Understanding and Constraining Bulk and Sea Spray Heat Fluxes in High Winds Using Direct Covariance Heat Flux Observations

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AMS Tropical 2026, San Diego

1. Introduction

- Bulk heat flux models widely assume similarity between sensible and latent heat transfer coefficients (C_{h10N} and C_{e10N}) in high winds (U_{10} > 20 m/s).
- Sea spray is thought to affect high-wind air-sea heat fluxes, but limited direct flux data impedes progress in understanding physics and calibrating models.
- Sea spray heat fluxes depend on (1) spray generation by breaking waves, (2) droplet transport and heat transfer, and (3) spray layer feedback (Fig. 1).

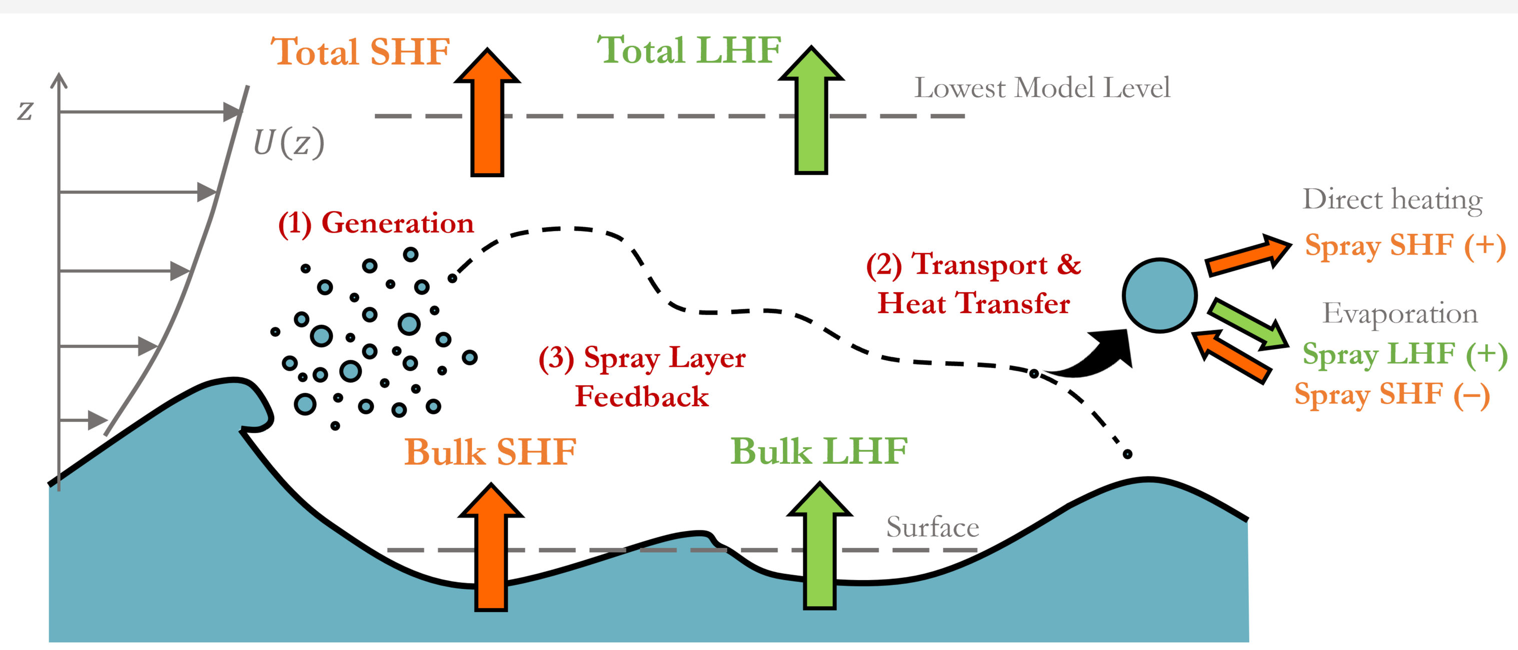

Figure 1. Physical processes in Barr et al. (2023) wave-dependent heat flux parameterization with spray.

- We use direct covariance (DC) flux observations and a parameterization for air-sea heat fluxes with spray (Barr et al. 2023, i.e. BCF23) to address the following:
  1. *Do C_{h10N} and C_{e10N} from DC obs show similar behavior in high winds?*
  2. *Does incorporating spray physics improve high-wind heat flux predictions?*
  3. *Do spray physics suggest similarity between thermal and moisture roughness lengths (z_{0t} and z_{0q}) rather than transfer coefficients?*

2. Direct Covariance Data

- We examine DC flux observations from Ocean Observatories Initiative (OOI) buoys (Irminger Sea, Pioneer, Endurance, Southern Ocean Arrays) and field campaigns (CLIMODE, DYNAMO, SPURS 1/2, FASTEX, HiWinGS).
- OOI buoys have anemometers for SHF but no gas analyzer for moisture. So, data coverage for SHF is much better than for LHF.
- Data coverage drops in high winds. Irminger Sea and CLIMODE provide most points for C_{h10N}, and CLIMODE and FASTEX provide most for C_{e10N}.
- Data for C_{e10N} follows the COARE 3.6 model in high winds, but COARE over-predicts C_{h10N} in high winds.

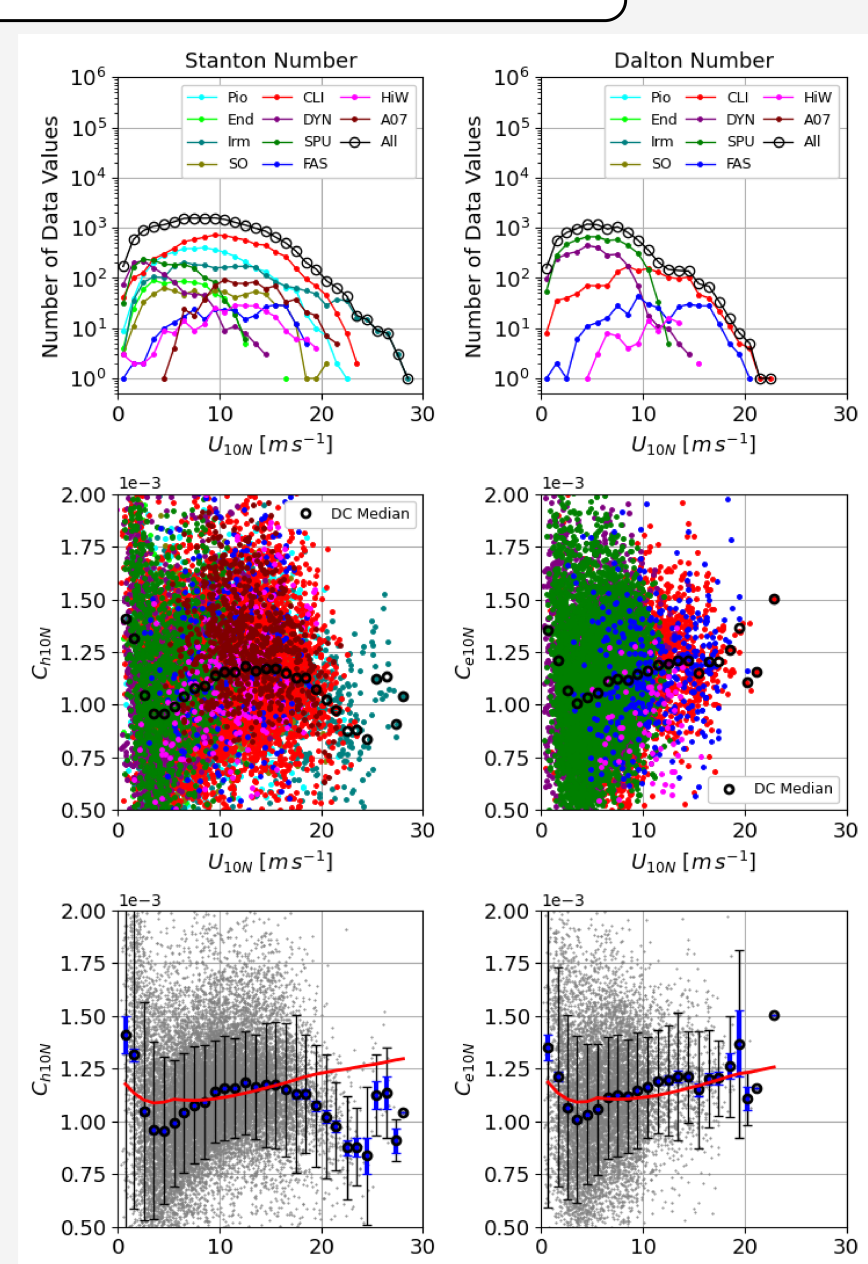

Figure 2. DC heat flux data and transfer coefficients for (left) SHF and (right) LHF. (Top) Number of data values for all sites vs windspeed. (Middle) Data scatter colored by site, with all-data medians. (Bottom) Data scatter and medians with +/-1 standard deviation (black) and +/-1 standard error (blue). Also shows corresponding medians of predictions from COARE 3.6 (red), for which C_{h10N} = C_{e10N}.

3. Bulk and Sea Spray Heat Fluxes in High Winds

- Spray evaporation per BCF23 produces moistening and cooling (i.e., positive spray LHF and negative spray SHF) in the observed wind range (Fig. 3, middle).
- Calibrating a heat flux model that combines COARE 3.6 with BCF23 spray heat fluxes produces better agreement with data in high winds (Fig. 3, top).
- Equivalent (i.e., bulk + spray) scalar roughness lengths inferred from DC total heat fluxes do not agree with COARE 3.6. Removing the effect of spray to produce interfacial-only roughness lengths improves correspondence between the COARE 3.6 model and observations (Fig. 3, bottom).
- A new model for scalar roughness (COARE 4.X) based on similarity between z_{0t} and z_{0q} improves correspondence in low-to-moderate winds and maintains the improvement due to spray physics in high winds (Fig. 4).

$$\frac{z_{0t}}{z_{0q}} = \exp\left[13.6\kappa\left(Sc^{2/3} - Pr^{2/3}\right)\right]$$

- COARE 4.0 is an upcoming COARE release that addresses the effects of spray empirically. The physics-based COARE 4.X shows comparable skill to COARE 4.0 (Fig. 4, top).

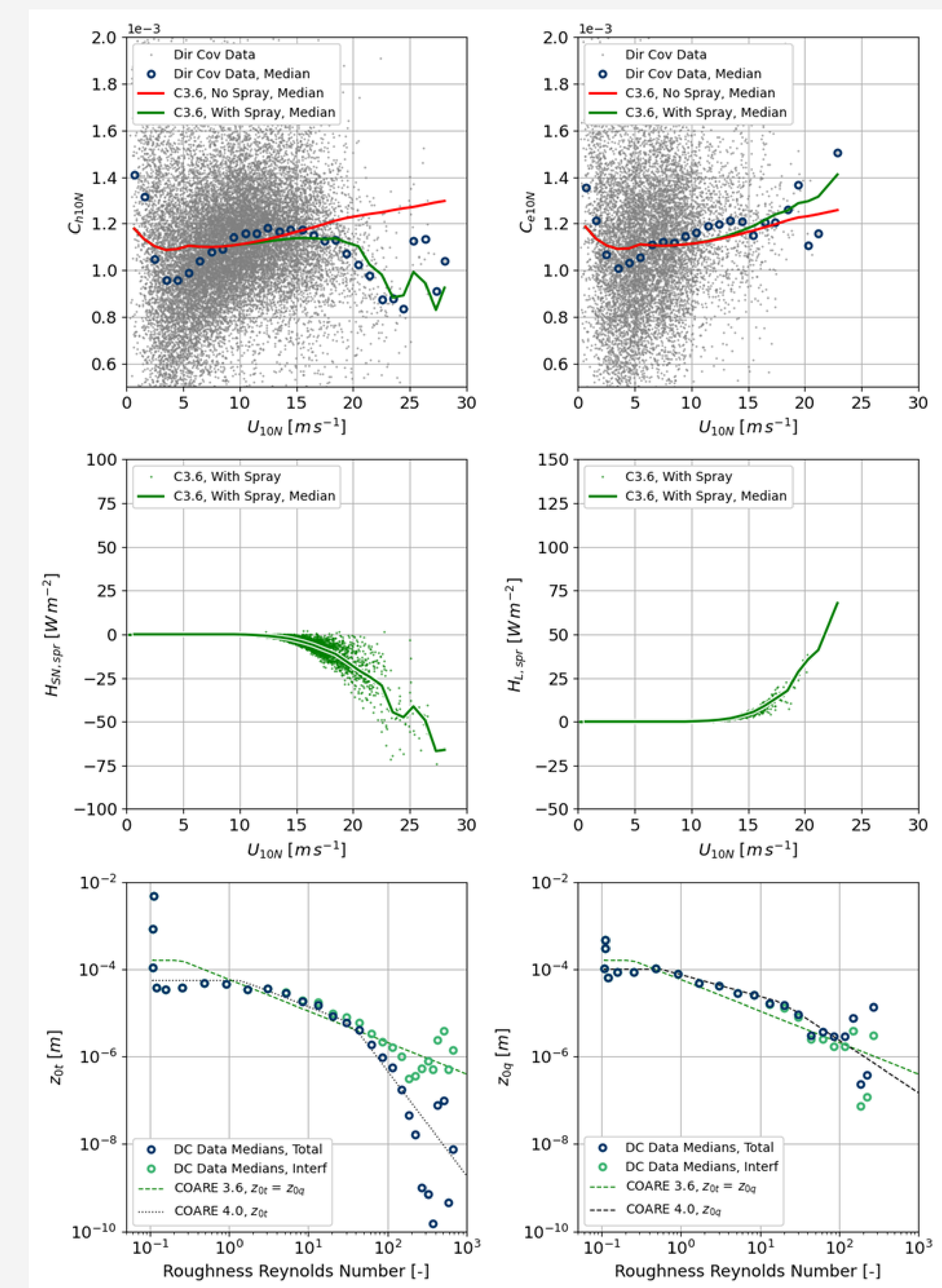

Figure 3. Heat flux analysis using COARE 3.6 scalar roughness lengths and BCF23 spray model for (left) SHF and (right) LHF. (Top) Heat transfer coefficients. (Middle) Spray SHF ($H_{S,spr}$) and spray LHF ($H_{L,spr}$). (Bottom) Scalar roughness lengths based on DC observations, estimated using total heat fluxes ("Total") and with spray effect removed ("Interf"). COARE scalar roughness parameterizations also shown.

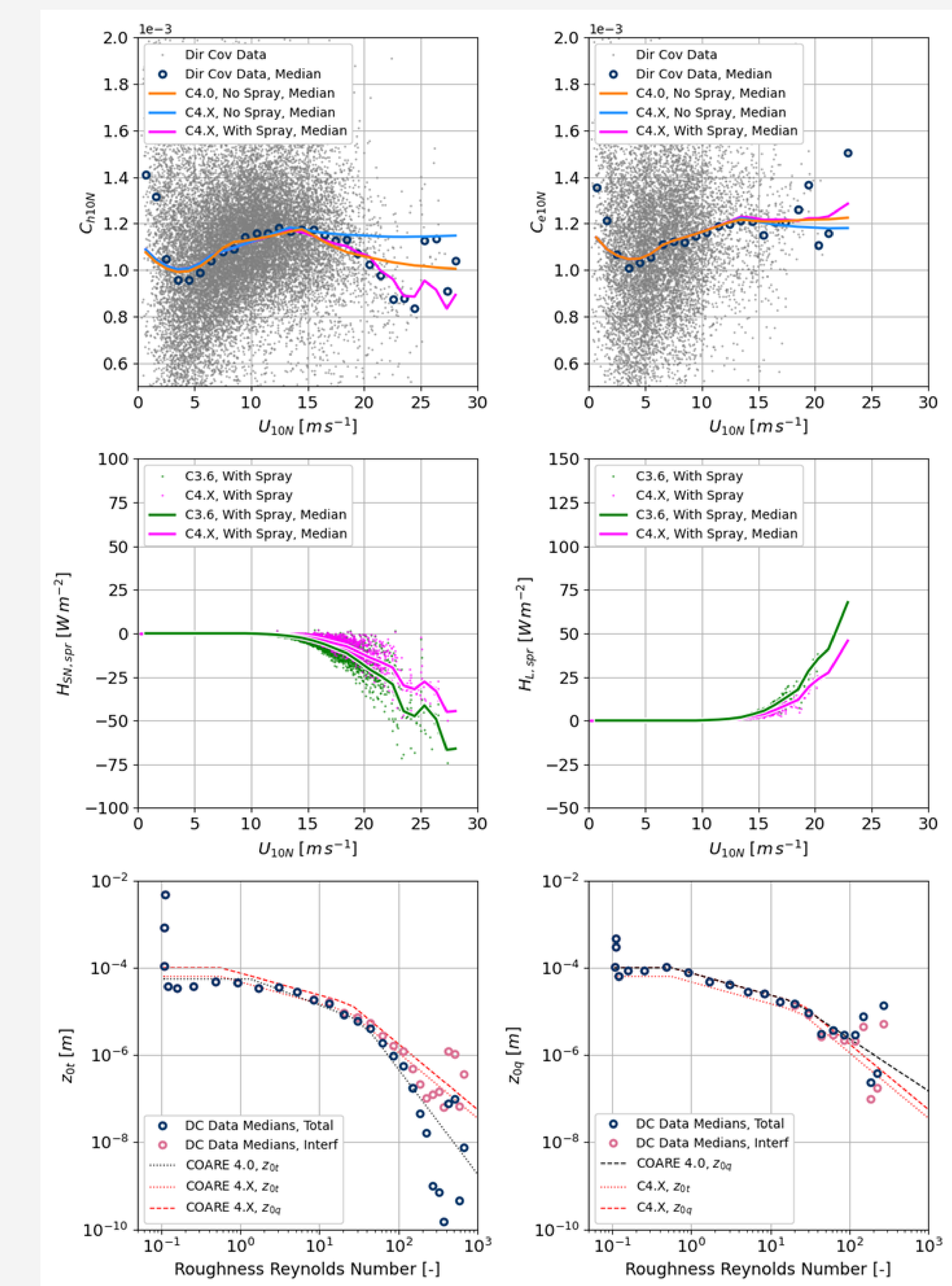

Figure 4. Same as Figure 3 but using similarity-based COARE 4.X scalar roughness model.

4. Summary and Outlook

- DC observations show divergent behavior of C_{h10N} and C_{e10N} in high winds, contrary to conventional assumptions.
- Spray physics (i.e., droplet evaporation) explains this behavior, and including spray in the COARE 3.6 algorithm improves heat flux predictions in high winds.
- Due to similarity of interfacial scalar flux physics, interfacial thermal and moisture roughness lengths may be self-similar in high winds, with spray heat fluxes accounting for divergent behavior in heat fluxes and transfer coefficients.
- Simultaneous observations of waves, spray, and heat fluxes in high winds are needed to understand spray physics and to calibrate models. Existing infrastructure (e.g., OOI buoys) and emerging technologies (e.g., Wave Gliders, expendable wave buoys) show promise for obtaining these critical measurements (Fig. 5).
- The new bulk + spray algorithm is currently being implemented and tested in the coupled atmosphere-wave-ocean SCOAR modeling system to explore impacts of spray on typhoons in the West Pacific.

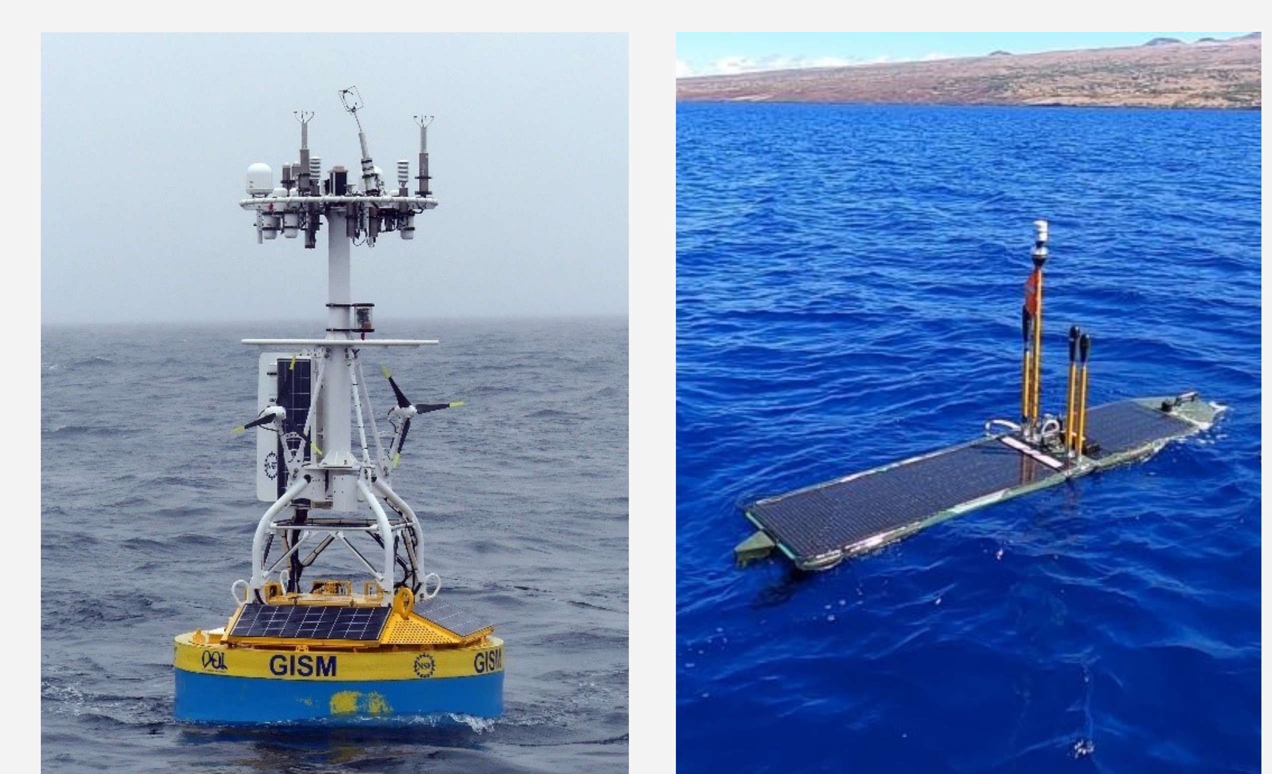

Figure 5. Potential observational platforms for advanced air-sea-wave-spray measurements. (Left) The OOI Irminger Sea surface buoy (photo: OOI) and (right) a Liquid Robotics Wave Glider (photo: NOAA Fisheries).