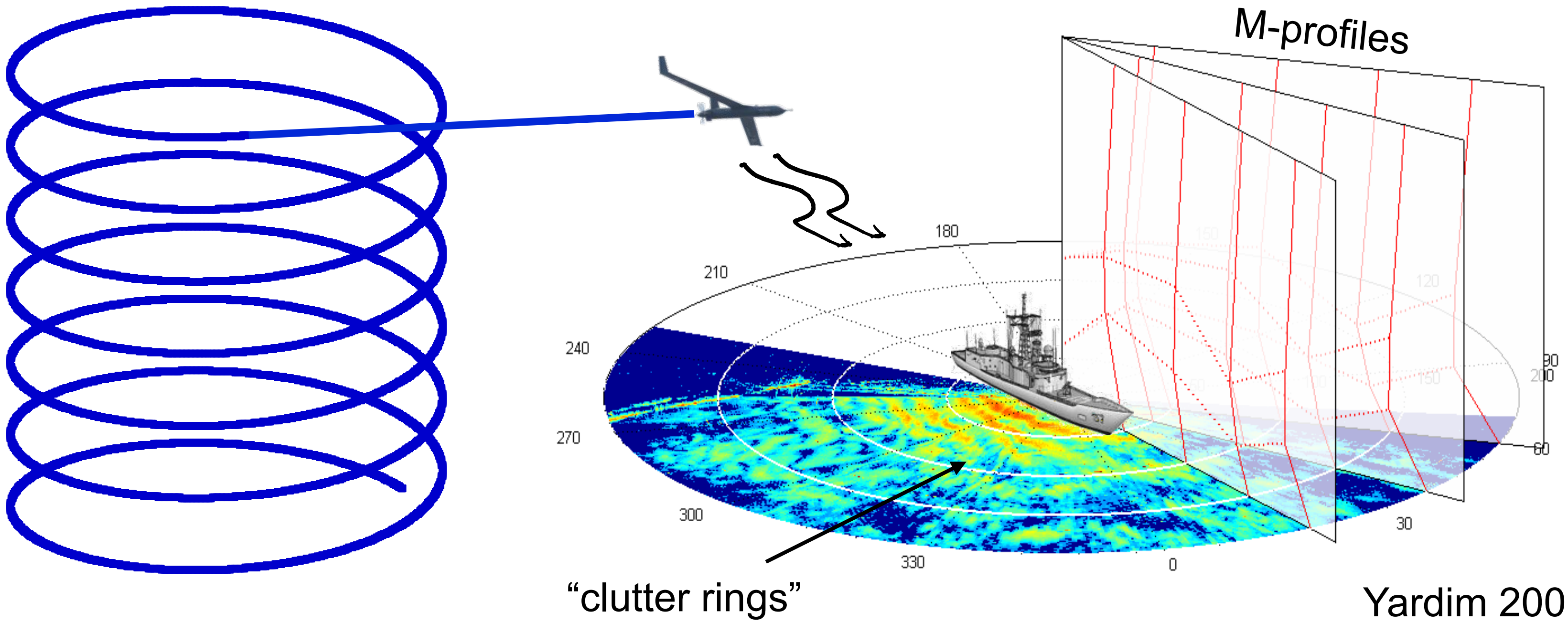


http://www.youtube.com/watch?feature=player_embedded&v=QjIxRMWM5do



ScanEagles in Trident Warrior 2013: demonstrate real-time nowcast and forecast

- Sample MABL over O(10) km range surrounding the ship
- Capture spatial, temporal variability
- Data transmitted back to Scripps in **real-time**, loaded to NRL's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)
- Generate M-profiles in near real-time!

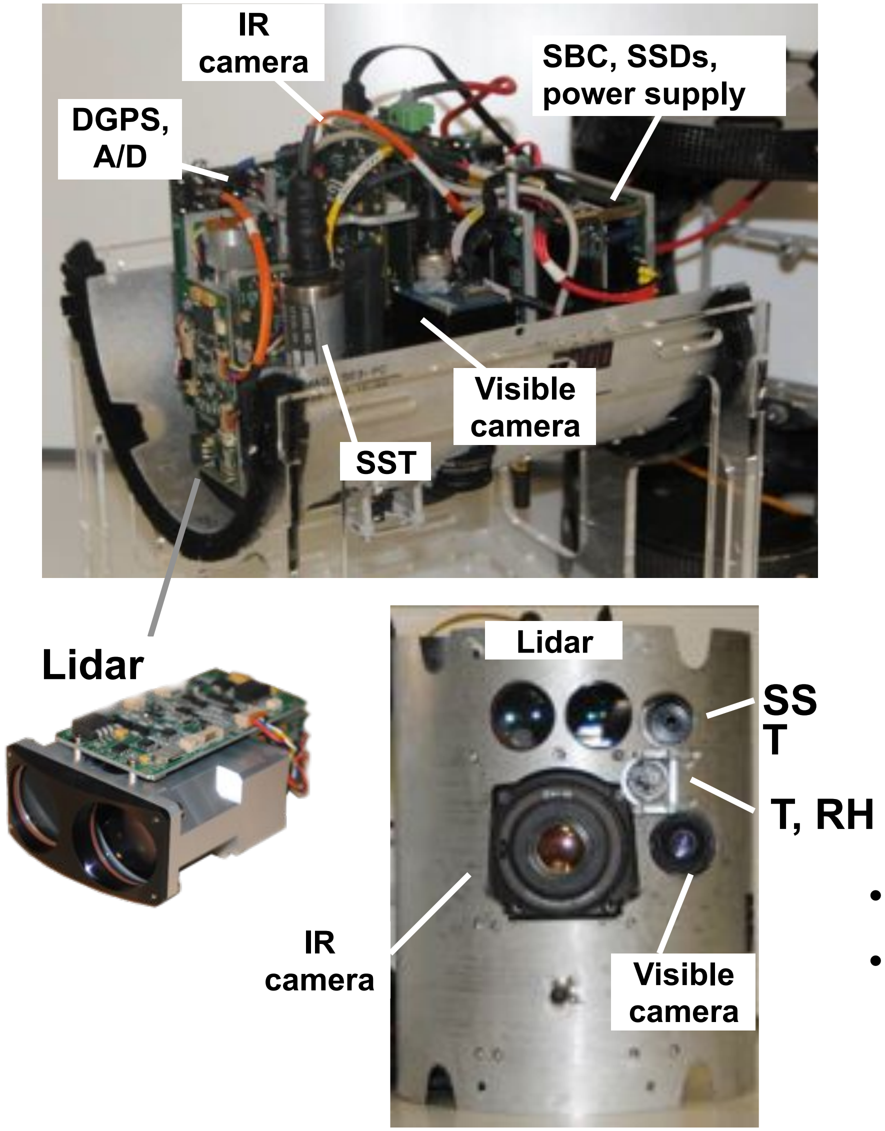


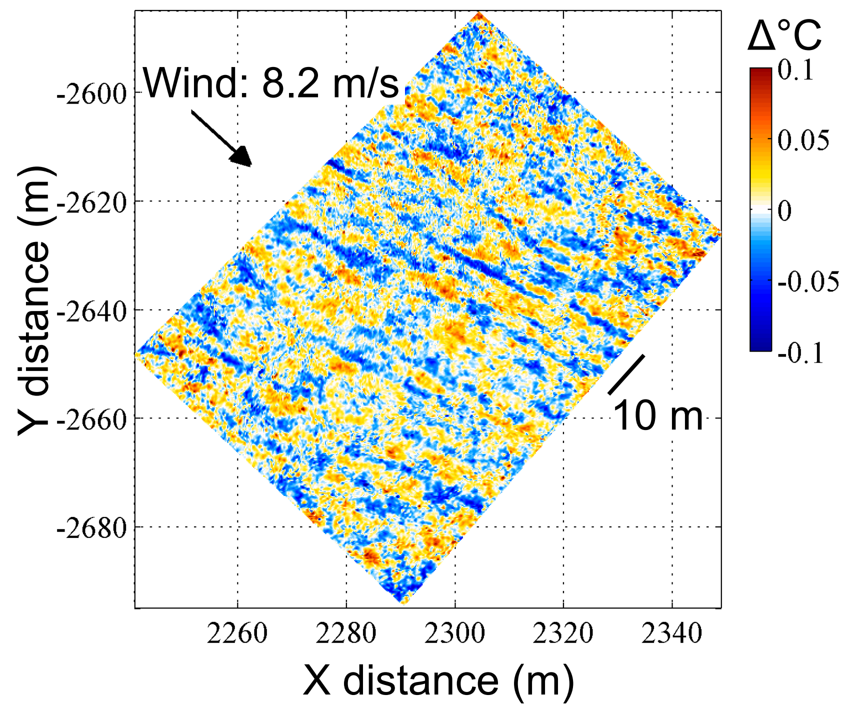
Yardim 2007

Thank you!

"Imaging" payload: visible and infrared imaging (ScanEagle only)

- FLIR long-wave (7.5 – 13 μm) IR camera





- 190 m above Potomac River, 12 Apr 2012
- Langmuir circulation cells, 4 – 6 m spacing (water depth ≈ 3 m)

Reineman et al., 2013

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Electromagnetic wave propagation: Modified refractivity profile

Speed of light in vacuum

- Index of refraction, $n = c/v$

$n \approx 1.000250 - 1.000400$

EM velocity

- Refractivity, $N = (n - 1) \times 10^6$

$N = N(Temperature, RH, Pressure)$

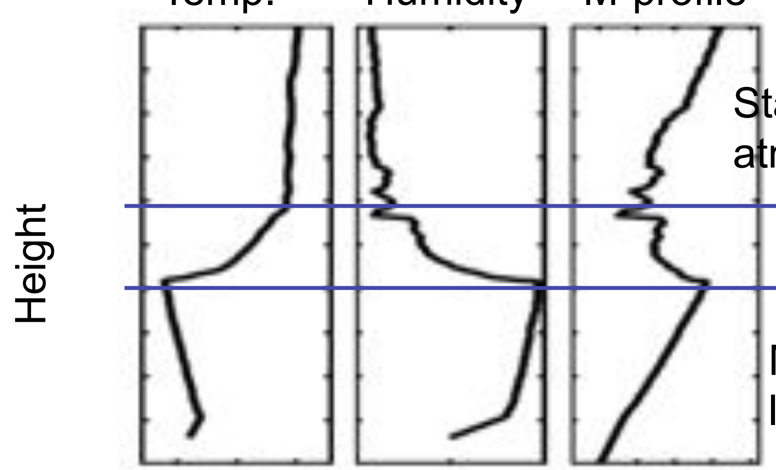
- Modified refractivity, M

changes into a "flat earth" problem

$\Delta M/\Delta z = 0 \rightarrow$ rays stay at const. altitude (curve downward at same rate as earth's curvature)

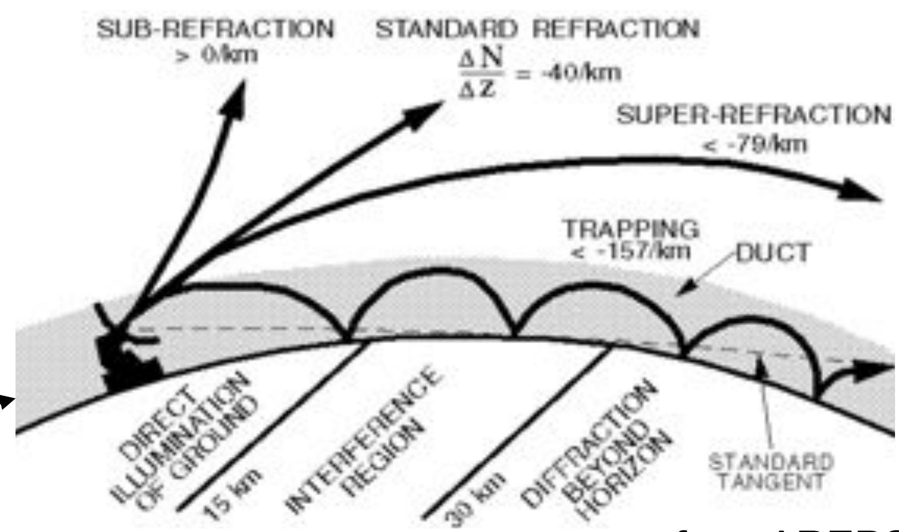
$\Delta M/\Delta z > 0 \rightarrow$ rays bend up

$\Delta M/\Delta z < 0 \rightarrow$ rays bend down



Yardim 2007

$$\frac{\partial M}{\partial z} < 0$$



from AREPS Manual, 2005