Modeling Turbulent Air-Sea Exchange in High Winds

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LONG-TERM GOALS

The goal is to investigate, theoretically and through analyzing existing data, the role that sea spray plays in transferring heat, moisture, and momentum across the air-sea interface, especially in high winds. Ultimately, I plan to develop simple, fast, physics-based parameterizations for these air-sea fluxes for use in large-scale models, especially those simulating tropical and extratropical storms.

OBJECTIVES

1. By analyzing turbulent flux data sets, develop simple, fast parameterizations for the air-sea sensible and latent heat fluxes, the total enthalpy flux, and the surface stress in high winds, where sea spray is mediating all of these exchanges.

2. Theoretically extend these parameterizations to high winds, up to hurricane strength (~60 m/s).

3. Collaborate with large-scale modelers to implement and test these formulations in state-of-the-art coupled atmosphere-ocean models.

APPROACH

This work is theoretical and analytical; it has no experimental component. Andreas is the only NWRA participant, but he has been collaborating with large-scale modelers elsewhere—primarily Will Perrie at Bedford Institute, Dartmouth, Nova Scotia—to implement his spray parameterization in mesoscale storm simulations.

Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theory also predicts how sea spray production should depend on wind speed. The analytical part involves developing parameterizations for the various spray transfer processes by simplifying model results or by synthesizing various data sets and observations. Checking the parameterizations against available data is also another aspect of what I call analytical work.

Conceptually, momentum and sensible and latent heat can cross the air-sea interface by two routes: as interfacial fluxes that are adequately parameterized by the COARE bulk flux algorithm (Fairall et al. 1996) and as fluxes mediated by sea spray. In low winds, say 10 m/s or less, the spray route is negligible. As spray concentration increases with increasing wind speed, however, the spray route

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14. ABSTRACT

The goal is to investigate, theoretically and through analyzing existing data, the role that sea spray plays in transferring heat, moisture, and momentum across the air-sea interface, especially in high winds. Ultimately, I plan to develop simple, fast, physics-based parameterizations for these air-sea fluxes for use in large-scale models, especially those simulating tropical and extratropical storms.

15. SUBJECT TERMS

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becomes increasingly important until, in hurricane-strength winds, it is the dominant air-sea exchange route (e.g., Emanuel 2003; Andreas 2004a). I have been developing a unified algorithm that predicts the flux contributions through both routes (Andreas 2003, 2004b).

My algorithm assumes that the total sensible ($H_{s,Tot}$) and latent ($H_{L,Tot}$) heat fluxes that would be measured by eddy-correlation instruments at a height above the spray layer are the sums of the interfacial (i.e., H_s, H_L) and spray contributions. My microphysical model (Andreas 1989, 1992), combined with an estimate of the spray generation function (Andreas 2002), predicts the nominal spray sensible ($\overline{Q}_S$) and latent ($\overline{Q}_L$) heat fluxes. With these contributions, the total fluxes are (e.g., Andreas and DeCosmo 2002; Andreas 2003)

$$H_{s,Tot} = H_s + \beta \overline{Q}_S - (\alpha - \gamma)\overline{Q}_L \ , \tag{1a}$$

$$H_{L,Tot} = H_L + \alpha \overline{Q}_L \ . \tag{1b}$$

The α, β, and γ are small, non-negative coefficients that ultimately tune the model to data. In a modeling sense, the total fluxes represented as the left sides of (1) would serve as the lower flux boundary condition for an atmospheric model.

My flux algorithm uses the COARE Version 2.6 algorithm (Fairall et al. 1996; Andreas and DeCosmo 2002) to compute H_s and H_L in (1). The $\overline{Q}_S$ and $\overline{Q}_L$ values in (1) come from my full microphysical model, but this model is too computer-intensive for large-scale modeling. Hence, I have greatly parameterized the results from that model such that my current bulk flux algorithm predicts the spray sensible and latent heat fluxes, $Q_{S,sp}$ and $Q_{L,sp}$, from

$$\beta \overline{Q}_S - (\alpha - \gamma)\overline{Q}_L \equiv Q_{S,sp} = \rho_w c_w \left(T_s - T_{eq,100}\right) V_S(u_*) \ , \tag{2a}$$

$$\alpha \overline{Q}_L \equiv Q_{L,sp} = \rho_w L_v \left\{ 1 - \left[\frac{r(\tau_{f,50})}{50\,\mu\text{m}} \right]^3 \right\} V_L(u_*) \ . \tag{2b}$$

In these, ρ_w is the density of seawater; c_w, the specific heat of seawater; L_v, the latent heat of vaporization of water; T_s, the sea surface temperature; and $T_{eq,100}$, the equilibrium temperature of spray droplets that originally formed with a radius of 100 μm. Both $Q_{S,sp}$ and $Q_{L,sp}$ have units of W/m^2.

Furthermore, in (2b), r is the radius as a function of time (t) of a droplet that started with a radius of 50 μm. In general, for any spray droplet,

$$r(t) = r_{eq} + (r_0 - r_{eq}) \exp(-t/\tau_r) \quad (3)$$

is a good approximation. Here, r_0 is the initial radius of the droplet, r_{eq} is its equilibrium radius, and τ_r is the e-folding time for the droplet's evolution to this equilibrium radius. In (2b), $\tau_{f,50}$ is the atmospheric residence time of a droplet that started with a radius of 50 μm. Thus, in essence, I approximate $Q_{L,sp}$ from the behavior of 50-μm droplets. Likewise, (2a) estimates $Q_{S,sp}$ from the behavior of 100-μm droplets. Finally, in (2), $V_S(u_*)$ and $V_L(u_*)$ are empirical functions of the friction velocity, u_*.

WORK COMPLETED

Andreas and DeCosmo (1999, 2002) identified a spray signature for winds, nominally, above 12 m/s in the turbulent heat flux data from HEXOS (the experiment to study Humidity Exchange over the Sea). To the HEXOS set, I have added the larger high-wind data set from FASTEX (the Fronts and Atlantic Storm-Tracks Experiment; Persson et al. 2005). I have recently reported my isolating a spray signature in the combined HEXOS/FASTEX set (Andreas et al. 2007a, 2007b).

That analysis takes two steps. First, Andreas et al. (2007a, 2007b) showed that a state-or-the-art bulk turbulent flux algorithm (namely, COARE version 2.6; Fairall et al. 1996) can explain neither the magnitude nor the wind speed dependence of the high-wind HEXOS/FASTEX data set. But, next, by incorporating spray effects as in (1), Andreas et al. found order-one α, β, and γ values such that (1) can explain the magnitude and wind speed dependence of the HEXOS/FASTEX set. This analysis also let Andreas et al. separate the measured turbulent heat fluxes into interfacial and spray contributions.

RESULTS

With the spray contributions identified, Andreas et al. (2007a, 2007b) used (2) to obtain the wind functions $V_S(u_*)$ and $V_L(u_*)$. Their results are

$$V_S = 2.30 \times 10^{-6} u_*^3 , \quad (4a)$$

$$V_L = 1.10 \times 10^{-7} u_*^{2.22} , \quad (4b)$$

where both V_S and V_L have units of m/s when u_* is in m/s.

With (1)–(4), my bulk flux algorithm is complete and becomes

$$H_{s,Tot} = H_s + Q_{S,sp} , \quad (5a)$$

$$H_{L,Tot} = H_L + Q_{L,sp} . \quad (5b)$$

That is, the algorithm has separate and unique parameterizations for the interfacial and spray fluxes.

Figures 1 and 2 demonstrate how well this unified bulk flux algorithm reproduces the combined HEXOS and FASTEX data set. In similar plots without the spray contributions $Q_{S,sp}$ and $Q_{L,sp}$ in (5) (not shown), both measured sensible and latent fluxes are significantly higher than the corresponding modeled fluxes. Adding the spray contributions in Figures 1 and 2, however, produces scatter plots with data that cluster around the 1:1 line with very small bias errors: 0.3 W/m^2 for sensible heat flux, and 5.7 W/m^2 for latent heat flux.

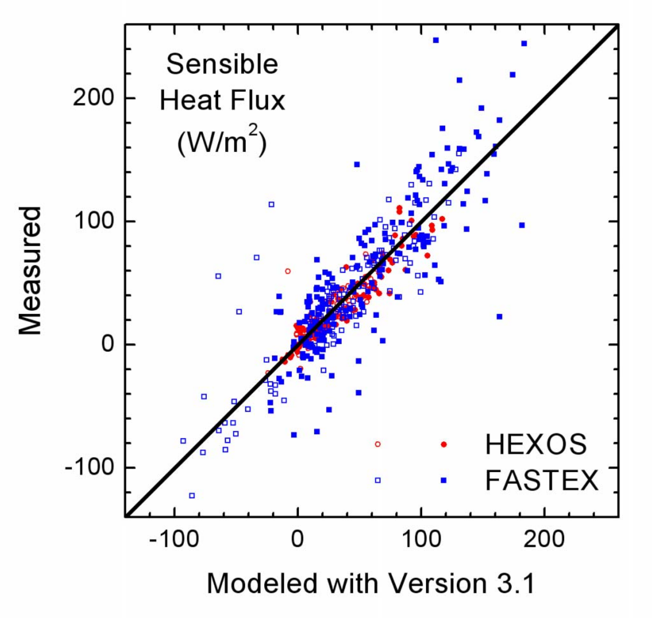

Fig. 1. A scatter plot of the HEXOS and FASTEX measurements of sensible heat flux versus the flux modeled with my unified bulk flux algorithm, (5). Filled symbols denote cases where the spray term in (5a) ($Q_{S,sp}$) is at least 10% of the interfacial term (H_s). The best fit line through the data points deviates only slightly from the 1:1 line shown.

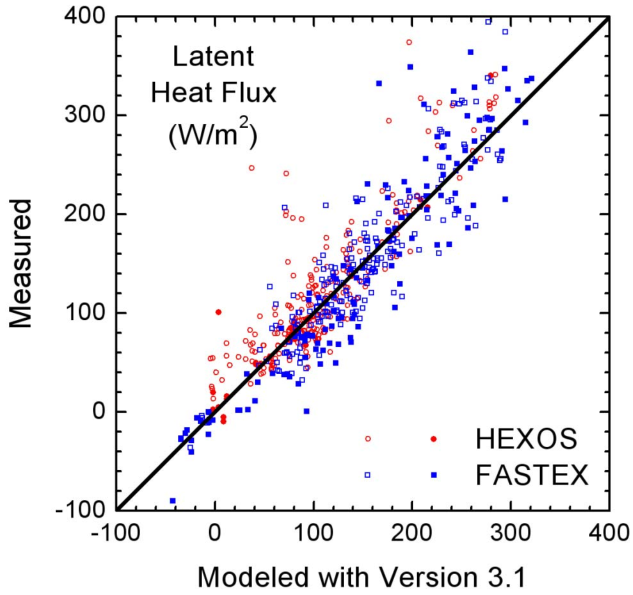

Fig. 2. A scatter plot of the HEXOS and FASTEX measurements of latent heat flux versus the flux modeled with my bulk flux algorithm, (5). Filled symbols denote cases where the spray term in (5b) ($Q_{L,sp}$) is at least 10% of the interfacial term (H_L). Again, the best fit line through these data would deviate only slightly from the 1:1 line shown.

Figures 3 and 4 show two sets of sensitivity calculations that demonstrate a profound and fundamental result of my analyses: The interfacial and spray fluxes do not scale the same. Consequently, trying to parameterize the total turbulent heat fluxes in high winds with a transfer coefficient is a conceptual mistake (e.g., Drennan et al. 2007). A turbulent transfer coefficient works only for the interfacial fluxes, H_s and H_L; the spray fluxes require different scaling.

An essential piece of information for quantifying spray effects is the spray generation function, dF/dr_0—the rate at which spray droplets with given initial radius r_0 are formed at the sea surface. For example, this quantity is embedded in the $\overline{Q}_S$ and $\overline{Q}_L$ terms in (1). I have thus put a lot of effort into understanding the behavior of this function (Andreas 1992, 1998, 2002; Andreas and DeCosmo 1999).

The recent paper by Petelski and Piskozub (2006) therefore caught my attention. They reported the first estimates of the spray generation function based on a flux-gradient relation, which is a common tool for estimating other fluxes in the atmospheric surface layer. On the basis of their measurements and analysis, Petelski and Piskozub concluded that current best estimates of the spray generation function may underestimate that function because these functions appear to be significantly lower than Petelski and Piskozub's results. But among possible other errors, Petelski and Piskozub left the von

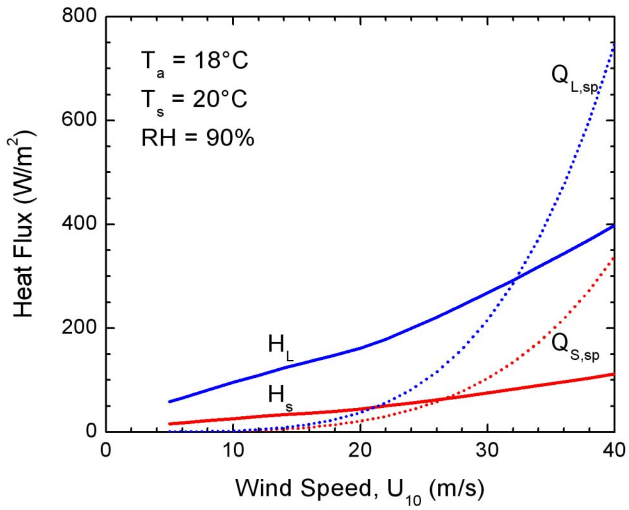

Fig. 3. Calculations made with the bulk flux algorithm described here of the interfacial (H_s and H_L) and spray ($Q_{S,sp}$ and $Q_{L,sp}$) fluxes as functions of the 10-m wind speed, U_{10}, which ranges from 5 to 40 m/s. Air temperature is fixed at 18°C, surface temperature is 20°C, relative humidity is 90%, surface salinity is 34 psu, and barometric pressure is 1000 mb. Both interfacial fluxes increase approximately linearly with wind speed, while both spray fluxes increase faster than the square of the wind speed [see (4)].

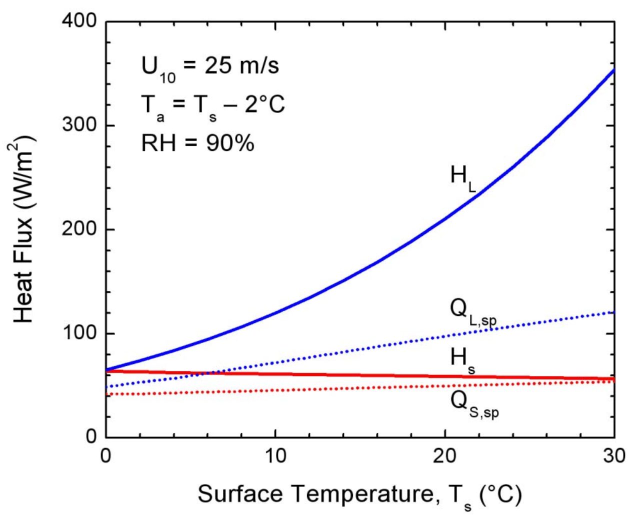

Fig. 4. As in Figure 3, except here the 10-m wind speed is fixed at 25 m/s; and the fluxes are plotted against surface temperature, which ranges from 0° to 30°C. Again, the relative humidity is 90%, but the air temperature is always 2°C less than the surface temperature. The interfacial latent heat flux increases more rapidly with surface temperature than the spray latent heat flux. The sensible heat fluxes depend only weakly on surface temperature but vary oppositely: The interfacial sensible heat flux decreases slightly with increasing surface temperature, while the spray flux increases slightly.

Kármán constant (0.4) out of their flux-gradient relation and thereby overestimated their spray generation function by at least a factor of 2.5.

Figure 5 shows my correction to Petelski and Piskozub's reported spray generation function for a 10-m wind speed of 10 m/s (Andreas 2007). My revised version of their functions falls right in the middle of functions that I had earlier judged to be the most reliable (Andreas 2002). Petelski and Piskozub's highest wind speed was 13 m/s, and their data here do seem to be biased high. But other plots like Figure 5 at lower wind speeds show better agreement than Petelski and Piskozub had reported (Andreas 2007). We do seem to be reducing the uncertainty in this essential function.

IMPACT/APPLICATIONS

The unified turbulent flux algorithm that I have developed has three features that are not all present in any other air-sea flux algorithm: It explicitly recognizes two routes by which heat and momentum cross the air-sea interface, the usual interfacial route and the spray-mediated route; it has been verified

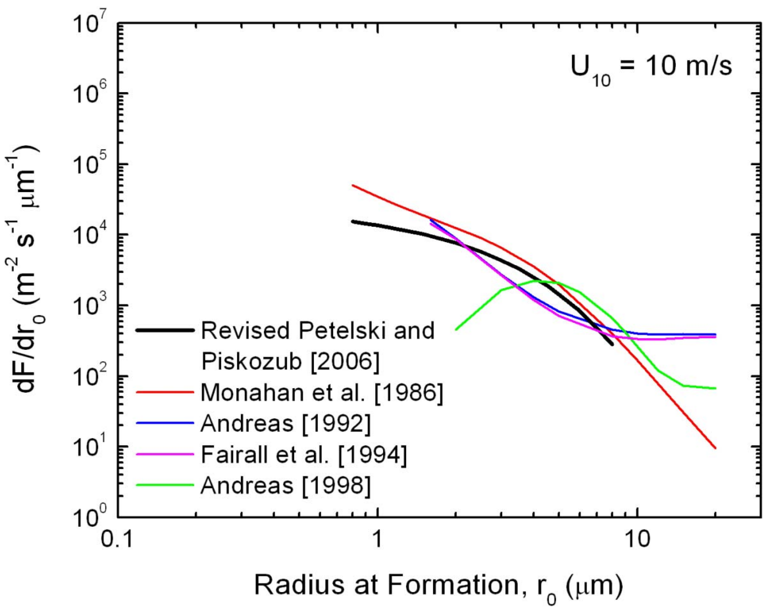

Fig. 5. My revised version of the Petelski and Piskozub (2006) spray generation functions is compared with four other spray generation functions that I feel are reliable in the given radius range (Andreas 2002). These are from Monahan et al. (1986), Andreas (1992, 1998), and Fairall et al. (1994). The wind speed at 10 m, U_{10}, is 10 m/s. Both the droplet radius and the spray generation functions are in terms of the droplet radius at formation, r_0. This plot shows better agreement among functions than Petelski and Piskozub had realized.

against data; and it is theoretically based and, therefore, can be extrapolated to high-wind conditions, where we currently need an air-sea flux algorithm but have few reliable data on which to base an empirical one.

We still need to see if such an algorithm improves predictions of ocean storms, however. I have been trying to answer that question, primarily through my collaboration with colleagues at Bedford Institute.

Our simulations with an earlier version of my flux algorithm (Version 1.1; Andreas 2003) suggest that including the spray heat fluxes in a mesoscale atmospheric model gives better predictions for the intensity of extratropical storms than does a more conventional surface flux parameterization when central pressure and maximum surface-level wind speed are used as metrics for storm intensity (Li et al. 2003; Perrie et al. 2004a, 2004b, 2005, 2006; Zhang et al. 2006).

TRANSITIONS

Besides the journal articles and conference papers that I have written to describe my work on sea spray and the resulting bulk flux algorithm, I have developed a software "kit" that contains the instructions and FORTRAN tools necessary to implement this algorithm. Version 3.1 is the algorithm I have described here and is in my current kit. I have distributed this kit to several collaborators—for example, Shouping Wang at NRL-Monterey. Wang reports that my spray algorithm, indeed, increases the intensity of tropical storms compared to conventional surface flux parameterizations in mesoscale models.

The transition of my work that has progressed the furthest, however, is at Bedford Institute, where Will Perrie and his colleagues have introduced my unified surface flux parameterization into the Canadian mesoscale compressible community model (MC2) and have been simulating Atlantic storms with it. This work is already documented in several papers (Li et al. 2003; Perrie et al. 2004a, 2004b, 2005, 2006; Zhang et al. 2006). Although these papers used Version 1.1 of my algorithm, Perrie and colleagues have also run simulations with Versions 2.0 and 3.1. They find that, during differing periods in the life cycle of storms, spray effects can compete with or even dominate other air-sea processes, such as wave drag.

Another form of transition derives from my membership on the American Meteorological Society's Committee on Air-Sea Interaction. Specifically, I was a co-chairperson of the program committee for the 15th Conference on Air-Sea Interaction, which was held in August in Portland, Oregon. In that role, I recruited speakers and formulated sessions to discuss my favorite air-sea interaction topics: tropical and extratropical storms, waves and the resulting aerosol, and turbulent surface flux measurements and parameterizations.

RELATED PROJECTS

I have no other support for this type of work.

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HONORS/AWARDS/PRIZES

In May, Ed Andreas was inducted into the Gallery of Distinguished Alumni of Sterling High School, Sterling, Illinois.