3.4 AN ALGORITHM TO PREDICT THE TURBULENT AIR-SEA FLUXES IN HIGH-WIND, SPRAY CONDITIONS

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1. INTRODUCTION

In high winds, breaking waves and whitecaps disrupt the ocean surface; spray proliferates. Because these spray droplets start with the same temperature and salinity as the surface water, they effectively increase the ocean's surface area and may thereby enhance the exchange of any constituent normally transferred across the air-sea interface. Here I focus on how spray affects the air-sea exchanges of momentum (τ) and sensible (H_s) and latent (H_L) heat.

Normally, we model these three turbulent fluxes with a bulk flux algorithm that takes the form

$$\tau = \rho C_{Dr} U_r^2 , \qquad (1a)$$

$$H_s = \rho c_p C_{Hr} U_r \left(T_s - T_r\right) , \qquad (1b)$$

$$H_L = \rho L_v C_{Er} U_r \left(Q_s - Q_r\right) . \qquad (1c)$$

Here, ρ is the air density; c_p, the specific heat of air at constant pressure; L_v, the latent heat of vaporization; U_r, T_r, and Q_r, the wind speed, potential temperature, and specific humidity at reference height r; and T_s and Q_s, the temperature and specific humidity at the surface. Finally in (1), the transfer coefficients for momentum (C_{Dr}, the drag coefficient), sensible heat (C_{Hr}), and latent heat (C_{Er}) are often modeled as

$$C_{Dr} = \frac{k^2}{\left[\ln\left(\frac{r}{z_0}\right) - \psi_m\left(\frac{r}{L}\right)\right]^2} , \qquad (2a)$$

$$C_{Hr} = \frac{k^2}{\left[\ln\left(\frac{r}{z_T}\right) - \psi_h\left(\frac{r}{L}\right)\right]\left[\ln\left(\frac{r}{z_0}\right) - \psi_m\left(\frac{r}{L}\right)\right]} , \qquad (2b)$$

$$C_{Er} = \frac{k^2}{\left[\ln\left(\frac{r}{z_Q}\right) - \psi_h\left(\frac{r}{L}\right)\right]\left[\ln\left(\frac{r}{z_0}\right) - \psi_m\left(\frac{r}{L}\right)\right]} . \qquad (2c)$$

Here, k is the von Kármán constant (= 0.40); L is the Obukhov length, a stratification parameter; and ψ_m and ψ_h are "known" functions of the stratification.

The crux of the bulk flux algorithm usually is parameterizing the roughness lengths for wind speed (z_0), temperature (z_T), and humidity (z_Q). For example, the COARE algorithm, version 2.0 (Fairall et al. 1996), bases parameterizations for z_0 on Smith's (1988) suggestion and for z_T and z_Q on the theoretical model of Liu et al. (1979).

When spray is present, however, (1) is no longer accurate or complete. The momentum (e.g., Andreas and Emanuel 2001) and heat fluxes (e.g., Andreas 1994) mediated by the spray do not scale linearly with wind speed nor are the heat fluxes necessarily driven by the air-sea temperature and humidity differences. Here I augment the COARE algorithm with an algorithm that specifically treats spray's contribution to the turbulent air-sea fluxes.

2. MODEL FOR SPRAY HEAT FLUX

Andreas (1992) developed equations to estimate the sensible and latent heat that spray droplets can carry across the air-sea interface. These fluxes depend on the initial radius r_0 of a spray droplet and on the wind speed at a 10-meter reference height, U_{10}. Denote these radius-specific fluxes of sensible and latent heat as $Q_S\left(U_{10}, r_0\right)$ and $Q_L\left(U_{10}, r_0\right)$, respectively. If we integrate these fluxes over all radii, we get $\overline{Q}_S\left(U_{10}\right)$ and $\overline{Q}_L\left(U_{10}\right)$, quantities Andreas and DeCosmo (2002) termed the "nominal" spray fluxes.

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$\overline{Q}_S$ and $\overline{Q}_L$ are nominal because they are theoretically based on spray microphysics and, therefore, should depend properly on wind speed, temperature, and humidity. But because they also depend on an expression for the spray generation function, which is still uncertain by about half an order of magnitude (Andreas 2002), we need to tune the spray fluxes with data.

Andreas (1992) originally assumed that the nominal spray fluxes just added to the interfacial fluxes modeled with the COARE algorithm, for example, to produce the total heat fluxes that would be measured with instruments placed just above the droplet evaporation layer (e.g., Andreas et al. 1995). That is,

$$H_{L,T} = H_L + \overline{Q}_L , \qquad (3a)$$

$$H_{s,T} = H_s + \overline{Q}_S . \qquad (3b)$$

Fairall et al. (1994) pointed out, however, that the droplet evaporation layer must supply most of the heat to evaporate the droplets. As a result, evaporating droplets are a sink for sensible heat. Hence, any spray latent heat added in (3a) must be subtracted from (3b). Consequently, in concept, their expressions for the total heat fluxes are

$$H_{L,T} = H_L + \alpha\overline{Q}_L , \qquad (4a)$$

$$H_{s,T} = H_s + \alpha\overline{Q}_S - \alpha\overline{Q}_L , \qquad (4b)$$

where they inserted α (= 0.5) to imply that not all of the spray heat escapes out the top of the droplet evaporation layer.

Katsaros and DeCosmo (1990) and DeCosmo et al. (1996) further speculated that feedback processes are at work in the droplet evaporation layer. Evaporating spray moistens the near-surface air and would thus slow the interfacial latent heat flux because of the reduced humidity gradient in (1c). Likewise, evaporating spray cools the near-surface air. This process would enhance the sea-air temperature difference in normal oceanic conditions and would, thus, enhance the interfacial sensible heat flux according to (1b). Edson and Andreas (1997) and Andreas and DeCosmo (1999, 2002), therefore, revised (4) still further as

$$H_{L,T} = H_L + \alpha\overline{Q}_L , \qquad (5a)$$

$$H_{s,T} = H_s + \beta\overline{Q}_S - (\alpha-\gamma)\overline{Q}_L , \qquad (5b)$$

where α, β, and γ are now presumed to be small, non-negative constants that tune the model to data.

In (5a), the α term models the latent heat flux coming out the top of the droplet evaporation layer that the spray has contributed. This same quantity must appear with the opposite sign in (5b) to reflect the sensible heat that evaporating spray extracts from this layer. The β term models the sensible heat that spray droplets generally give up in cooling from T_s to their equilibrium temperature (e.g., Andreas 1995). Finally, the γ term in (5b) adds more interfacial sensible heat to the layer because of the increased sea-air temperature difference that results from the spray's evaporative cooling of the layer. I expect $\gamma \le \alpha$.

Edson and Andreas (1997) and Andreas and DeCosmo (1999, 2002) report three different sets of α, β, and γ values depending on how (5) was tuned and on which spray generation function was used for computing $\overline{Q}_L$ and $\overline{Q}_S$. Here I report yet a fourth set: α = 3.3, β = 5.7, and γ = 2.8. These values are fairly close to the values that Andreas and DeCosmo (2002) report but are slightly smaller because, to obtain them, I used the Fairall et al. (1994) spray generation function to compute $\overline{Q}_L$ and $\overline{Q}_S$. Andreas and DeCosmo (2002) had used the Andreas (1992) spray generation function instead. Andreas (2002) demonstrates that the Fairall et al. (1994) and Andreas (1992) spray generation functions are quite similar. But because of its parameterization for wind speed dependence, the Fairall et al. (1994) function is a little better behaved and thus more reliable for extrapolating to high winds.

Andreas and DeCosmo (1999, 2002), in effect, partition the total latent and sensible heat fluxes in (5) into contributions from both interfacial and spray processes. That is,

$$H_{L,T} = H_L + Q_{L,sp} , \qquad (6a)$$

$$H_{s,T} = H_s + Q_{S,sp} , \qquad (6b)$$

where

$$Q_{L,sp} = \alpha\overline{Q}_L , \qquad (7a)$$

$$Q_{S,sp} = \beta\overline{Q}_S - (\alpha-\gamma)\overline{Q}_L \qquad (7b)$$

are the spray fluxes.

Andreas's (1992) microphysical model, however, is too computationally intensive to use routinely in large-scale models for computing $\overline{Q}_L$ and $\overline{Q}_S$ in (7). Sample calculations of $Q_S(U_{10}, r_0)$ and $Q_L(U_{10}, r_0)$ reported in Andreas (1992), Andreas et al. (1995), and Andreas and DeCosmo (1999), though, suggest that droplets with initial radii near 100 μm carry most of the spray sensible heat (cf. Andreas and Emanuel 2001), while droplets with initial radii near 50 μm carry most of the spray latent heat. Hence, I hypothesize that these droplets are the bellwethers for the total spray fluxes and parameterize these fluxes as

$$Q_{L,sp} = \rho_w L_v \left[1 - \left(\frac{r_{eq,50}}{50\,\mu\text{m}}\right)^3\right] V_L(u_*) , \qquad (8a)$$

$$Q_{S,sp} = \rho_w c_w \left(T_s - T_{eq,100}\right) V_S(u_*) . \qquad (8b)$$

Here, ρ_w is the density of seawater; c_w is the specific heat of seawater; $r_{eq,50}$ is the equilibrium radius (in micrometers) of droplets whose initial radius is 50 μm; and $T_{eq,100}$ is the equilibrium temperature in air of spray droplets whose initial radius is 100 μm. $V_L(u_*)$ and $V_S(u_*)$ are functions of the friction velocity [$u_* = (\tau/\rho)^{1/2}$] that must be evaluated empirically.

I have computed the spray fluxes on the right sides of (7a) and (7b) (with units W m^{-2}), as in Andreas and DeCosmo (1999, 2002), using DeCosmo's (1991) data from HEXOS, the Humidity Exchange over the Sea experiment. Here, though, I use the Fairall et al. (1994) spray generation function. Andreas's (1992) microphysical model routinely computes $T_{eq,\,100}$ and $r_{eq,50}$. Figures 1 and 2 show these spray fluxes plotted in the forms that (8) suggests.

Many sources suggest that the spray generation function should go as the cube of the wind speed or the cube of u_* (e.g., Andreas et al. 1995; Andreas 2002). Andreas and Emanuel (2001) therefore fitted an equation similar to (8b) with a wind function that went as u_*^3. Figures 1 and 2 show that such u_*^3 functions fit both data clouds well. That is,

$$V_L = 4.75 \times 10^{-8}\, u_*^3 , \qquad (9a)$$

$$V_S = 1.65 \times 10^{-6}\, u_*^3 , \qquad (9b)$$

which give V_L and V_S in m s^{-1} when u_* is in m s^{-1}.

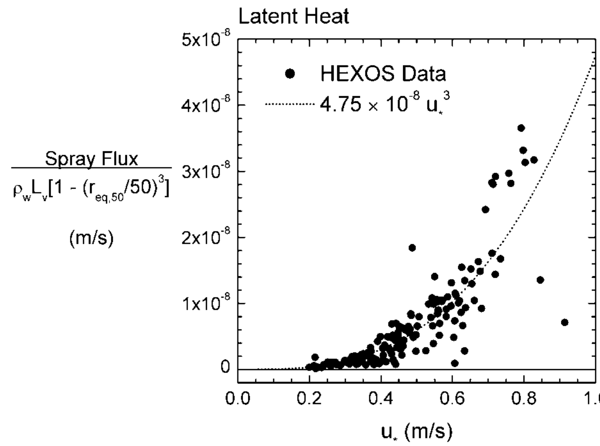

Fig. 1. The spray latent heat flux, $Q_{L,sp}$, computed from HEXOS data according to (7a) and parameterized according to (8a). That is, this plot shows $V_L(u_*)$.

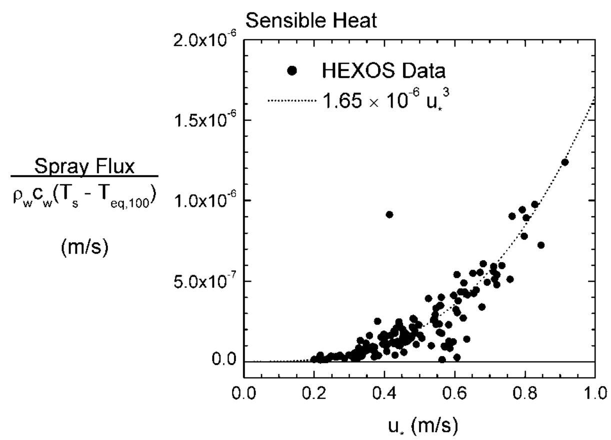

Fig. 2. The spray sensible heat flux, $Q_{S,sp}$, computed from HEXOS data according to (7b) and parameterized according to (8b). That is, this plot shows $V_S(u_*)$.

In implementing the spray algorithm, I do not use Andreas's (1992) microphysical model to compute $T_{eq,100}$ and $r_{eq,50}$. Rather, I use Andreas's (1996) simpler method to calculate $T_{eq,100}$ and Fitzgerald's (1975) procedure to calculate $r_{eq,50}$.

I also do not use all of the features in the COARE version 2.0 algorithm (Fairall et al. 1996) to compute H_s and H_L. Because my algorithm is for high winds, I ignore the routines in the COARE algorithm for treating convective transfer in light winds and basically extract only its parameterizations for z_0, z_T, and z_Q.

The z_T and z_Q values that the COARE algorithm computes, however, are smaller than the mean free path of an air molecule when u_* exceeds roughly 0.88 m s^{-1}. It seems unphysical for z_T and z_Q to be smaller than this length. Hence, I set z_T and z_Q to 7.0×10^{-8} m, the typical mean free path in air, if they are ever computed to be less than this length (cf. Andreas and Emanuel 2001).

I also modify the COARE algorithm's parameterization for the roughness length z_0. In my algorithm

$$z_0 = 0.135\frac{\nu}{u_*} + 0.0185\frac{u_*^2}{g} \quad . \qquad (10)$$

Here, ν is the kinematic viscosity of air; g is the acceleration of gravity; and the Charnock constant, 0.0185, is larger than in Fairall et al. (1996) to reflect the rougher sea surface typical for higher wind speeds (Wu 1982; Johnson et al. 1998).

3. MODEL FOR SPRAY MOMENTUM FLUX

When spray droplets are thrown up into the air, they quickly accelerate to the local wind speed. This process extracts momentum from the wind. When these droplets then plunge back to the sea surface, they transfer this momentum to the water in the form of a spray surface stress.

Using this conceptual picture, I can estimate the spray surface stress τ_{sp} from what I know about spray production. The fundamental equation is

$$\tau_{sp} = \frac{4\pi}{3}\rho_w U \int_{r_{LO}}^{r_{HI}} r_i^3 C_0(r_i) u_f(r_i) dr_i \quad . \qquad (11)$$

Here, r_i is the radius of an arbitrary droplet; $u_f(r_i)$ is its terminal fall speed; $C_0(r_i)$ is the near-surface concentration of droplets with this radius; and U is some near-surface wind speed, the assumed horizontal speed of all droplets. The limits of integration r_{LO} and r_{HI} encompass all radii that are important to this momentum exchange, typically 1 to 500 μm.

If we substitute the radius at formation r_0 for r_i in (11), we can make the usual assumption that

$$C_0(r_0) u_f(r_0) = \frac{dF}{dr_0} \quad , \qquad (12)$$

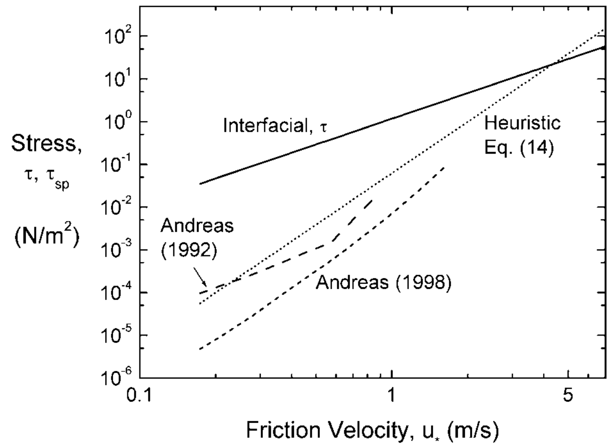

Fig. 3. The interfacial (τ) and spray (τ_{sp}) stresses as functions of the friction velocity. The Andreas (1992) and Andreas (1998) lines derive from (13) and the two spray generation functions in those papers. The heuristic model (14) is in the current bulk algorithm.

where dF/dr_0 is the spray generation function. Then (11) simply becomes

$$\tau_{sp} = UM_{sp} \quad , \qquad (13)$$

where M_{sp} is the vertical mass flux of the spray being produced at the sea surface.

M_{sp} typically goes as u_*^3 (Andreas 1998, 2002). For U, I simply evaluate the semi-logarithmic wind speed profile at a height of one significant wave amplitude. Thus, U is proportional to u_*. Andreas and Emanuel (2001) therefore realized that τ_{sp} should go approximately as u_*^4 ; τ, on the other hand, goes as u_*^2.

Figure 3 shows τ (= ρu_*^2) and τ_{sp} evaluated with (13) using the Andreas (1992) and Andreas (1998) spray generation functions. These two calculations suggest the approximate level of the spray stress and confirm a dependence near u_*^4. Andreas and Emanuel (2001) therefore developed a "heuristic" model for τ_{sp},

$$\tau_{sp} = 6.2\times10^{-2} u_*^4 \quad , \qquad (14)$$

that produced reasonable results in Emanuel's (1986, 1995) balanced, axi-symmetric tropical cyclone model (Andreas and Emanuel 2001). In (14), τ_{sp} is in N m^{-2} when u_* is in m s^{-1}. Equation (14) is what I use to represent the spray stress in my current bulk algorithm.

Figure 3 suggests that the spray stress is largely negligible until u_* reaches values in excess of about 2 m s^{-1}. This u_* limit corresponds to a 10-meter wind speed of about 36 m s^{-1}. That is, the spray stress is likely significant for all hurricane-strength winds.

4. TESTS WITH THE ALGORITHM

My current bulk algorithm predicts the interfacial momentum and sensible and latent heat fluxes from (1), (2), and (10). It predicts the spray fluxes from (8), (9), and (14). The total surface stress is simply

$$\tau_T = \tau + \tau_{sp} , \qquad (15)$$

and the total sensible and latent heat fluxes just above the droplet evaporation layer come from (6).

The spray and interfacial fluxes in the algorithm currently are not coupled. That is, the algorithm solves iteratively for the bulk interfacial fluxes as if there were no spray effects. Then the algorithm uses the u_* value that results to compute the three spray fluxes, τ_{sp}, $Q_{S,sp}$, and $Q_{L,sp}$.

Figures 4 and 5 show simulations of DeCosmo's (1991) HEXOS data made with this bulk algorithm. These plots are similar to ones in Andreas and DeCosmo (1999, 2002), but there we used Andreas's (1992) full microphysical model to simulate the fluxes. The one exception to the bulk algorithm here is that I did not use (10) for these computations. Because HEXOS was a shallow-water site, (10) is not appropriate. Instead, to compute u_* in these simulations, I used the drag coefficient that Smith et al. (1992) deduced for the HEXOS site.

Figures 4 and 5 show ratios of measured HEXOS sensible and latent heat fluxes to values of $H_{s,T}$ and $H_{L,T}$, respectively, computed with the bulk algorithm. The data cloud in each figure averages about 1, and the ratios show no tendency with wind speed. These results mean that the new algorithm predicts both the magnitude and the wind speed dependence of the HEXOS heat flux data well.

In Figs. 4 and 5, the filled circles indicate cases with a 10% spray contribution. That is, for these, the spray terms in (6) are at least 10% of the corresponding interfacial terms. Most of the cases in Fig. 4 above a wind speed of 12 m s^{-1} show at least a 10% spray effect. In Fig. 5, the 12 m s^{-1} threshold for a 10% spray effect is even more striking. Similar plots in Andreas and DeCosmo (1999, 2002) that are based on Andreas's (1992) full microphysical model show this same result: For winds about 12 m s^{-1}, almost

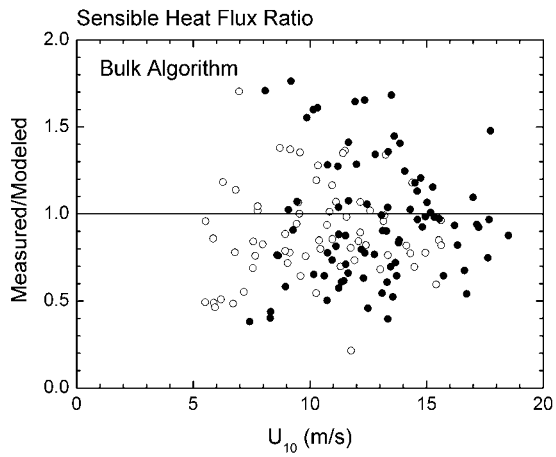

Fig. 4. The ratio of HEXOS measurements of sensible heat flux to the corresponding flux modeled with the bulk algorithm. Filled circles denote cases when the modeled spray flux ($Q_{S,sp}$) is at least 10% of the modeled interfacial flux (H_s). The average of the ratios plotted in this figure is 0.945, and their correlation coefficient with wind speed is 0.035.

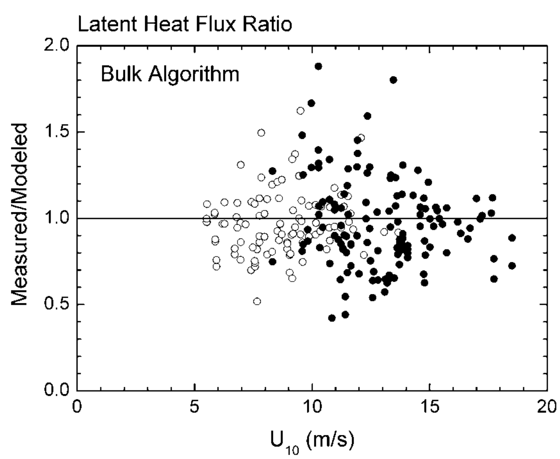

Fig. 5. As in Fig. 4 except this shows the latent heat flux ratio. Filled circles denote cases when the modeled spray flux ($Q_{L,sp}$) is at least 10% of the modeled interfacial flux (H_L). The average of the ratios in this figure is 1.010, and their correlation coefficient with wind speed is 0.066.

all the HEXOS data show at least a 10% spray effect. Consequently, the current bulk algorithm is producing results that are comparable to the full microphysical model that Andreas and DeCosmo (1999, 2002) used.

5. DISCUSSION

You might complain that I am not using the most current version of the COARE algorithm (i.e., Bradley et al. 2000; Fairall et al. 2001, 2002). This is a scientifically based choice. COARE version 2.0 uses the theoretical model of Liu et al. (1979) for parameterizing z_T and z_Q. Fairall et al. (1996) verify that this is an accurate parameterization for 10-meter wind speeds up to about 10 m s^{-1}. Grant and Hignett (1998) and Chang and Grossman (1999) basically concur.

In other words, COARE version 2.0 is theoretically based and validated for conditions where sea spray has little or no effect on the surface heat fluxes (see Figs. 4 and 5). I therefore feel safe in extrapolating it to higher wind speeds to predict the interfacial fluxes H_s and H_L.

A major change in newer versions of the COARE algorithm, however, is that z_T and z_Q are empirical fits to flux data collected in winds up to almost 20 m s^{-1}, where spray effects are no longer negligible. That is, the new z_T and z_Q parameterizations probably include contributions from spray and are, thus, not useful for partitioning the fluxes into strict interfacial and spray contributions. While these new parameterizations for the scalar roughnesses may be reliable for predicting total fluxes for the wind speed range for which they were evaluated, I have no confidence that I can extrapolate them to higher wind speeds, as I do in my algorithm with the Liu et al. (1979) parameterizations.

As I have demonstrated above, the interfacial and spray fluxes scale differently. Trying to model $H_{s,T}$ and $H_{L,T}$ under conditions when spray is important with a parameterization formulated as in (1) and (2) cannot be generally useful. I therefore choose to extrapolate the theoretically based Liu et al. (1979) formulation for z_T and z_Q rather than the empirically based z_T and z_Q parameterizations in the newer version of the COARE algorithm.

In closing, I have an executable file that will let you test this new bulk flux algorithm. I can provide you a copy if you contact me. At this conference, Li et al. (2003) also are reporting their implementation of this algorithm in their simulations of extratropical storms.

6. ACKNOWLEDGMENTS

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