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Predicting the Turbulent Air-Sea Surface Fluxes, Including Spray Effects, from Weak to Strong Winds

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LONG-TERM GOALS

The goal is to investigate, through theory and by analyzing existing data, sea surface physics and air-sea exchange in winds that range from weak to hurricane strength. Ultimately, we want to develop unified parameterizations for the fluxes of momentum, sensible and latent heat, and enthalpy across the air-sea interface. These flux parameterizations will provide improved model coupling between the ocean and the atmosphere and, in essence, set the lower flux boundary conditions on atmospheric models and the upper flux boundary conditions on ocean models.

OBJECTIVES

1. Develop a physics-based framework for predicting air-sea fluxes from mean meteorological conditions and apply uniform analyses, based on this framework, to datasets that we will assemble.
2. Assemble a large collection of quality air-sea flux data that represents a wide variety of conditions.
3. Compute fluxes from these datasets using an improved analysis that better accommodates measurements made over heterogeneous surfaces, such as coastal zones. Focus the analyses on common problems where existing bulk formulations perform poorly—such as for stable stratification, over surface heterogeneity, in weak winds, and in very strong winds.
4. Develop a unified algorithm for predicting the turbulent air-sea surface fluxes that spans the environmental range in our datasets and obeys theoretical principles.

APPROACH

This project—in its fifth and final year under ONR's Unified Parameterization Departmental Research Initiative—is a collaboration between Ed Andreas and Larry Mahrt. Dean Vickers of Oregon State University is a subcontractor on the project. Mahrt has focused on boundary-layer processes in weak winds, when stratification and surface heterogeneity are important issues, when turbulent fluxes are often hard to evaluate, and when models tend to perform poorly. Andreas, in contrast, has been concentrating on high winds when sea spray is an important agent for heat and moisture transfer. Vickers brings expertise in processing large datasets—especially, aircraft data—and in parameterizing air-sea exchange. Together, we are developing flux parameterizations that span wind speeds from near zero to hurricane strength.

In outline, our flux algorithm is

$$\tau \equiv \rho u_*^2 = \rho\left[f\left(U_{N10}\right)\right]^2, \tag{1a}$$

$$H_{L,T} = H_{L,int} + H_{L,sp}, \tag{1b}$$

$$H_{s,T} = H_{s,int} + H_{s,sp}, \tag{1c}$$

$$Q_{en,T} = \left(H_{s,int} + H_{L,int}\right) + Q_{en,sp}. \tag{1d}$$

Here, τ is the surface stress or momentum flux; and $H_{L,T}$, $H_{s,T}$, and $Q_{en,T}$ are the *total* air-sea fluxes of latent heat, sensible heat, and enthalpy. These fluxes serve as the flux boundary conditions in atmospheric models and would be inserted at the lowest atmospheric modeling node.

In (1a), ρ is the air density, and u_* is the friction velocity. A key result of this project was our developing a new air-sea drag relation (Andreas et al. 2012). The $f(U_{N10})$ in (1a) represents this relation; it is a hyperbola that is continuous and differentiable at all wind speeds. In other words, instead of obtaining the surface stress by parameterizing a drag coefficient or a roughness length (z_0), which is common practice in most air-sea flux algorithms (e.g., Smith 1988; Garratt 1992, p. 97–104; Fairall et al. 1996, 2003; Jones and Toba 2001), we estimate u_* directly from the neutral-stability, 10-m wind speed, U_{N10}.

In (1b)–(1d), the first term on the right side in each equation represents the *interfacial* flux (subscript int). Molecular processes right at the air-sea interface control these fluxes. Meanwhile, the second terms on the right in (1b)–(1d) represent the *spray-mediated* fluxes (subscript sp). Microphysics at the surface of the sub-millimeter spray droplets controls these fluxes. The left sides of (1) are total air-sea fluxes (subscript T)—presumably what is actually measured by eddy-covariance and the quantity that atmospheric models need at their lower boundary. Virtually every existing flux algorithm, except ours, computes only the interfacial heat fluxes.

To develop this flux algorithm, we have assembled a large set of air-sea flux data and are still seeking other datasets. We currently have in hand over 20 datasets comprising thousands and thousands of air-sea flux measurements. In this set, surface-level wind speeds range from near zero to 72 m/s, and sea surface temperatures range from –1° to 32°C.

WORK COMPLETED

Our main accomplishments in the last year include publishing a paper that describes the full flux algorithm represented in (1) (Andreas et al. 2015a) and another paper (Vickers et al. 2015) that built on Andreas et al. (2012) and, thus, reported another attempt to further simplify the air-sea drag relation. We also developed Fortran code for testing and implementing the new flux algorithm. That code is freely available at www.nwra.com/resumes/andreas/software.php.

Figure 1 demonstrates the kind of predictions this new bulk flux algorithm makes. The figure shows calculations of the interfacial and spray sensible and latent heat fluxes in (1b) and (1c) as functions of wind speed for one set of environmental conditions. Both interfacial fluxes ($H_{L,int}$ and $H_{s,int}$) increase almost linearly with wind speed. The spray-mediated fluxes ($H_{L,sp}$ and $H_{s,sp}$), in contrast, increase at between the second and third power of wind speed. Therefore, for these particular conditions, the spray fluxes are much less than the interfacial fluxes for wind speeds up to about 10 m/s; but at wind speed between 20 and 30 m/s, each spray flux passes it respective interfacial flux. The spray fluxes thus dominate air-sea transfer in hurricane-strength winds.

RESULTS

The Andreas et al. (2015a) paper raised issues about how we have been parameterizing the interfacial heat fluxes $H_{L,int}$ and $H_{s,int}$ in (1). We have been using the Liu et al. (1979) parameterization for the roughness lengths for temperature (z_T) and humidity (z_Q) because it was validated in the COARE version 2.6 algorithm (Fairall et al. 1996; Chang and Grossman 1999; Grant and Hignett 1998). But the choice of interfacial algorithms is crucial because we must extrapolate that algorithm to high winds where it has been impossible to measure z_T and z_Q over the ocean because of the confounding effects of spray-mediated heat transfer.

We realized, however, that the data that Jeong et al. (2012) obtained in the ASIST wind-water tunnel at the University of Miami represented strict interfacial transfer for neutral-stability, 10-m winds (U_{N10}) up to 40 m/s. To establish this fact, Andreas and Mahrt (2015) developed theoretical models for both the interfacial and the spray-mediated enthalpy transfer (1d) in the Miami tunnel and compared these predictions with the total enthalpy fluxes that Jeong et al. reported. Figure 2 shows this comparison.

In Figures 2, the modeled values of the interfacial fluxes are based on parameterizations for z_T and z_Q from both Liu et al. (1979) and Andreas (1987). Both models yield fluxes that are near the measured enthalpy flux. Our estimate of the spray-mediated flux, although it increases rapidly with wind speed, is always orders of magnitude less than the measured flux. Andreas and Mahrt (2015) therefore concluded that, in the Miami tunnel, Jeong et al. (2012) documented strict interfacial transfer; Andreas and Mahrt then used this information to evaluate z_T and z_Q up to U_{N10} of 40 m/s—an analysis that is not possible over the open ocean.

Figure 3 shows the values for the enthalpy roughness, z_K, that Andreas and Mahrt (2015) obtained from the Jeong et al. (2012) data. The figure also shows theoretical models for z_T, which should be a good estimator of the enthalpy roughness. (None of the models predict z_K.) The Liu et al. (1979) parameterization for z_T and z_Q is what the Andreas et al. (2015a) algorithm currently uses. But for high winds, Figure 3 suggests that the parameterizations in Andreas (1987) or Garratt (1992) may represent z_T and z_Q better. We are currently trying to corroborate this insight with other data.

We examined data from the Air-Sea Interaction Tower (ASIT) collected during the CBLAST Weak-Wind Experiment to further explore the dependence of the friction velocity on the wind speed, V. This

dependence, $u_*(V)$, for weak winds is significantly larger for more active nonstationary submeso motions. However, $u_*(V)$ is not systematically related to the air-sea temperature difference, even for differences greater than 3°C. For offshore flow against the swell, $u_*(V)$ is larger compared to that for onshore flow following the swell (Figure 4). Advection of turbulence from land could, however, contribute to the larger $u_*(V)$ at the tower for short-fetch, offshore flow. Short-fetch cases include thin, stable boundary layers with depths of only a few tens of meters.

For weak winds, $u_*(V)$ increases with increasing submeso variability even when the calculation of V resolves the submeso motions (Figure 5). Evidently, $u_*(V)$ is greater with non-equilibrium conditions due to profile distortion, including near-surface wind maxima, inflection points, and wind directional shear, as found in previous studies over land.

The relationship of $u_*(V)$ with the air-sea temperature difference is very weak except for short-fetch, offshore flow with V stronger than the transition value of about 4 m/s (Figure 4). Although the relationship between $u_*(V)$ and air-sea temperature difference is weak or undetectable for most cases, the variation in z/L accounts for relatively large variations in $\phi_m(z/L)$ for this dataset. Here, z is the measurement height, L is the Obukhov length, and z/L is the traditional stability parameter in Monin-Obukhov similarity theory. $\phi_m(z/L)$ is the nondimensional wind shear and accounts for curvature in the wind profile (e.g., Dyer 1974). z/L, however, is an internal stability parameter that is strongly influenced by variations in u_* and is not well correlated with the stratification, represented here as the air-sea temperature difference. This realization may explain why the air-sea temperature difference can be relatively unimportant yet the turbulence and nondimensional shear are sensitive to z/L.

IMPACT/APPLICATIONS

One of our goals is to develop Fortran code for a bulk air-sea flux algorithm that provides a unified treatment of fluxes for winds from near zero to hurricane strength. Of necessity, for treating high winds, this code must account for spray-mediated transfer. We have thus created Version 4.0 of this flux algorithm, posted it on Andreas's webpage (mentioned above), shared it with interested scientists, and described it in Andreas et al. (2015a).

An application for this work is for coupling atmosphere and ocean in regional and global models. As such, we have provided the code to modelers at NRL-Monterey, and Jim Ridout at NRL has been testing it in the Navy's global model, NAVGEM. Because the algorithm especially targets the high winds of tropical cyclones, it is the only physics-based model that can reasonably be extrapolated for use in these wind speeds. Hence, Richter and Stern (2014) used it successfully to study the wind speed dependence of the surface enthalpy flux in tropical cyclones.

Shouping Wang at NRL tested COAMPS against our LongEZ profiles in the boundary layer from the CBLAST Weak-Wind experiment and, surprisingly, found that the model performed better for offshore, weak-wind stable stratification than for long-fetch onshore flow with weak stratification. We are investigating this finding further.

TRANSITIONS

Journal articles and conference presentations document our work on air-sea exchange. Andreas has also developed a software "kit" that contains instructions, supporting documents, and the Fortran

programs necessary to implement the bulk air-sea flux algorithm described by Andreas et al. (2012, 2015a). The current version of that code is 4.0, and the kit is posted at http://www.nwra.com/resumes/andreas/software.php, where it can be freely downloaded.

As mentioned above, we have also sent this code directly to modelers at NRL-Monterey for their testing and evaluation.

RELATED PROJECTS

Andreas and Kathy Jones of the Army's Cold Regions Research and Engineering Laboratory started in FY12 a project to study spray icing of offshore structures that was funded under ONR's Arctic program. In January 2013, we carried out a month-long field experiment on Mt. Desert Rock, a small, well-exposed island 24 miles out into the Atlantic from Bar Harbor, Maine (Jones and Andreas 2013).

During that experiment, we made continuous measurements of spray droplet concentrations with a cloud imaging probe that could count and size droplets in 12.5-µm radius bins from near 0 µm to 755 µm. Figure 6 shows one result from this project. From the spray concentration measurements, Andreas (2015) was able to deduce the spray generation function for waves crashing against the abrupt, rocky shoreline of Mt. Desert Rock. Figure 6 shows that spray generation functions. Because of the energy in the surf zone at Mt. Desert Rock, spray generation for droplets up to about 100 µm in radius, where data from the cloud imaging probe at this site are most reliable, is three orders of magnitude higher than over the open ocean. To our knowledge, these are the first spray measurements in such an energetic natural environment.

In June 2014, Andreas began a collaborative project with Penny Vlahos and Ed Monahan at the University of Connecticut to study spray-mediated air-sea gas transfer (Andreas et al. 2015b). The National Science Foundation is funding this work. Briefly, ocean scientists have been investigating bubble-mediated air-sea gas transfer for over 30 years, but no one has yet looked at the mirror-image process of spray-mediated air-sea gas transfer. This NSF project will complement and build on Andreas's current work for ONR because, to estimate the rate of spray-mediated gas transfer, we will also need to know the spray generation function. And, as with spray-mediated heat transfer, microphysics in and around spray droplets controls how efficient the droplets are in transferring gases between the ocean and the atmosphere.

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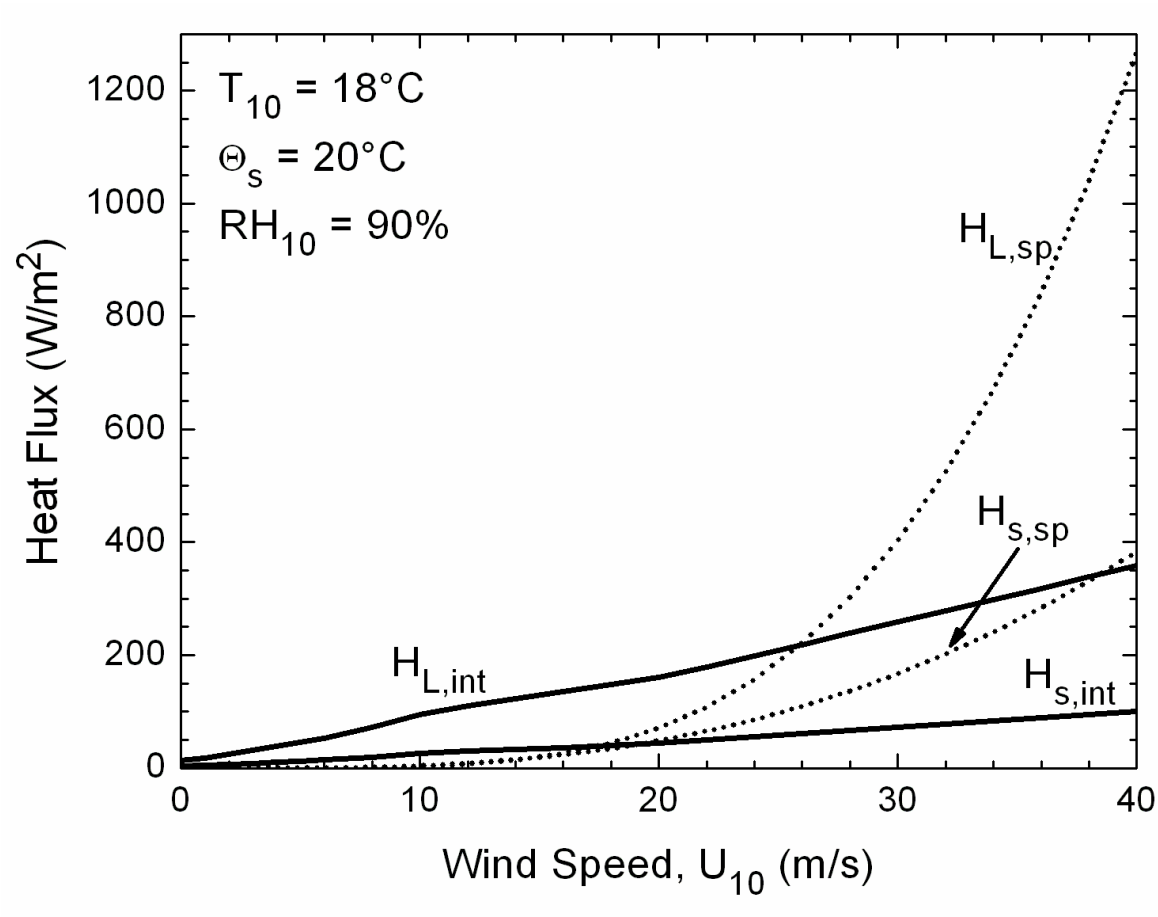

Figure 1. Calculations of the interfacial and spray-mediated latent and sensible heat fluxes from the Andreas et al. (2015a) bulk flux algorithm for a range of 10-m wind speeds, U_{10}. The sea surface temperature (Θ_s = 20°C) and 10-m values of the air temperature (T_a = 18°C) and relative humidity (RH_{10} = 90%) are fixed. The sea surface salinity is 34 psu. Both interfacial fluxes increase linearly with wind speed. Both spray fluxes start near zero but increase with wind speed to the power 2–3. The spray sensible heat flux thus exceeds the interfacial sensible heat flux for U_{10} above 20 m/s, and the spray latent heat flux exceeds the interfacial latent heat flux for U_{10} above 26 m/s.

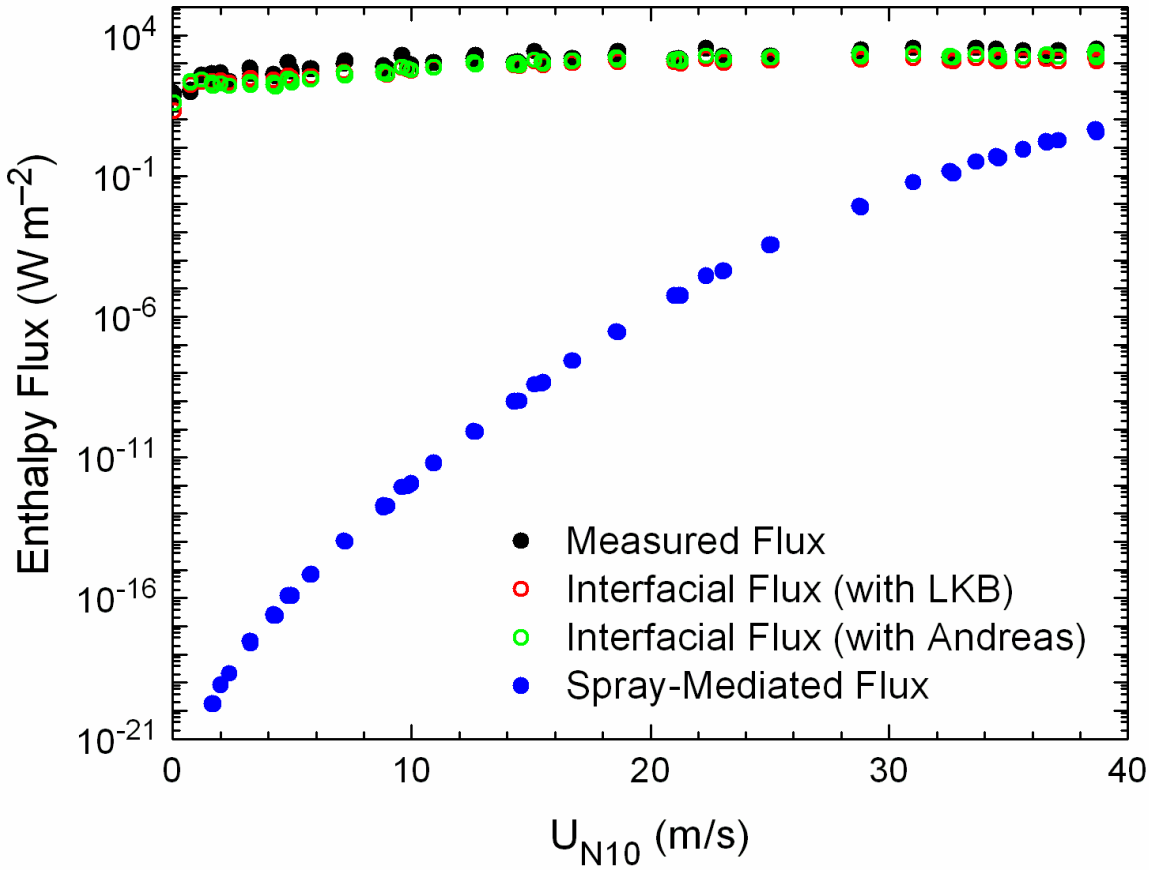

Figure 2. The measured enthalpy flux in the Miami wind tunnel from Table 1 in Jeong et al. (2012) as a function of the equivalent 10-m, neutral-stability wind speed, U_{N10}. The figure also shows model estimates of the interfacial enthalpy flux based on two parameterizations for the scalar roughness lengths z_T and z_Q: from Liu et al. (1979, "LKB") and from Andreas (1987). Finally, the figure shows our model estimate of the spray-mediated enthalpy flux. Both model estimates of the interfacial enthalpy flux are near the Jeong et al. measurements of the enthalpy flux. The modeled spray-mediated flux, on the other hand, is orders of magnitude less than the measured flux for all reported wind speeds—up to 40 m/s. Consequently, in this facility, enthalpy is transferred almost exclusively by interfacial processes.

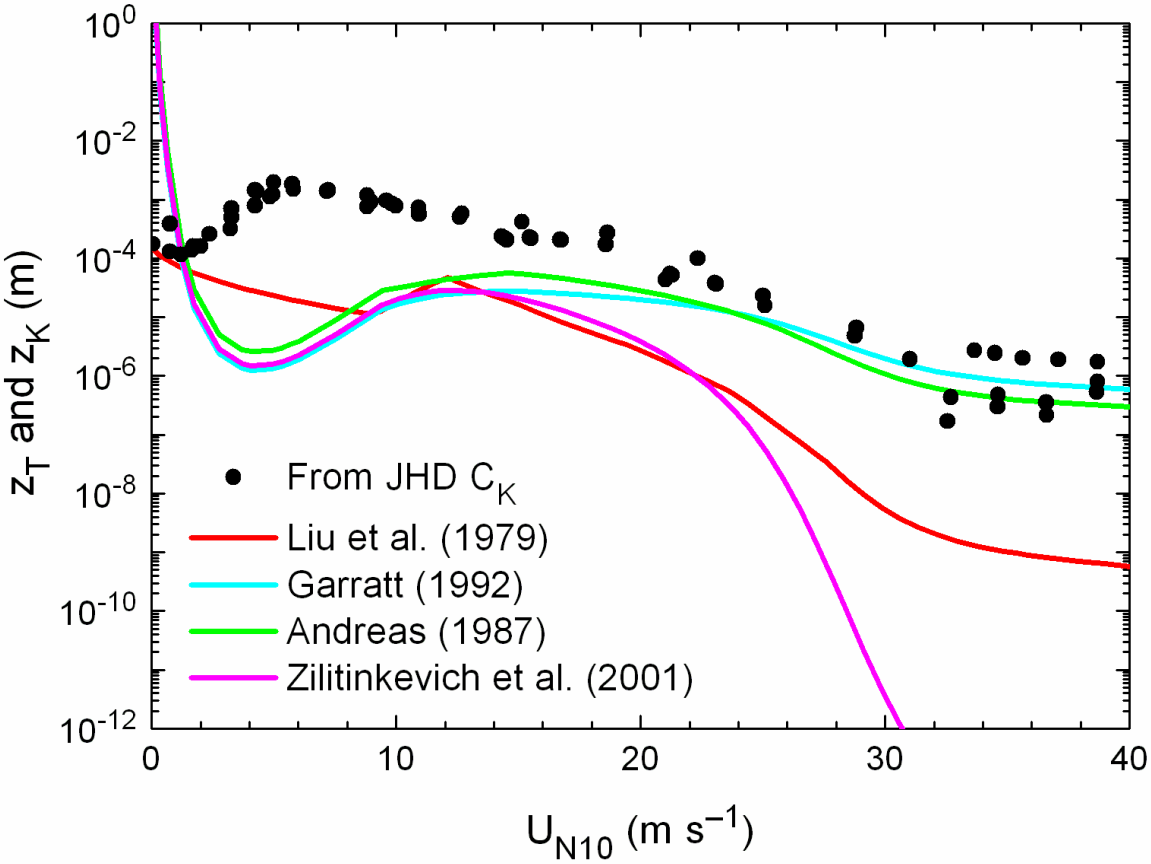

Figure 3. Values of the roughness length for enthalpy, z_K, as a function of U_{N10} are computed from the data tabulated by Jeong et al. (2012). The plot also shows four theoretical expressions for the temperature roughness, z_T, which should be near z_K: Liu et al. (1979), Andreas (1987), Garratt (1992), and Zilitinkevich et al. (2001). The Liu et al. model for z_T and z_Q is what the Andreas et al. (2015a) flux algorithm currently uses to predict the interfacial fluxes, but it and the Zilitinkevich et al. model fall much faster than the data for U_{N10} above 14 m/s. The Andreas and Garratt parameterizations both follow the data well for U_{N10} up to 40 m/s.

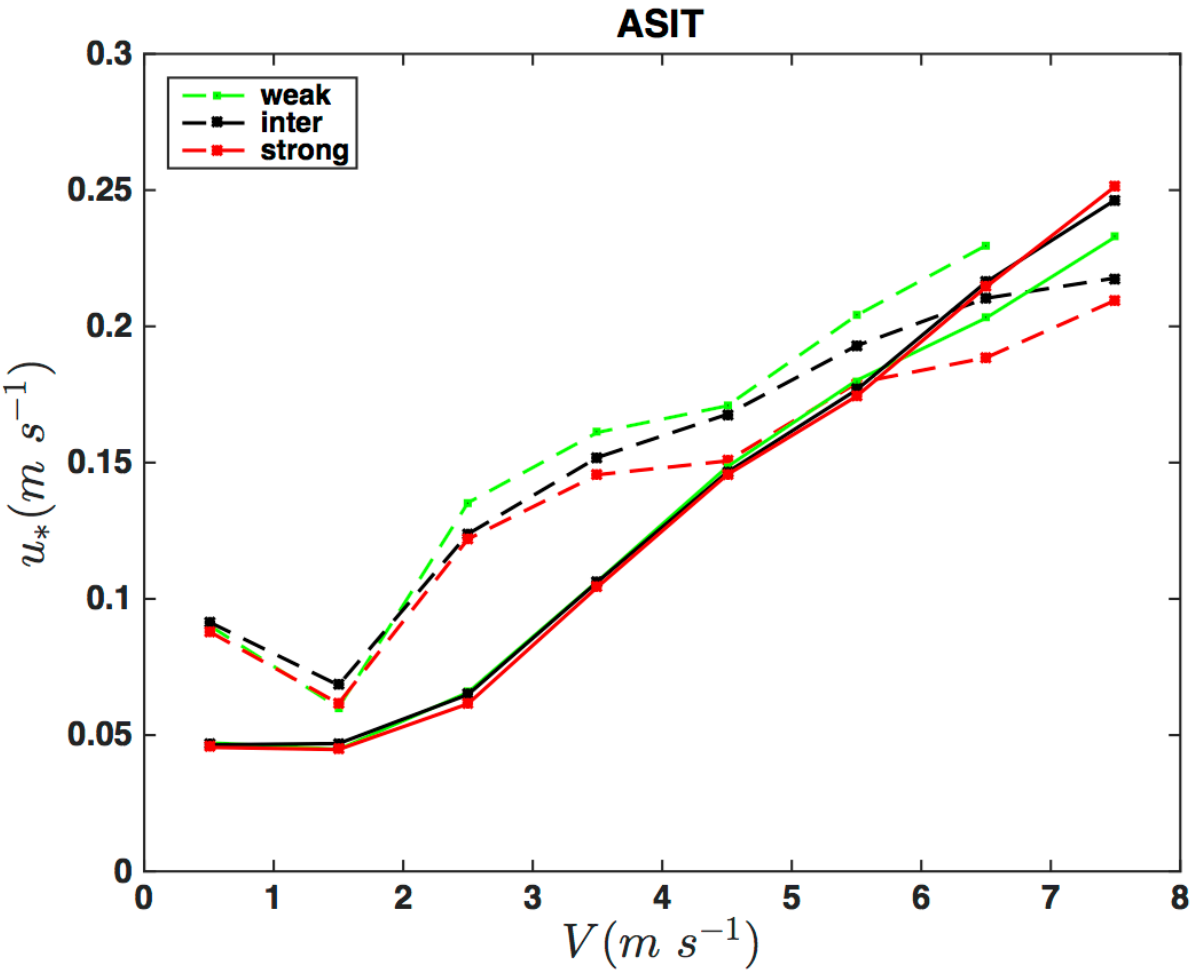

Figure 4. The dependence of the interval-averaged u_* on V from the ASIT site for three classes of air-sea temperature difference $\delta\theta_v$ defined as weak (0 K < $\delta\theta_v$ < 0.75 K, green), intermediate (0.75 K < $\delta\theta_v$ < 2.0 K, black), and strong ($\delta\theta_v$ > 2.0 K, red) stratification for onshore wind directions between 150° and 225° (solid lines) and for offshore wind directions between 330° and 360° (dashed lines). Both groups suggest two regimes: At low winds (V up to about 3 m/s), u_* depends only weakly on V; at higher winds, u_* increases roughly linearly with V. Only with offshore flow does the stratification affect the $u_*(V)$ relationship: Above 3 m/s, $u_*(V)$ is lower with increasing stratification.

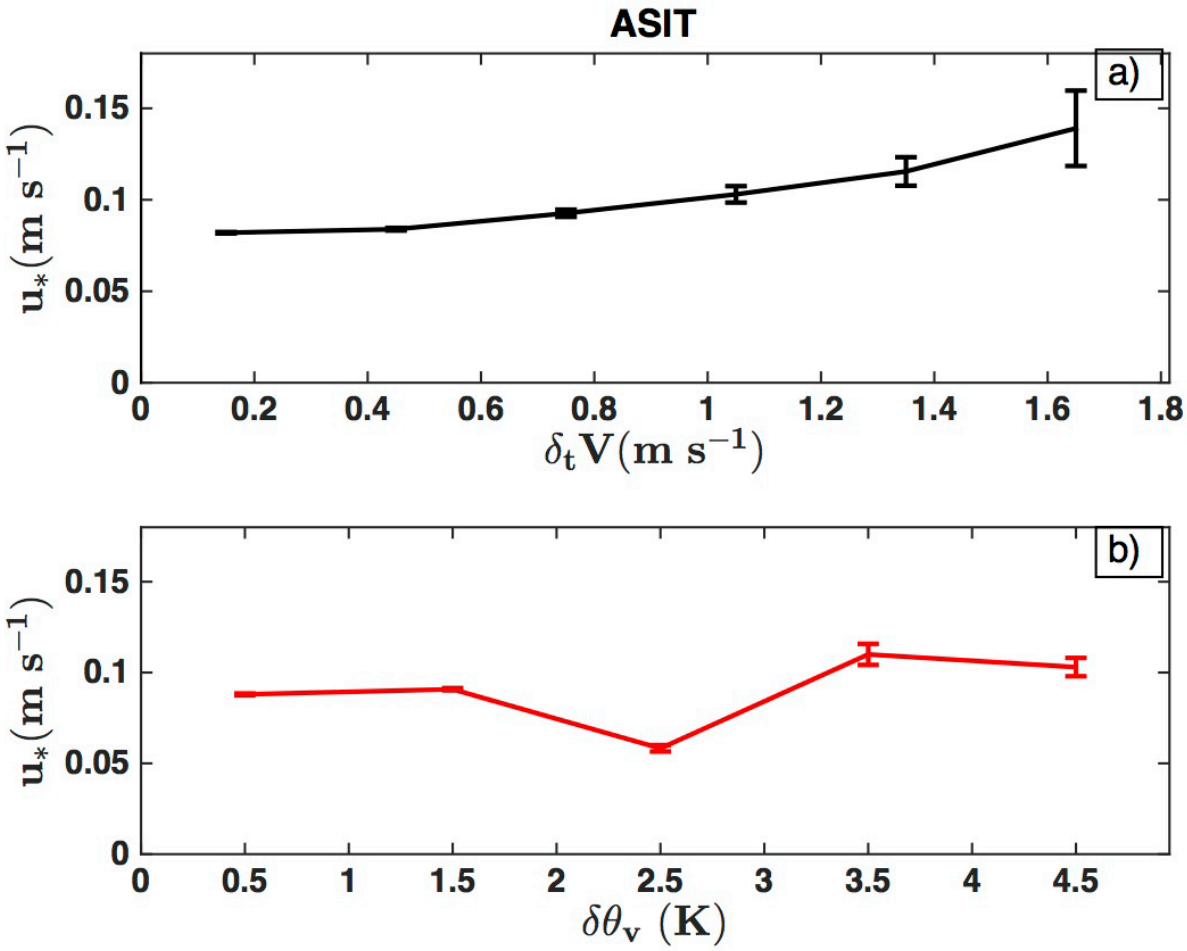

Figure 5. Eddy-covariance measurements of u_* from the ASIT site. a) The dependence of the bin-averaged u_* on $\delta_t V$ for $V < 4$ m/s, where $\delta_t V$ is the bin-averaged two-point wind speed difference across a 6-min interval, designed to represent the general activity of the nonstationary submeso motions. b) The dependence of the interval-averaged u_* on $\delta\theta_v$ for $V < 4$ m/s, where $\delta\theta_v$ is the air-sea difference of virtual potential temperature. Vertical brackets indicate the standard error. In panel a, u_* increases with increasing submeso variability in the wind speed; but in panel b, u_* appears to have no detectable relationship with the stratification.

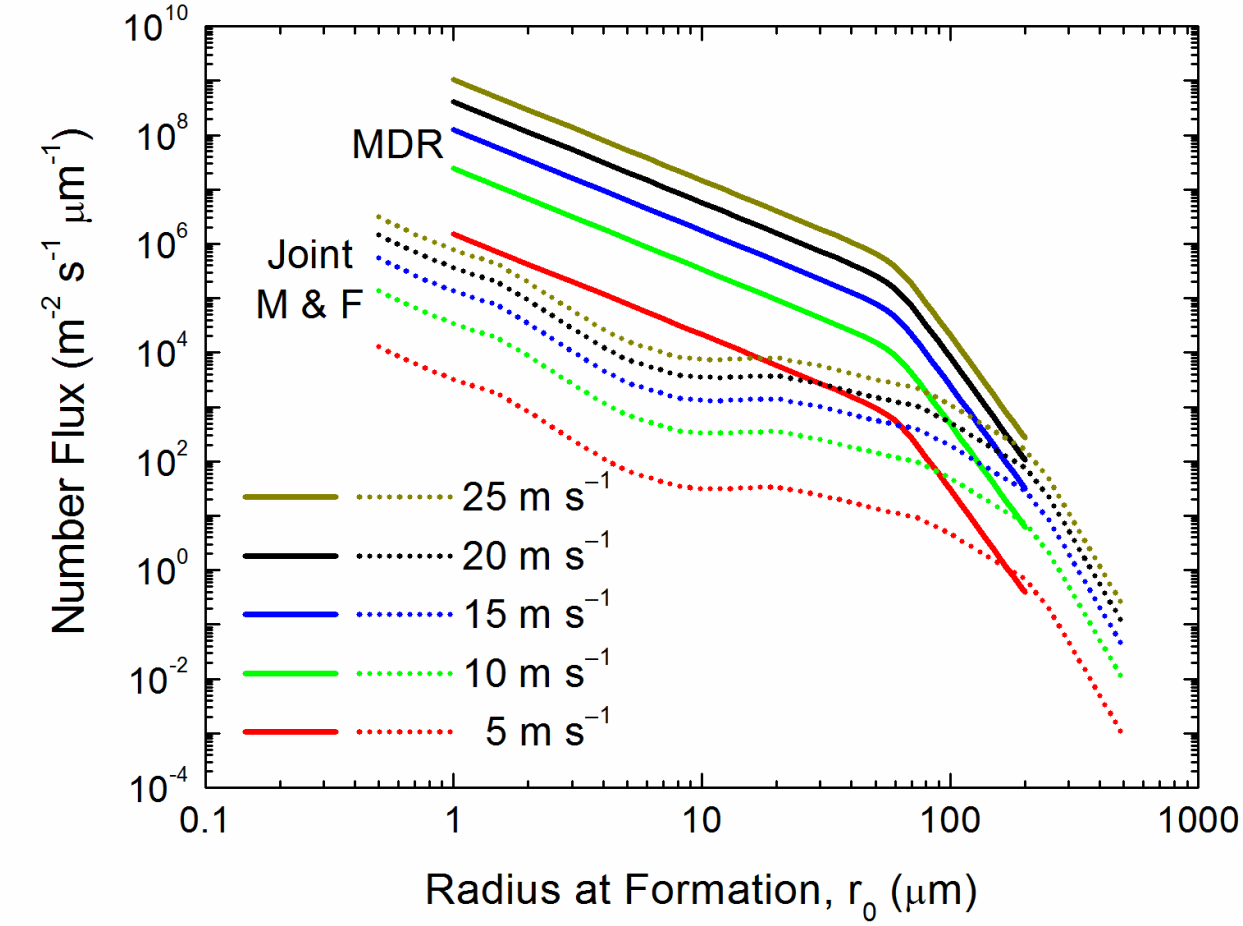

Figure 6. In a related project, Andreas (2015) deduced the spray generation function for the energetic surf zone at the rocky shoreline of Mt. Desert Rock ("MDR" curves). For comparison, the plot shows a typical spray generation function for the open ocean—this one ("M&F") is a combination of the Monahan et al. (1986) bubbles-only term for small droplets and the Fairall et al. (1994) expression for large droplets. [See Andreas et al. (2010) for the formulation.] Here, the spray generation function is the number flux—the number of droplets with the given radius produced per square meter of sea surface, per second, per micrometer increment in droplet radius. For wind speeds from 5 to 25 m/s and for droplets with radius of about 100 μm and smaller, spray generation at the shore of Mt. Desert Rock is three orders of magnitude higher than over the open ocean.