Coupled ocean-atmosphere boundary layer measurements (with an initial emphasis on fluxes)

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

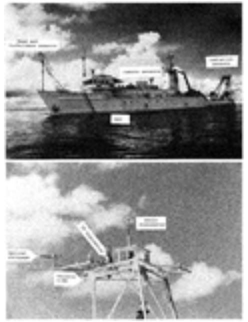
Momentum Flux: $\tau_o = \rho_a \overline{uw} = \rho_a C_D S_r \Delta U$ Drag Coefficient

Sensible Heat Flux: $Q_H = \rho_a c_p \overline{wT} = \rho_a c_p C_H S_r \Delta\Theta$ Stanton Number

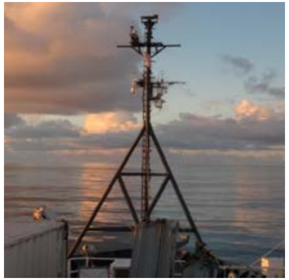
Latent Heat Flux: $Q_E = \rho_a L_v \overline{wq} = \rho_a L_v C_E S_r \Delta Q$ Dalton Number

- Moving platforms require motion correction of anemometers
- Minimize flow distortion
- Add capabilities

$$\mathrm{E} = Q_E/(\rho_w L_v)$$



1992 TOGA COARE



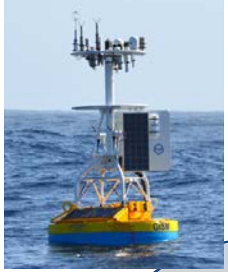
2017 NASA SPURS

Air-Sea Interaction Spar (ASIS)

CLIMODE Year long

SPURS Latent Heat Flux

OOI & TPOS Real-time Fluxes



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Ship-based Flux Systems

- DCFS
- Open path hygrometers
- Closed path hygrometer
- Aspirated RH/T sensors
- Solar/IR sensors
- Optical rain gauge
- Self-siphoning rain gauge

Challenge: Reduce 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.
- Approximately half the flux bias have been removed on ships.

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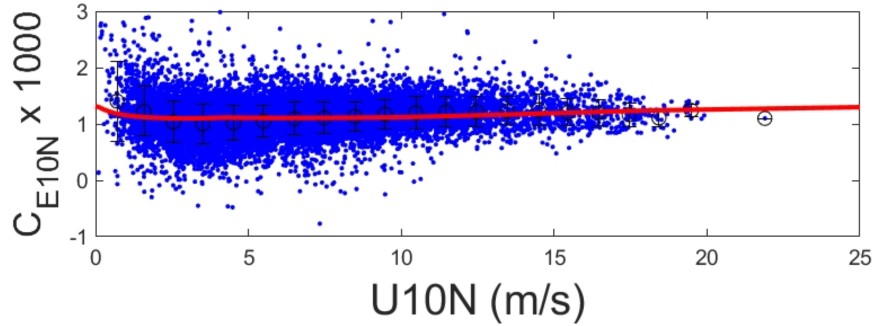
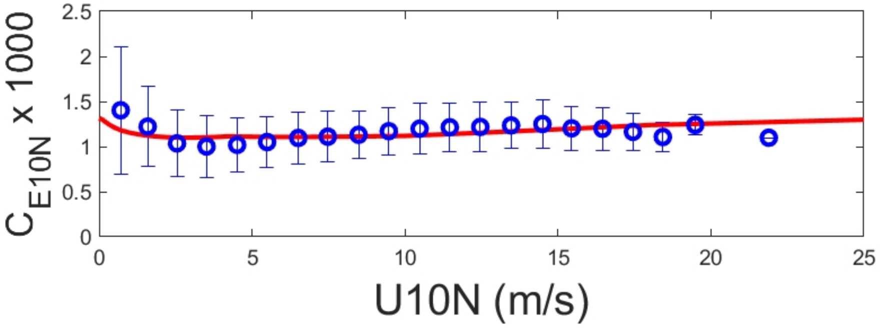
Ship & Buoy-based Transfer Coefficients

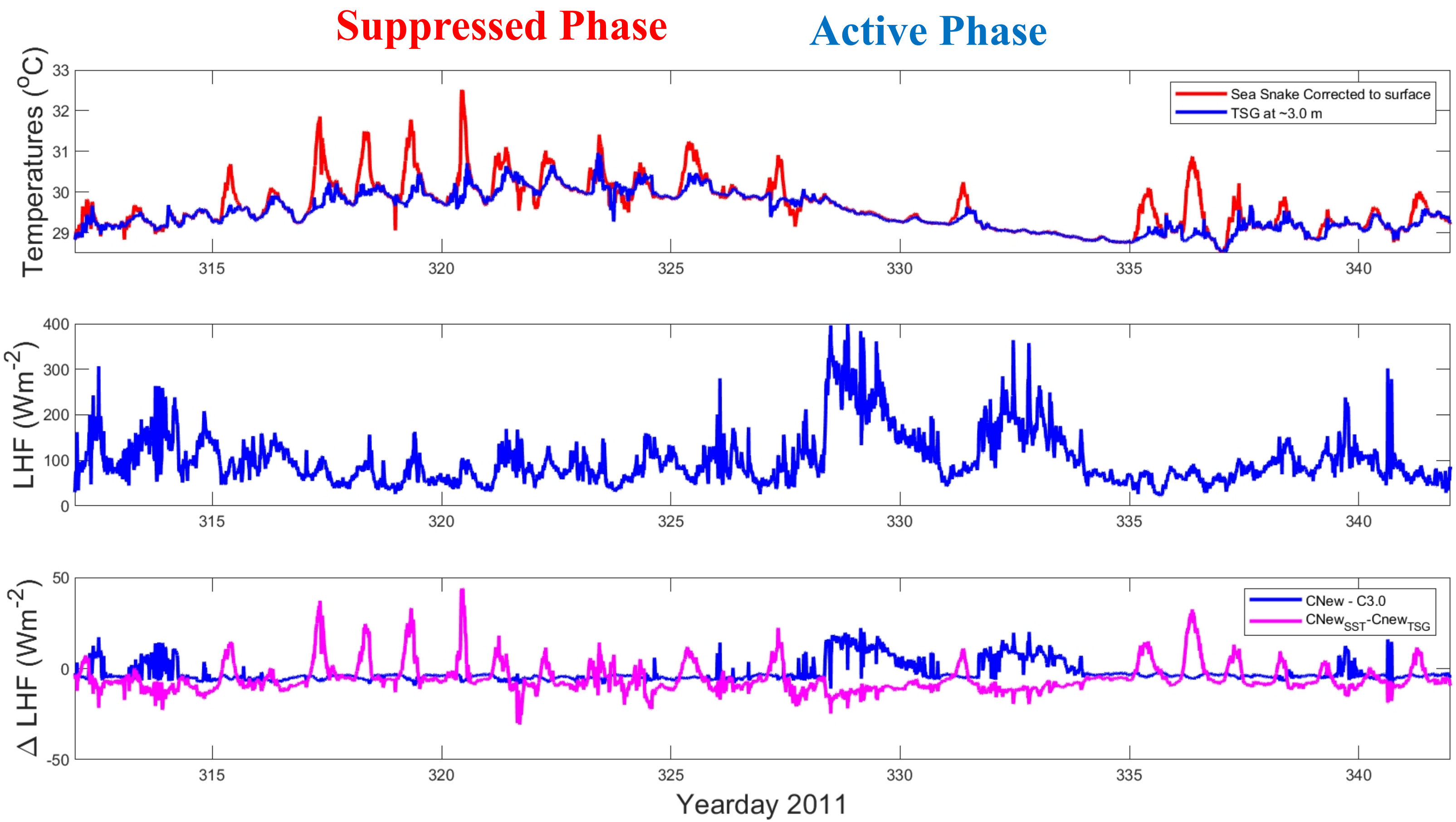




- Excluding high winds (> 20 m/s), COARE algorithm very small errors in the mean
- But: unresolved processes remain, causing "real" scatter
- Needs:
  - Directional wave measurements
  - Sea-spray analysis
  - Droplet analysis

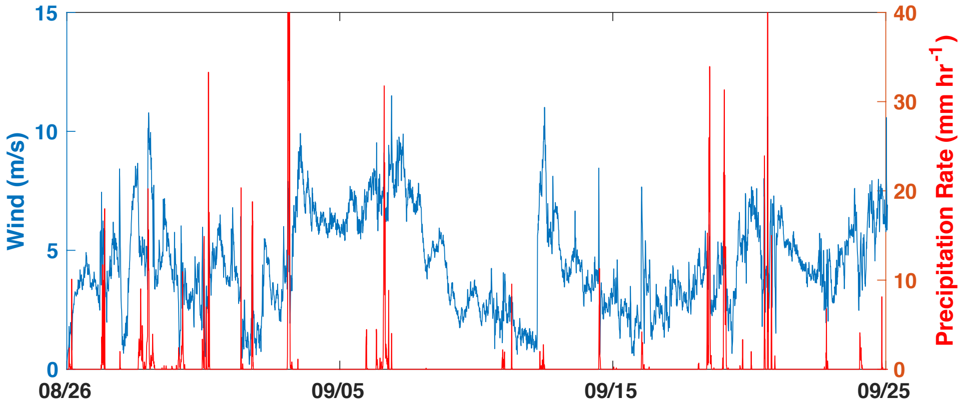
For process studies: we still need direct flux measurements

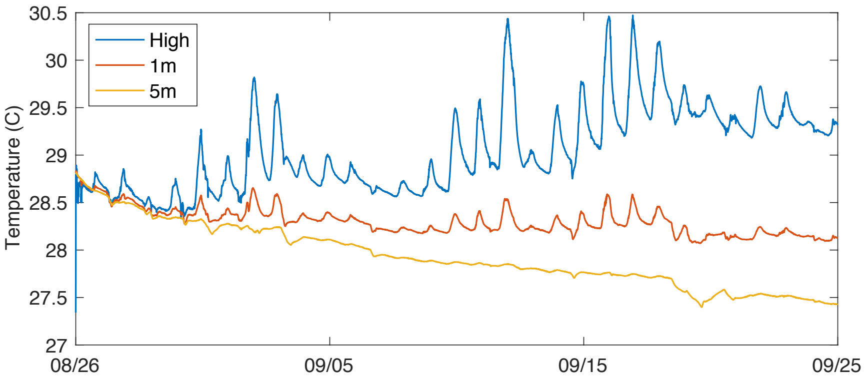
Parameterizations and State Variables

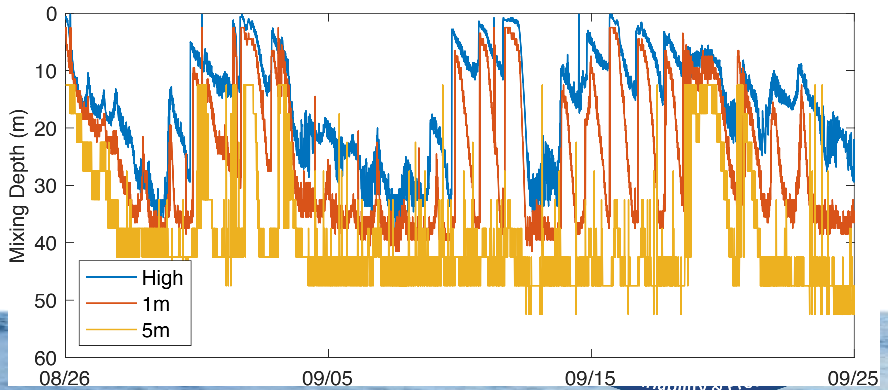


Resolution in upper ocean matters

- Need high resolution data
- Increased resolution models







Recent relevant community requests

- ESAS Decadal Survey
  - https://www.nap.edu/download/24938
- WCRP Surface Flux white paper
  - https://www.earthsystemcog.org/projects/surflux/whitePaper
- OceanObs19 paper
  - https://www.frontiersin.org/articles/10.3389/fmars.2019.00430/full
- TPOS 2020 2nd Report
  - http://tpos2020.org/wp-content/uploads/TPOS%202020%20Second%20Report_2019May30.pdf
- NAS Future of Boundary Layer Observing workshop
  - http://dels.nas.edu/Workshop-Summary/Future-Atmospheric-Boundary-Layer/25138
- CLIVAR Air-Sea Interaction and Convection meeting

ESAS Decadal Survey

- H-1. How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?
- H-2. How do anthropogenic changes in climate, land use, water use, and water storage, interact and modify the water and energy cycles locally, regionally, and globally and what are the short- and long-term consequences?
- W-1. What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?
- W-2. How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?
- W-3. How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, cryosphere) and thereby influence weather and air quality?
- E-2. What are the fluxes (of carbon, water, nutrients, and energy) between ecosystems and the atmosphere, the ocean, and solid Earth, and how and why are they changing?
- C-2h. Reduce the IPCC AR5 total aerosol radiative forcing uncertainty by a factor of 2.
- C-4a. Improve the estimates of global air-sea fluxes of heat, momentum, water vapor (i.e., moisture) and other gases (e.g., CO2 and CH4) to the following global accuracy in the mean on local or regional scales: (1) radiative fluxes to 5 W/m2, (2) sensible and latent heat fluxes to 5 W/m2, (3) winds to 0.1 m/s, and (4) CO2 and CH4 to within 25%, with appropriate decadal stabilities.
- C-7a. Quantify the changes in the atmospheric and oceanic circulation patterns, reducing uncertainty by a factor of 2, with desired confidence levels of 67% (likely in IPCC parlance).
- C-8a. Improve our understanding of the drivers behind polar amplification by quantifying the relative impact of snow/ice-albedo feedback versus changes in atmospheric and oceanic circulation, water vapor, and lapse rate feedback.
- C-8b. Improve understanding of high-latitude variability and midlatitude weather linkages (impact on midlatitude extreme weather and changes in storm tracks from increased polar temperatures, loss of ice and snow cover extent, and changes in sea level from increased melting of ice sheets and glaciers).
- C-8c. Improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea-ice cover, including sea-ice fraction (within 5%), ice thickness (within 20 cm), location of the ice edge (within 1 km), timing of ice retreat and ice

Most/very important science questions that specifically call out improved ocean-atmosphere fluxes and/or ocean/atmosphere boundary layer profiles

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Results from ESAS Decadal Survey

- PBL satellite placed in the incubation category (1 of 2)
- Recent NASA call for Study Team to outline what a PBL satellite would need to be
  - What in situ is needed?
  - What modeling improvements are needed?
- Decadal study had the following requirements for PBL satellite:
  - three-dimensional diurnally-varying structure of the PBL with 0.2 km vertical resolution, 2-3 hourly temporal resolution, and 5-20 horizontal resolution.

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WCRP WDAC SurFlux Task Team white paper

- Major recommendations
  - Consistent collaboration between *in situ* and satellite communities for more useful in situ data and improved error statistics
  - Land, ice, and ocean observationalists should be encouraged to collaborate more consistently.
  - Increased focus on co-location of various *in situ* flux networks and observations. In corollary, expand number of sites measuring not only surface parameters, but also observations that will improve understanding of physics for modeling and satellite algorithm development of coupled boundary layers.
  - Clear guidelines need to be established for assessment and quality-control of new platforms and sensors
  - Closer integration of the observational and modeling communities
  - Clear guidelines need to be established to estimate the uncertainty and to quality control in situ, gridded products and satellite data.
  - Improvements in the following aspects of re-analysis systems are of high priority: (i) constrain top of atmosphere radiation by satellite observations, (ii) develop coupled land/atmosphere and coupled sea-ice/atmosphere data assimilation systems to obtain more satellite constraint on surface fluxes, and (iii) to include global constraints on energy fluxes in the variational algorithms.
  - Foster use of high resolution models to evaluate importance of temporal and spatial variability of turbulence and radiative fluxes, and to identify key locations and parameters to focus on when suggesting additional measurements for improved climate simulations.
  - Establish a forum to report results of comparisons, possible model errors and improvements for communities who use models for both predictive purposes (such as the NWP community) and for producing global gridded products (such as the continental satellite flux community).
- 6 other recommendations

OceanObs19 paper

- **Major Recommendation #1**
  - Create a remote-sensing retrieval system designed for accurate boundary layer measurement of air temperature, humidity, SST, and surface stress. This would involve a holistic approach to improve resolution of satellite retrievals, time coincidence of remotely sensed surface flux EOVs/ECVs, and algorithms that relate the retrievals to near-surface conditions.
- **Major Recommendation #2**
  - Create a global *in situ* array of flux observing platforms, built around an expanded OceanSITES network of time series reference station moorings. The global array would include ~500–1000 platforms including ASVs, moored and drifting buoys, and RVs, with 1–3 platforms in nominal 10° by 10° boxes. The OceanSITES network of 22 flux sites must be maintained and expanded in up to 19 key regions. In addition, the *in situ* array should include a few super sites with enhanced observations of the coupled boundary layer.

OceanObs19 paper roadmap

- TRL for ASV and other new flux platforms must be increased before being used to form a large global network. These platforms must be continually evaluated against satellite and proven technology, including RVs, flux towers with vertical extent, and OceanSITES and OOI moorings. It is recommended that an international ASV expert group form to coordinate ASV data stream, evaluate data, and develop best practices and standardizations.
- Array designs for the *in situ* flux network must be studied. Determining the optimal array design will require both model studies and pilot field studies.
- International coordination of data management and archival must be extended to flux-related data streams
- With the expanded *in situ* array of the state of the art bulk aerodynamic flux algorithm can be improved, leading to reduced uncertainties. It is critical that the bulk algorithm in NWP be improved.
- Parameterizations for transforming bulk EOV/ECV into bulk algorithm state variables must be improved. These include (but are not limited to) extrapolation of bulk sea surface state variables to the air-sea interface, and parameterizations of albedo and emissivity.
- Cross-platform and cross-product intercomparisons must take place and differences must be reconciled. Sensors across all *in situ* platforms should have laboratory calibrations traceable to international standards, and field intercomparisons to verify consistency. Identification of field errors should lead to changes in best practices.

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Some PBL workshop recommendations

- Examples of suggested measurements for marine boundary layers:
  - heat, mass, and momentum fluxes at moderate to high winds as well as sea-spray and droplet concentration measurements at high winds (1-1,000 μm)
- Measurements needed for all BLs:
  - Remotely sensed measurement of specific humidity (mixing rates) and temperature with some ability to provide estimates at several levels in the BL
  - Wind speed, specific humidity, temperature, gases, and aerosols from in situ measurement platforms including sondes, drones, and towers
  - Use of chemical tracers to study BL structure over urban BL and, for example, entrainment studies
  - Kinematic profiles of means and fluxes, low power, high resolution, rugged

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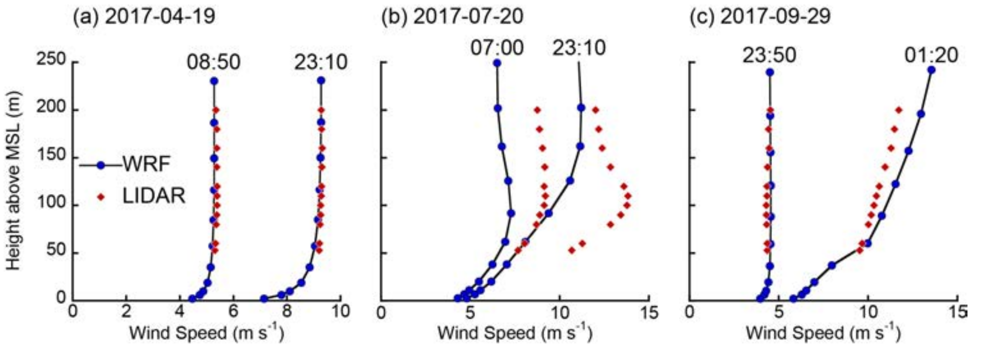
Comments from CLIVAR Air-Sea Interaction & Convection meeting

Progress:

- Air-sea-wave coupling in numerical model
- Recognition of the importance of SST and salinity gradient to surface fluxes/air-sea interaction across a variety of scales
- Observations and modeling of diurnal coupling
- Improvement of stratus cloud of the eastern Pacific in GCMs
- Observations of TC cold SST trails
- Recognition of TC as a coupled phenomenon
- Buoy-based lidar profilers (surface – 300 m)
- Coupled models for NWP
- Propagation mechanisms of MJO
- Improved instrumentation



Comparisons from LIDAR wind observations and WRF model simulations from the ASIT under three separate conditions. All plots show two times during the same day. (a) On shore, convective conditions. (b) On shore, stably stratified conditions. (c) Off shore, slightly unstable conditions.

Gaps:

- Observations and knowledge of turbulence in the PBL
- Observations of moisture variability associated with cold pools
- Observations of the vertical structure and evolution of cold pools at min resolution
- Observations of SST fronts, their processes, surface fluxes, and PBL
- Not using the most advanced surface flux algorithms in numerical models
- Coupled atmosphere-wave boundary layer/flux parameterization in the presence of swell and high wind
- Net effect of small-scale phenomena on air-sea interaction (mesoscale, fresh lenses)

Some recommendations from CLIVAR Air-Sea Interaction & Convection meeting

- Optimal locations for continuous (≥ three years) field observations (supersites) should cover all or most scenarios of air-sea coupling (strong vs. weak winds, uniform SST vs. strong SST gradients, types of waves, etc.), convection (shallow to deep), open water vs. coast. Should provide for horizontal coverage as well as vertical
- Enhanced model-observation integration: ensure applications of most advanced observational products to model development.
- Surface fluxes should be used as a metric to evaluate (coupled or uncoupled) model performance over the ocean. Comparisons with satellite gridded products are encouraged, and product improvement should continue
- Modelers should not select a flux parameterization that produces the results they want. They should use a consensus flux algorithm (such as COARE) as standard surface flux scheme to reduce one tunable parameter in models
- Measurements of vertical profiles of atmospheric boundary layer key to improvements (state variables, fluxes).
  - Need continued technological development to bring down power needs and sizes
  - Note developments where other partners have interests (e.g. wind power industry)
- Measurements of a spatial domain are needed to understand air-sea interactions on various scales. Examples:
  - Observations of the vertical structure and evolution of cold pools at min resolution
  - Observations of SST fronts, their processes, surface fluxes, and PBL
- Significant differences shown between model simulations with differing ABL vertical resolution and parameterization
  - Vertical resolution in the boundary layer of ocean has progressed, but what about vertical resolution in atmosphere models?
  - Need a focus on PBL mixing schemes and improvements

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Final thoughts

- New platforms show promise for some measurements, but careful analysis needed
- Bulk flux algorithms very accurate in mean, but processes level studies need directly measured fluxes
  - Directional wave measurements
  - Sea spray and droplets
- High-resolution profiles in the vertical (and horizontal) needed in BOTH marine boundary layer and ocean boundary layer