A BULK AIR-SEA FLUX ALGORITHM FOR HIGH-WIND, SPRAY CONDITIONS,VERSION 2.0

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Reference:

Andreas, E. L, 2004: A bulk air-sea flux algorithm for high-wind, spray conditions, Version 2.0. Preprints, 13th Conference on Interactions of the Sea and Atmosphere, Portland, ME, 9-13 August 2004, American Meteorological Society, CD-ROM P1.5, 8 pp.

Outline

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1. INTRODUCTION

1. In high winds, spray processes could conceivably dominate the exchange of sensible heat,latent heat, and momentum across the air-sea interface (Emanuel 2003; Andreas 2004).(1.jet droplets,2.film droplets,3.spume droplets,4.other mechanisms)

2. In low winds, when spray droplets are not plentiful, the exchange of heat and momentum across the air-sea interface is strictly by interfacial processes that the COARE algorithm (Fairall et al. 1996) does well in predicting.

3. (TOGA) COARE : Coupled Ocean –Atmosphere Response Experiment

4. A BULK AIR-SEA FLUX ALGORITHM FOR HIGH-WIND, SPRAY CONDITIONS, Version 1.0(Andreas 2003)

It relied on the COARE algorithm to predict the interfacial fluxes of sensible heat, latent heat, and momentum but included a spray parameterization to account for how sea spray could enhance the heat fluxes in high winds.

5. However, that the spray component of that algorithm was not sensitive enough to temperature (Li et al. 2003) and that it also had flaws at very high relative humidity.

2.THE INTERFACIAL FLUXES

1. Traditional bulk flux algorithms predict only the interfacial fluxes of momentum (τ , also called the surface stress), sensible heat (Hs), and latent heat (H_L).

$$\tau = \rho \overline{w'u'} = \rho u_*^2 = \rho C_{Dr} U_r^2 \qquad (1a)$$

$$H_s = \rho c_p \overline{w'\theta'} = \rho c_P C_{Hr} U_r (T_s - T_r) \qquad (1b)$$

$$H_L = \rho L_V \overline{w'q'} = \rho L_V C_{Er} U_r (Q_s - Q_r) \qquad (1c)$$

- ρ is the air density
- c_p, the specific heat of air at constant pressure
- Lv, the latent heat of vaporization
- Ur, Tr, and Qr, the average wind speed, potential temperature, and specific humidity at reference height r
- Ts and Qs, are the average temperature and specific humidity at the surface
- Equation (1a) also defines the friction velocity u*

2. In essence, estimating the interfacial fluxes is a matter of choosing parameterizations for the roughness lengths for wind speed (z_0), temperature (z_T), and humidity (z_Q). I use, basically, the COARE Version 2.6 parameterization (Fairall et al. 1996) for these.

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

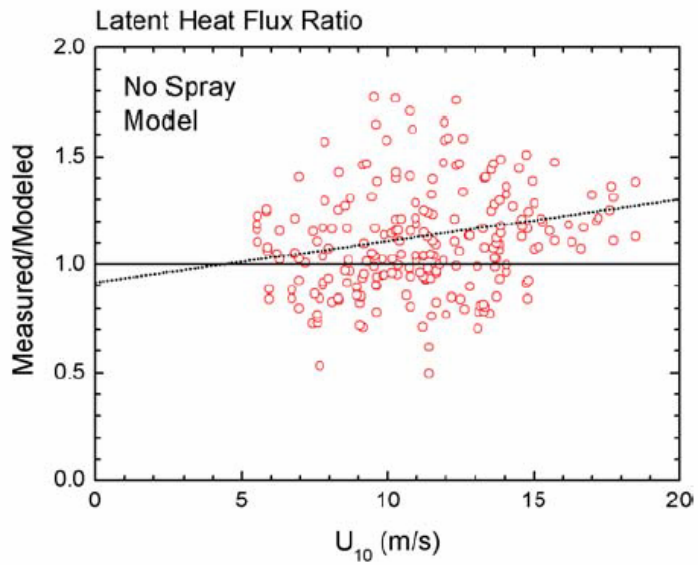
- ν is the kinematic viscosity of air
- g is the acceleration of gravity
- We deviate slightly from Fairall et al. by using a somewhat larger coefficient, 0.135, in the aerodynamically smooth term (Andreas and Treviño 2000) and a larger Charnock coefficient, $\alpha_c = 0.0185$.

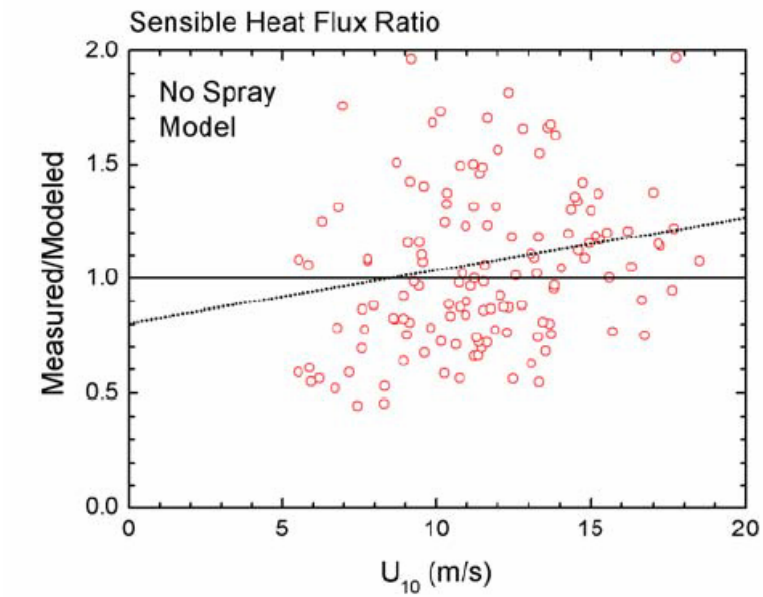
$$z_0 = 0.135\frac{\nu}{u_*} + \alpha_c \frac{u_*^2}{g} \qquad (3)$$

3. HEXOS (the Humidity Exchange over the Sea experiment)

The HEXOS data set (DeCosmo 1991; DeCosmo et al. 1996) is one of the better sets for investigating flux parameterizations in high winds. It includes eddy-correlation measurements of the momentum and sensible and latent heat fluxes over the North Sea in 10-m winds up to almost 20 m/s.

(Eddy-correlation instruments placed just above the DEL would thus measure total sensible ($H_{S,T}$) and latent ($H_{L,T}$) heat fluxes that reflect these combined interfacial and spray fluxes.)





- Fig. 1. HEXOS measurements of the latent and sensible heat fluxes are compared with values modeled strictly with the interfacial algorithm, (1)–(2). If the model were accurate, the ratios depicted would average one and would show no trend with the 10-m wind speed, U_{10}. The dashed lines, however, show the trends with wind speed.

- In the latent (sensible) heat flux panel, the ratios average 1.133(1.073), and their correlation coefficient with wind speed is 0.184(0.174).

- Andreas and DeCosmo (2002) interpret this behavior to be evidence of spray-mediated fluxes in the high winds.

3. PARTITIONING THE FLUXES

1. Andreas and DeCosmo (1999,2002) use Andreas's (1989, 1992) microphysical model to predict the spray latent ($\overline{Q}_L$)and sensible ($\overline{Qs}$) heat flux contributions and assume that these just add linearly to the interfacial fluxes predicted by (1) and (2);

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

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

- $H_{L,T}$ and $H_{s,T}$ are the total latent and sensible heat fluxes that eddy-correlation instruments would measure just above the droplet evaporation layer (Andreas et al. 1995; Andreas and DeCosmo 2002).

2. The $\overline{Q_L}$ and $\overline{Qs}$ values in (4) come from my microphysical spray model (Andreas 1992).

- This computes the radius-specific droplet sensible heat flux as

$$Q_S(r_0) = \rho_s c_w (T_s - T_{eq})[1 - \exp(-\tau_f / \tau_T)]\left(\frac{4\pi r_0^3}{3}\frac{dF}{dr_0}\right) \qquad (5)$$

- ρ_s is the density of seawater
- c_w is the specific heat of seawater at constant pressure
- T_{eq} is the equilibrium temperature of a saline droplet with initial radius r_0 (a function also of air temperature,relative humidity, and initial salinity; Andreas 1995,1996; Kepert 1996)
- τ_T is the e-folding time to reach this temperature
- τ_f is related to the droplet's residence time in the air
- dF/dr_0 is the spray generation function, the rate at which droplets of initial radius r_0 are produced at the sea surface.($m^{-2}s^{-1}\mu m^{-1}$)
- *QS* has units of a heat flux per increment in droplet radius, $Wm^{-2}\mu m^{-1}$.

3. The radius-specific spray latent heat flux has two parts.

Then, if $\tau_f > \tau_T$, we assume the droplet has reached its equilibrium radius, and

$$Q_L(r_0) = \rho_w L_V \left\{ 1 - \left(\frac{r_{eq}}{r_0} \right)^3 \right\} \left(\frac{4\pi r_0^3}{3} \frac{dF}{dr_0} \right) \qquad (6a)$$

On the other hand, if $\tau_f \leq \tau_T$

$$Q_L(r_0) = \rho_w L_V \left\{ 1 - \left[\frac{r(\tau_f)}{r_0} \right]^3 \right\} \left(\frac{4\pi r_0^3}{3} \frac{dF}{dr_0} \right) \qquad (6b)$$

- τ r is the e-folding time for a droplet with initial radius r_0 to reach its equilibrium radius r_{eq} (Andreas 1990, 1992).
- where $r(\tau_f)$ is the droplet radius at time τ_f
- ρ_w is the density of pure water

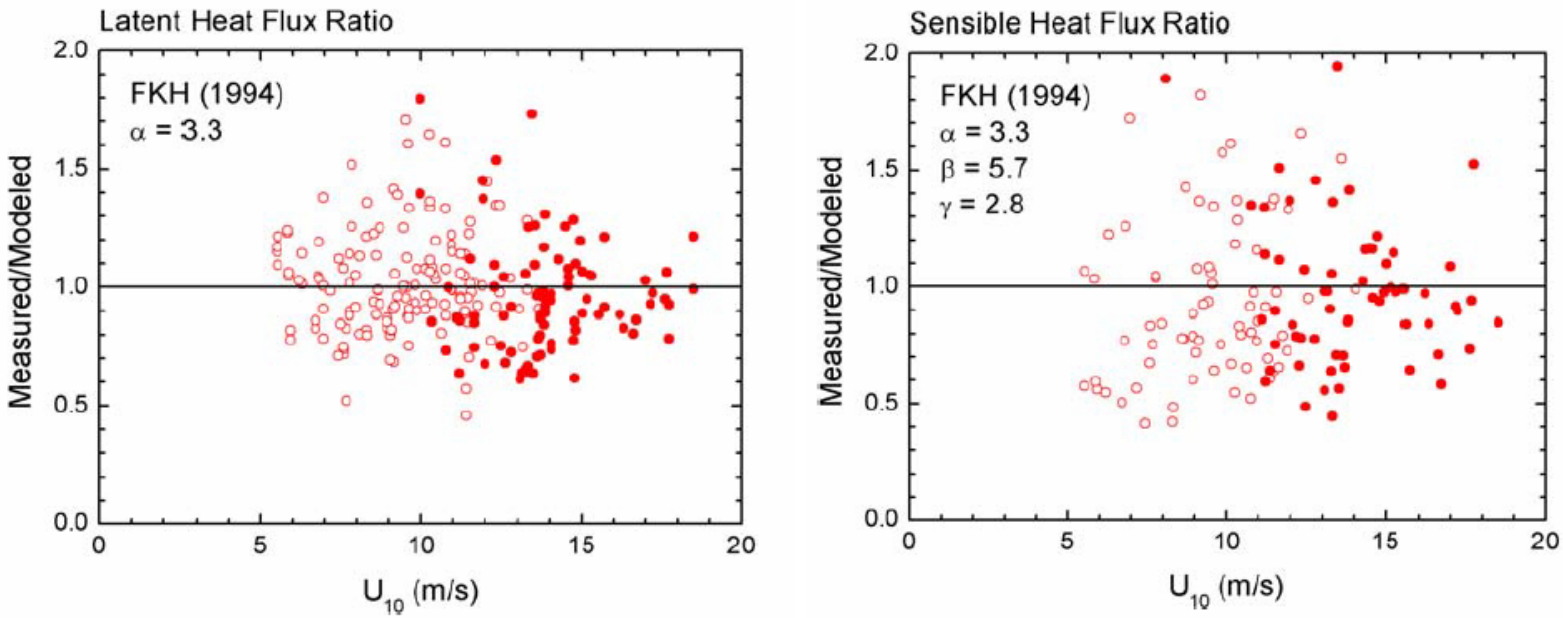
$$r(\tau_f) = r_{eq} + (r_0 - r_{eq}) \exp(-\tau_f / \tau_r) \qquad (7)$$

4. To get the $\overline{Q_L}$ and $\overline{Qs}$ terms in (4), we integrate (5) and (6) over all droplet sizes relevant to the spray transfer process

$$\overline{Q}_s = \int_{r_{lo}}^{r_{hi}} Q_s(r_0)dr_0 \qquad (8a)$$

rlo and rhi are, nominally, 1 μ m and 500 μ m,respectively

$$\overline{Q}_L = \int_{r_{lo}}^{r_{hi}} Q_L(r_0)dr_0 \qquad (8b)$$



- Fig. 2. As in Fig. 1, use (4) to model the HEXOS heat flux data. Equations (5) and (6) use the model by Fairall et al. (1994; FKH) for the spray generation function; and in (4), $\alpha = 3.3$, $\beta = 5.7$, and $\gamma = 2.8$.

- In the latent (sensible) heat flux panel, the ratios average 1.025(0.984), and their correlation coefficient with wind speed is –0.052(0.044).

- The filled circles denote cases for which the modeled spray contributions [the α, β, and γ terms in (4)] sum to at least 10% of the respective modeled interfacial fluxes [the Hs and HL terms in (4)].

- In essence, Fig. 2 shows that I have successfully partitioned the HEXOS measurements of total latent and sensible heat flux, $H_{L,T}$ and $H_{s,T}$, into interfacial contributions, H_L and Hs, and into spray contributions that I represent as postulate that

$$Q_{L,sp} = \alpha \overline{Q}_L \qquad (9a)$$

$$Q_{S,sp} = \beta \overline{Q}_s - (\alpha - \gamma)\overline{Q}_L \qquad (9b)$$

- We can use the COARE algorithm to estimate H_L and Hs; but rather than the full microphysical calculations, I also want a comparably fast algorithm for predicting $Q_{L,sp}$ and $Q_{S,sp}$.

4. SPRAY FLUX ALGORITHM

1. Andreas (1992) and Andreas et al. (1995) show, however, that $Q_S(r_0)$ and $Q_L(r_0)$ have dominant peaks at radii of 100 µm and 50 µm, respectively.

2. In (5), $\tau_f(100\mu m) > \tau_r(100\mu m)$. That is,100-µm droplets have essentially given up all their sensible heat by the time they fall back into the sea. Therefore, I further postulate that

$$Q_{S,sp} = \rho_w c_w (T_s - T_{eq,100}) V_S(u_*) \qquad (10)$$

- Teq,100 is the equilibrium temperature in the given ambient conditions of a spray droplet with initial radius 100 µm, and is an empirical function of the friction velocity.

In (6), $\tau_f(50\mu m) < \tau_r(50\mu m)$. Therefore, my postulate is

$$Q_{L,sp} = \rho_w L_v \left\{ 1 - \left[\frac{r[\tau_f(50\mu m)]}{50\mu m} \right]^3 \right\} V_L(u_*) \qquad (11)$$

- $r[\tau_f(50\mu m)]$ is <u>the radius at time</u> $\tau_f(50\mu m)$ of a droplet with initial radius 50 µm [see (7)], and $V_L(u_*)$ is another empirical function of u_*.
- We base τ_f on the time required for a droplet with initial radius r_0 to fall <u>one significant wave amplitude, $A_{1/3}$</u>, since droplets of radii 50 µm and 100 µm are probably spume droplets that are blown off the wave crests (Andreas 1992; Andreas and DeCosmo 2002).That is,

$$\tau_f(r_0) = \frac{A_{1/3}}{u_f(r_0)} \qquad (12)$$

u_f is the <u>terminal fall speed of a droplet with initial radius r_0</u> (Andreas 1989, 1992).

- This gives $A_{1/3}$ in meters when u_* is in ms-1. <u>We limit $A_{1/3}$ calculated with (13) to values of 20 m or less.</u>

$$A_{1/3} = 0.015\left(\frac{u_*}{k}\right)^2\left\{2u_*^2 - u_*\left[2\ln\left(\frac{10g}{\alpha_C}\right)+8\right]+\left[\left(\ln\left(\frac{10g}{\alpha_C}\right)\right)^2+2\ln\left(\frac{10g}{\alpha_C}\right)+4\right]\right\} \qquad (13)$$

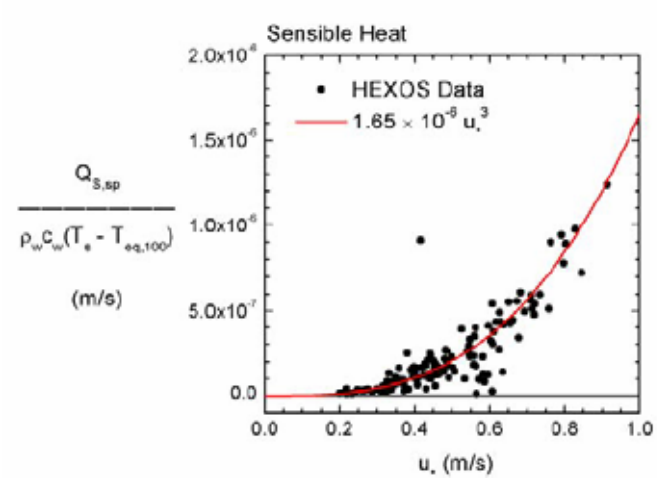
$$A_{1/3} = 0.015U_{10}^2$$

3. In Figs. 3 and 4, I test the postulates (10) and (11) using my partitioning of the HEXOS flux data.

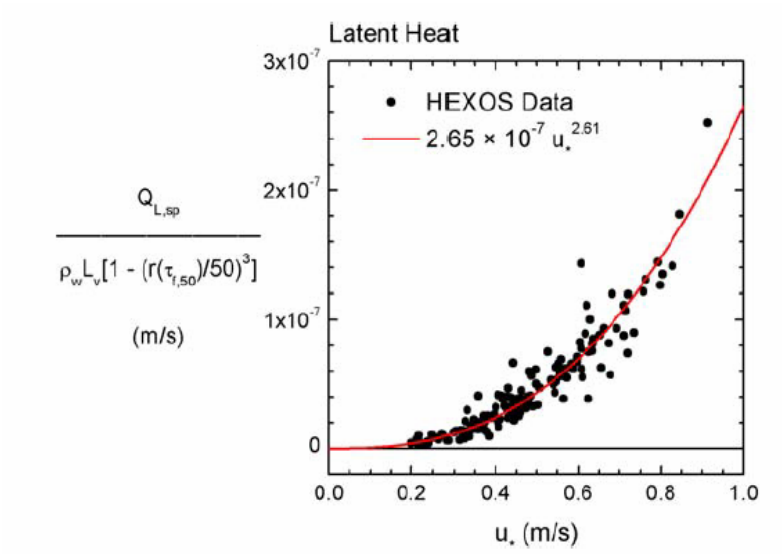
$$V_S = 1.65\times10^{-6}u_*^3 \qquad (14a)$$

$$V_L = 2.65\times10^{-8}u_*^{2.61} \qquad (14b)$$

These give V_S and V_L in ms^{-1} when u_* is in ms^{-1} and, in turn, produce values of $Q_{S,sp}$ and $Q_{L,sp}$ in wm^{-2} .



4. Fig. 3. The spray sensible heat flux, $Q_{S,sp}$, computed from the HEXOS data as (9b) and parameterized as (10). This plot therefore shows , equation (14a).



5. Fig. 4. The spray latent heat flux, $Q_{L,sp}$, computed from the HEXOS data as (9a) and parameterized as (11). Here, $\tau_{f,50}$ is the fall time, (12), of a droplet with initial radius 50 µm. This plot shows , equation (14b).

6. The procedure for computing the total sensible and latent heat fluxes when given conditions such as U_r, T_r, Q_r, T_s, and Q_s is therefore to first use (1) to compute H_s, H_L, and u_* .

Then use this u_* value and (10), (11), and (14) to compute the spray fluxes $Q_{S,sp}$ and $Q_{L,sp}$. Finally, sum these fluxes, to get the total heat fluxes.

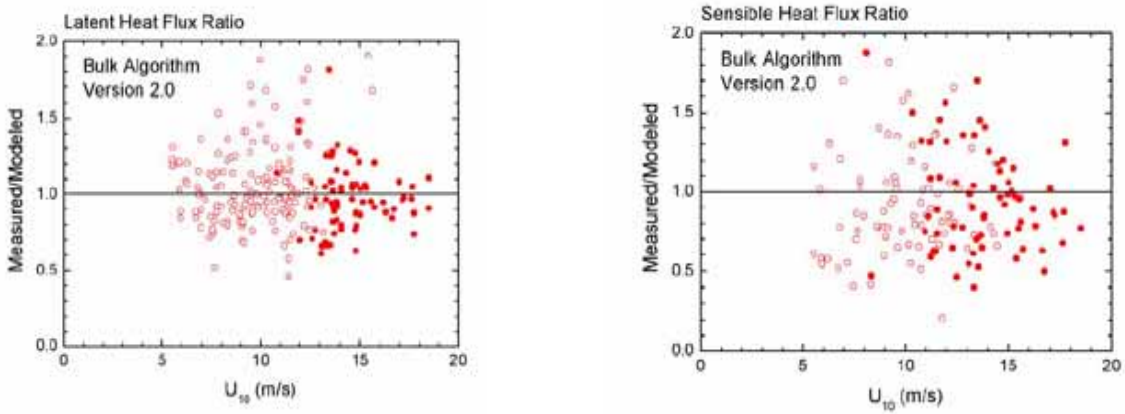
$$H_{s,T} = H_s + Q_{S,sp} \qquad (15a)$$

$$H_{L,T} = H_L + Q_{L,sp} \qquad (15b)$$

We also need the <u>equilibrium temperature of 100-µm droplets</u>, <u>T_{eq},100</u>, and the <u>equilibrium radius and radius e–folding time of 50-µm droplets</u>, <u>r_{eq}(50 µm) and τ_r (50 µm),</u> respectively.

5. DISCUSSION

1. To test this spray flux algorithm, we can use (15), instead of my full microphysical model, to model the HEXOS heat fluxes.



- Fig. 5. As in Fig. 2, but <u>use the bulk flux algorithm represented by (15)</u> to model the HEXOS latent and sensible heat fluxes.

- In the latent (sensible) heat flux panel, <u>the average of the flux ratios</u> is 1.055(0.948), and the correlation coefficient with wind speed is 0.001(-0.050).

- In both panels, the filled circles denote cases for which the <u>respective modeled spray flux ($Q_{L,sp}$ or $Q_{S,sp}$)</u> <u>is at least 10% of the modeled interfacial flux</u> (H_L or Hs).

2. Moreover, most of the measured HEXOS fluxes for wind speeds above 12 m/s include at least a 10% spray effect, as also suggested in Fig. 2. Finally, computing fluxes with Version 2.0 of the spray flux algorithm is approximately a hundred times faster than with the full microphysical spray model.

3. r as a function of τ_f and τ_r in (11), $Q_{L,sp}$ is now appropriately sensitive to temperature because τ_f decreases markedly as temperature increases (Andreas 1990, 1992) while τ_r changes little with temperature.

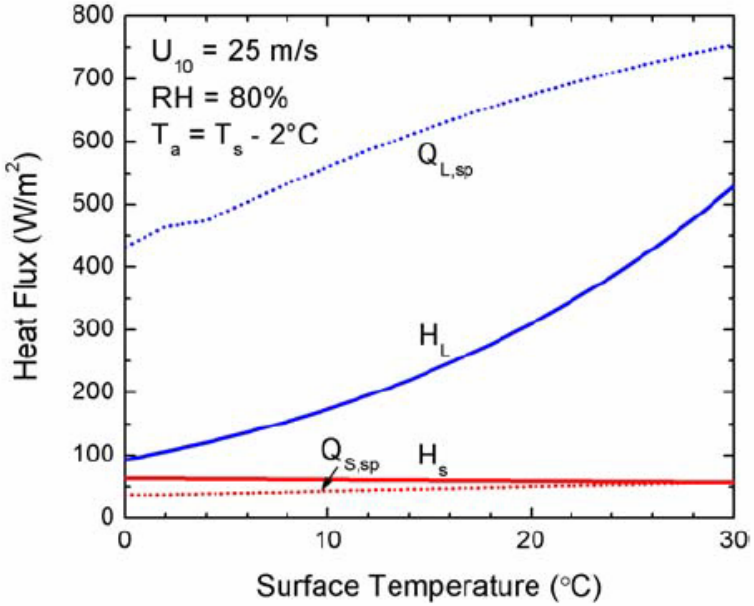


Fig. 6. Sample calculations with Version 2.0 of the bulk flux algorithm to demonstrate the temperature sensitivity. For all calculations, the 10-m wind speed U_{10} was 25 ms^{-1}, the relative humidity RH was 80%, the air temperature was 2°C less than the surface temperature (i.e.,), the barometric pressure was 1000 mb, and the surface salinity was 34 psu.

- Figure 6 therefore reproduces a plot like Fig. 2 in Li et al. (2003) but now using Version 2.0 of the spray algorithm. Here, $Q_{L,sp}$ now has the strong dependence on temperature reported by Andreas (1992).

- The upshot is that spray heat transfer should be more important in tropical storms than in high-latitude storms.

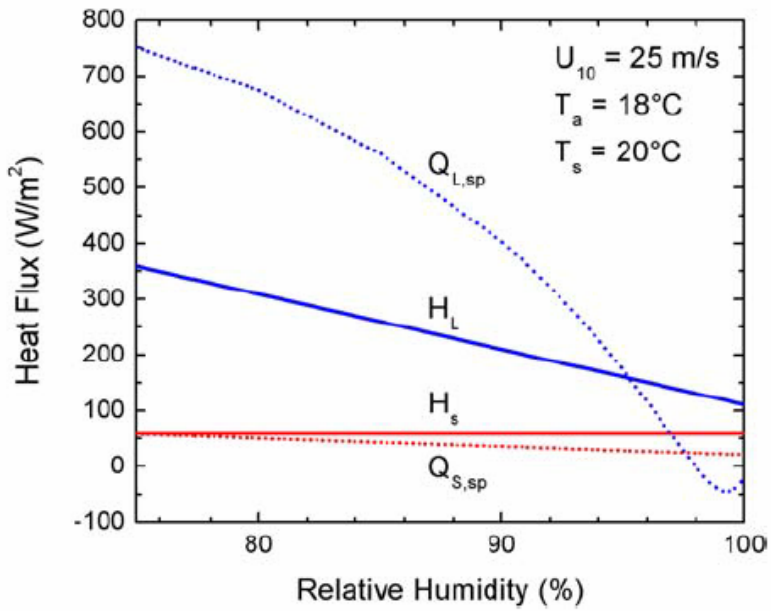


Fig. 7. Sample calculations with the bulk flux algorithm to demonstrate its humidity sensitivity. Conditions are as in Fig. 6, except here the relative humidity varies, the air temperature Ta is 18°C, and the surface temperature is 20°C.

- Figure 7 likewise demonstrates the algorithm's sensitivity to relative humidity. As the relative humidity increases from 75%, the equilibrium radius of droplets that started at 50 µm moves progressively closer to 50 µm.
- In other words, as the relative humidity increases, the droplets have less potential for giving up water vapor, and $Q_{L,sp}$ gets progressively smaller.

4. Once the relative humidity is higher than the saturation value for seawater—typically about 98% for seawater of salinity 34 psu—water actually begins condensing on these 50-µm droplets. They, thus, become a sink for latent heat, and $Q_{L,sp}$ goes negative.

5. Version 2.0 of the algorithm does not allow humidities above 100%, and it is hard to imagine how the humidity in the marine boundary layer can get much above the seawater-saturation value, 98%.

6. SUMMARY

1. We have developed a fast bulk flux algorithm for high-wind, spray conditions.

2. In essence, the spray part of the algorithm simplifies Andreas's (1989, 1992) microphysical spray model.

3. The algorithm predicts the interfacial fluxes with a standard bulk flux algorithm that uses the COARE Version 2.6 expressions for the roughness lengths z_0, z_T, and z_Q.

T H E E N D

2. These derive from Monin-Obukhov similarity theory (Garratt 1992, p.52 ff.).

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

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

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

- C_{Dr} is the transfer coefficient for momentum (also called the drag coefficient)
- C_{Hr} is the transfer coefficient for sensible
- C_{Er} is the transfer coefficient for latent heat
- k (= 0.40) is the von Kármán constant
- L is the Obukhov length, a stratification parameter
- ψ_m and ψ_h are known functions of the stratification,r/L

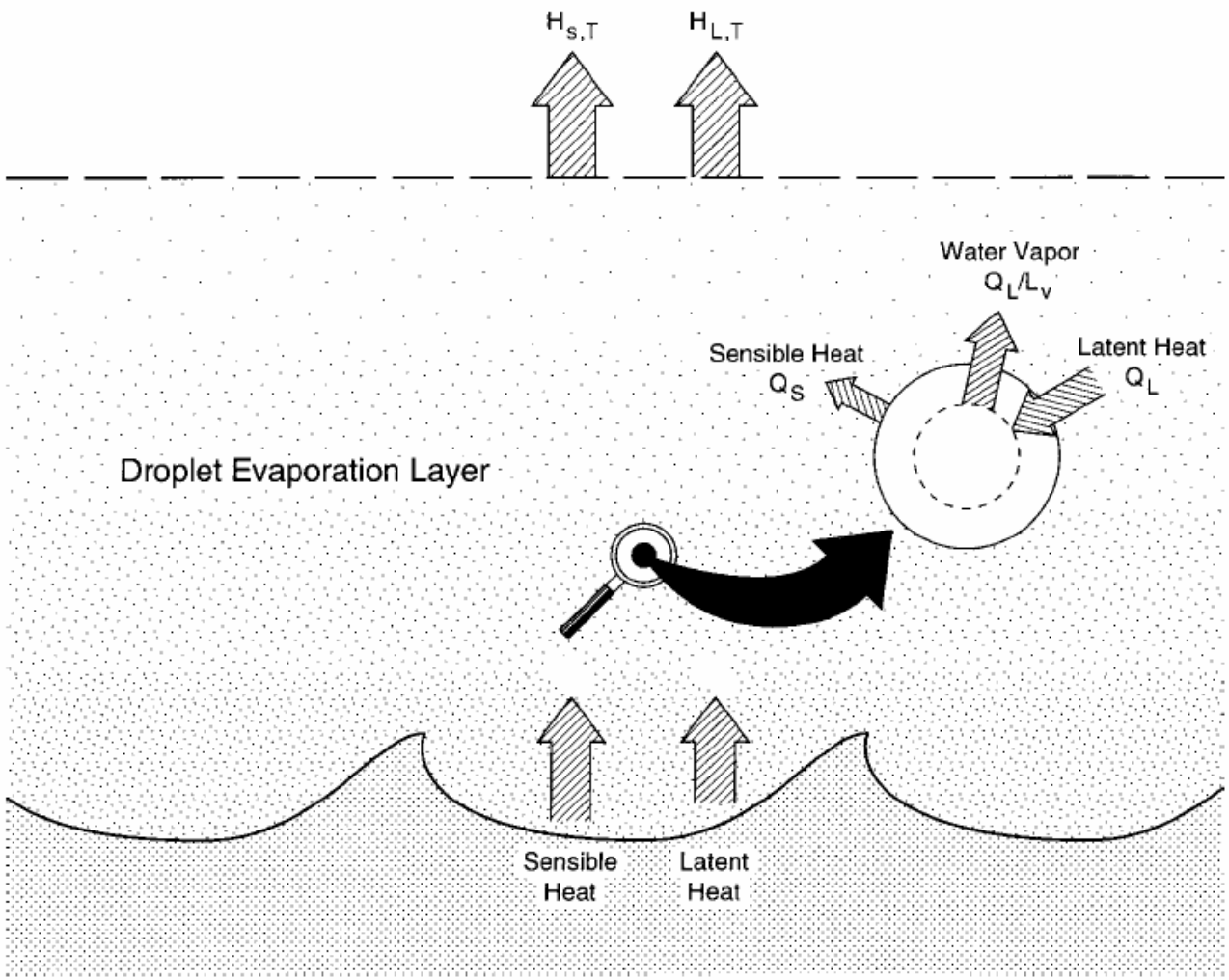


Figure 1. Our conceptual picture of processes in the droplet evaporation layer. The ocean exchanges sensible and latent heat through turbulent processes at its interface. The spray droplets also exchange water vapour and sensible and latent heat. The fluxes at the top of the DEL result from these several processes.

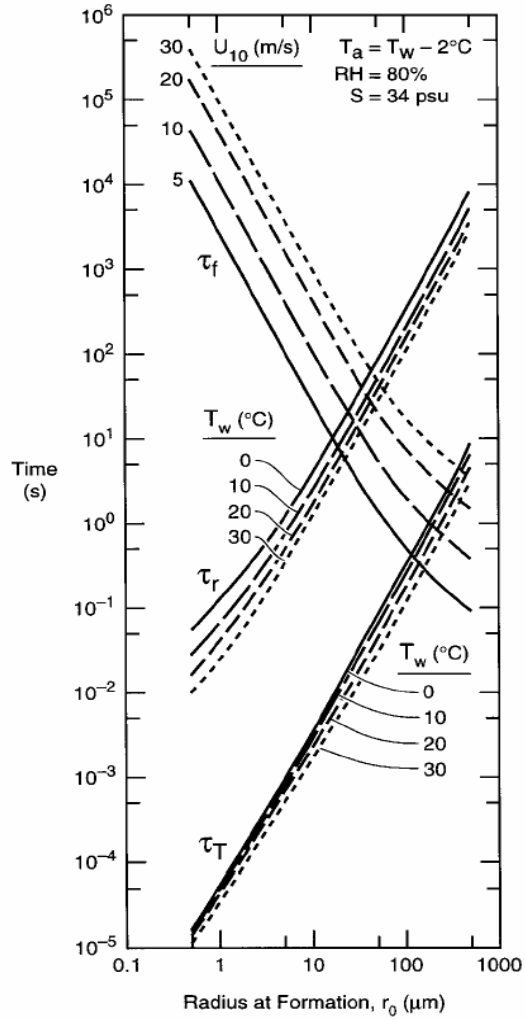


Figure 2. Spray droplet e-folding times for temperature (τ_T) and size (τ_r) evolution as a function of initial droplet radius (r_0) computed with Andreas's (1989) microphysical model. Surface water temperatures (T_w, also initial droplet temperature) are 0°, 10°, 20°, and 30 °C, as noted. For each case, the air temperature (T_a) is 2 °C less than the water temperature. τ_f is the time required for a droplet of radius r_0 to fall one significant wave amplitude (i.e., $A_{1/3}$) in still air. $A_{1/3}$ depends on the 10-m wind speed (U_{10}). The relative humidity (RH) is always 80%, the surface salinity (S) is 34 psu, and the barometric pressure is 1000 hPa.