

Modeling Turbulent Air-Sea Exchange in High Winds

Edgar L Andreas

U. S. Army Cold Regions Research and Engineering Laboratory

72 Lyme Road

Hanover, New Hampshire 03755-1290

phone: (603) 646-4436 fax: (603) 646-4644 email: eandreas@crrel.usace.army.mil

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<http://www.crrel.usace.army.mil/personnel/andreas.edgar.html>

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 existing data sets and CBLAST flux data as they become available from the hurricane experiments, 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 CRREL participant, aside from an occasional undergraduate student; 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

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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.					
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negligible. As spray concentration increases with increasing wind speed, however, the spray route 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.

My algorithm assumes that the total sensible heat ($H_{s,Tot}$), latent heat ($H_{L,Tot}$), and momentum (τ_{Tot}) 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 , $\tau_{int}(0)$] and spray [i.e., $Q_{S,sp}$, $Q_{L,sp}$, $\tau_{sp}(0)$] contributions:

$$H_{s,Tot} = H_s + Q_{S,sp} , \quad (1a)$$

$$H_{L,Tot} = H_L + Q_{L,sp} , \quad (1b)$$

$$\tau_{Tot} = \tau_{int}(0) + \tau_{sp}(0) . \quad (1c)$$

In (1c), the zeros remind us that the total momentum flux imposed by the large-scale atmospheric pressure gradient comprises both interfacial and spray components right at the sea surface. 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 , H_L , and $\tau_{int}(0)$ in (1). I estimate $\tau_{sp}(0)$ in (1c) from a simple mechanistic model and knowledge of the rate at which sea spray is generated (Andreas 2004a). Finally, a full microphysical model that I have developed (Andreas 1989) can estimate $Q_{S,sp}$ and $Q_{L,sp}$, 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 flux algorithm predicts $Q_{S,sp}$ and $Q_{L,sp}$ from

$$Q_{S,sp} = \rho_w c_w (T_s - T_{eq,100}) V_S(u_*) , \quad (2a)$$

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

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 .

Furthermore, in (2b), r is the radius, as a function of time (t), of a droplet that started with a radius of $50 \mu\text{m}$. In general, for any spray droplet,

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

where 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 $50 \mu\text{m}$. Thus, in essence, I approximate $Q_{L,\text{sp}}$ from the behavior of $50\text{-}\mu\text{m}$ droplets. Likewise, (2a) estimates $Q_{S,\text{sp}}$ from the behavior of $100\text{-}\mu\text{m}$ droplets.

Finally, in (2), $V_S(u_*)$ and $V_L(u_*)$ are empirical functions of the friction velocity, $u_* = (\tau_{\text{Tot}}/\rho_a)^{1/2}$, where ρ_a is the air density. I showed these function in my last annual report (also Andreas 2004b).

WORK COMPLETED

Equations (2) and (3) contain three microphysical quantities: T_{eq} , r_{eq} , and τ_r . For completeness, I also must mention that a spray droplet's temperature evolution can be characterized by a fourth micrometeorological quantity, τ_T , the e-folding time for the droplet to cool from T_s to T_{eq} (e.g., Andreas 1990). That is, a very good approximation for a spray droplet's temperature evolution is

$$\frac{T(t) - T_{\text{eq}}}{T_s - T_{\text{eq}}} = \exp(-t/\tau_T) . \quad (4)$$

My full microphysical model (Andreas 1989) computes all four of these quantities by numerically tracking the evolution of a spray droplet. But again, such tedious computing is too time-consuming to make (2) viable in large-scale modeling. Hence, during this past year, I developed approximation formulas and wrote FORTRAN code to compute T_{eq} , r_{eq} , τ_T , and τ_r for a wide range of droplet sizes and marine conditions (Andreas 2005).

Equation (2b) includes another time scale, τ_f , a spray droplet's atmospheric residence time. I estimate this as (Andreas 1992)

$$\tau_f(r_0) = \frac{H_{1/3}}{2u_f(r_0)} , \quad (5)$$

where $H_{1/3}$ is the significant wave height, and $u_f(r_0)$ is the terminal fall speed of a droplet with initial radius r_0 . [Hence, in (2.6), $\tau_{f,50}$ is evaluated from (5) for $r_0 = 50 \mu\text{m}$.] The relation I have been using to predict $H_{1/3}$, however, seems to give unusually high waves; τ_f is, therefore, too long; and the latent heat flux computed from (3) and (2b) is, in turn, too big. This year, with the help of a Dartmouth undergraduate student, I therefore completed the analysis of 18 years of wave data from NOAA ocean buoys and, thereby, developed a new parameterization for $H_{1/3}$ (Andreas and Wang 2006).

Lastly, this year, Perrie et al. (2005) published simulations of several midlatitude Atlantic storms that incorporated my spray flux algorithm. Our sensitivity studies suggest, in general, that accounting for spray heat transfer produces better simulations of maximum storm winds and minimum central pressure than simulations that include only the usual interfacial heat fluxes.

RESULTS

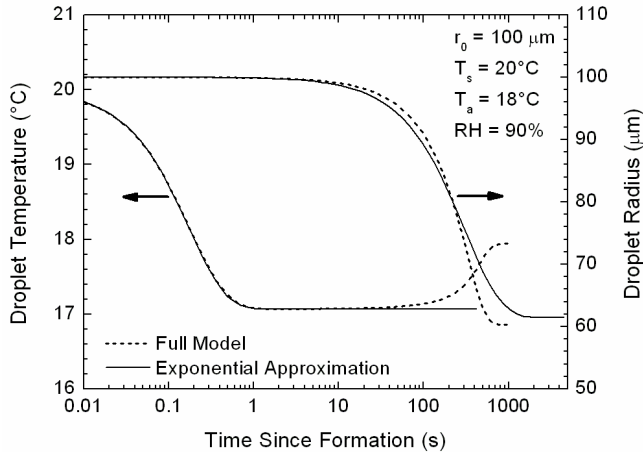


Figure 1. Temperature and radius evolution of a sea spray droplet (initial salinity 34 psu) that started with a radius of 100 μm and a temperature of 20°C. The droplet is ejected into air with a temperature of 18°C and a relative humidity of 90%. The dashed lines show the results from my full microphysical model; the solid lines represent the exponential approximations (3) and (4), which also rely on my approximation formulas for T_{eq} , τ_T , r_{eq} , and τ_r . The temperature curves are basically inseparable out to 20 seconds, while the exponential approximation predicts a slightly slower radius evolution than the full model.

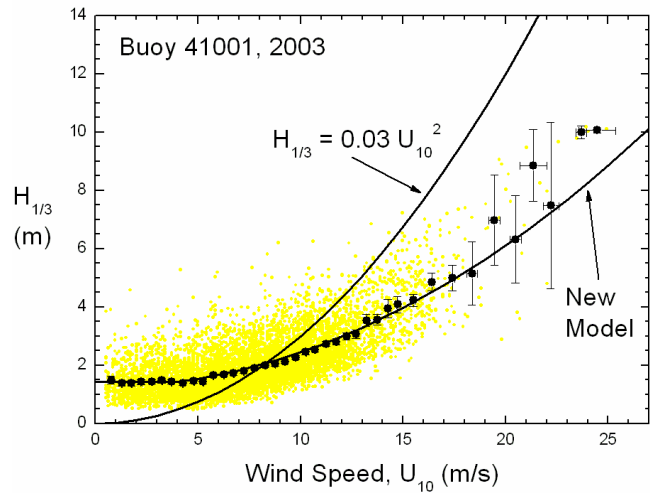


Figure 2. Significant wave height versus 10-m wind speed from a year (2003) of hourly data from NOAA buoy 41001, which was in 4427 m of water 150 nautical miles east of Cape Hatteras. The yellow symbols are the hourly data. The black circles are averages for wind speed bins that are 0.5 m/s wide; the error bars are ± 2 standard deviations in the bin means. The curves show our new model, (7), and the traditional wave height relation, (6). The traditional prediction for $H_{1/3}$ clearly gives waves that are much too high for wind speeds above 10 m/s.

The approximation formulas that I developed for predicting T_{eq} , r_{eq} , τ_T , and τ_r work well. With these, T_{eq} can be quickly estimated to within 0.02°C, r_{eq} and τ_T can be estimated to within about 5%, and τ_r can be estimated to within about 10% for typical oceanic conditions. Figure 1 supports this statement by showing computations for the evolution of a 100- μm droplet based on my full microphysical model and on the exponential approximations (3) and (4), with my new formulas for finding T_{eq} , r_{eq} , τ_T , and τ_r .

The results of our analysis of the wave data from the NOAA ocean buoys were surprising. My spray flux algorithm currently uses a typical equilibrium wave model to estimate $H_{1/3}$ in (5) (e.g., Earle 1979; Andreas 1992; Taylor and Yelland 2001):

$$H_{1/3} = 0.030 U_{10}^2 , \quad (6)$$

which gives $H_{1/3}$ in meters for the wind measured at 10 m, U_{10} , in m/s. Figure 2, however, shows that this relation does poorly in representing a year of hourly data from one of the buoys we studied.

Figure 2 is typical of 18 years of data that we analyzed from 12 different buoys off the northeast coast of the U.S. in waters with depths ranging from 18.9 to 4427 m. Each buoy record exhibits a range where the average wave height is constant for 10-m winds up to 4 m/s. Above this range, $H_{1/3}$ increases as U_{10}^2 , but not nearly as rapidly as (6) suggests.

From this analysis, we have developed a scheme to predict $H_{1/3}$ for all water depths; it takes the general form

$$H_{1/3} = C(D) \quad \text{for } 0 \leq U_{10} \leq 4 \text{ m/s} , \quad (7a)$$

$$H_{1/3} = a(D) + b(D) U_{10}^2 \quad \text{for } 4 \text{ m/s} \leq U_{10} . \quad (7b)$$

Here, $H_{1/3}$ is again in meters when U_{10} is in m/s; and C , a , and b are empirical functions of the water depth (D) only. The curve labeled “New Model” in Figure 2 is based on (7). For the 18 years of data that we have analyzed, (7) predicts the measured hourly wave height at each buoy with a correlation coefficient that is typically 0.7 or better.

IMPACT/APPLICATIONS

The unified turbulent flux algorithm that I have developed—represented formally as (1)–(3)—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 against data (Andreas 2003, 2004b); 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.

Developing such a high-wind air-sea flux algorithm is one of the central objectives of CBLAST. But we still need to see if such an algorithm improves predictions of ocean storms. 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 of 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).

Although I developed approximation formulas for the microphysical quantities T_{eq} , r_{eq} , τ_T , and τ_r specifically for use in my air-sea flux algorithm, the need for such microphysical quantities arises in many other applications. For instance, marine aerosols continually evolve, and these formulas can quickly predict the rates of these changes. Although my formulas currently treat only saline droplets, the microphysical theory on which they are based applies to all aqueous solution droplets. Consequently, with minor changes to account for the chemical properties of the solute, my formulas could be adapted for cloud droplets that have formed on a variety of cloud condensation nuclei—not just on sea-salt particles.

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 an electronic “kit” that contains the instructions and FORTRAN tools necessary to implement version 2.0 of this algorithm. I have distributed this kit to several CBLAST collaborators—namely, Bill Frank at Penn State and Shouping Wang at NRL-Monterey—and to several others.

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 doing simulations of Atlantic storms with it. This work is already documented in several papers (Li et al. 2003; Perrie et al. 2004a, 2004b, 2005).

RELATED PROJECTS

I have no other support for this type of work.

REFERENCES

Andreas, E. L., 1989: Thermal and size evolution of sea spray droplets. *CRREL Report 89-11*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 37 p.

Andreas, E. L., 1990: Time constants for the evolution of sea spray droplets. *Tellus*, **42B**, 481–497.

Andreas, E. L., 1992: Sea spray and the turbulent air-sea heat fluxes. *J. Geophys. Res.*, **97**, 11,429–11,441.

Andreas, E. L., 2003: An algorithm to predict the turbulent air-sea fluxes in high-wind, spray conditions. Preprints, 12th Conference on Interactions of the Sea and Atmosphere, Long Beach, CA, 9–13 February 2003, American Meteorological Society, CD-ROM 3.4, 7 pp.

Andreas, E. L., 2004a: Spray stress revisited. *J. Phys. Oceanogr.*, **34**, 1429–1440.

Andreas, E. L., 2004b: 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.

- Andreas, E. L., 2005: Approximation formulas for the microphysical properties of saline droplets. *Atmos. Res.*, **75**, 323–345.
- Andreas, E. L., and J. DeCosmo, 2002: The signature of sea spray in the HEXOS turbulent heat flux data. *Bound.-Layer Meteor.*, **103**, 303–333.
- Andreas, E. L., and S. Wang, 2006: Predicting significant wave height off the northeast coast of the United States. Preprints, 14th Conference on Interactions of the Sea and Atmosphere, Atlanta, GA, 29 January–2 February 2005, American Meteorological Society, CD-ROM P4.1, to appear.
- Earle, M. D., 1979: Practical determinations of design wave conditions. *Ocean Wave Climate*, M. D. Earle and A. Malahoff, Eds., Plenum Press, New York, 39–60.
- Emanuel, K. A., 2003: A similarity hypothesis for air-sea exchange at extreme wind speeds. *J. Atmos. Sci.*, **60**, 1420–1428.
- Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson and G. S. Young, 1996: Bulk parameterization of air-sea fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment. *J. Geophys. Res.*, **101**, 3747–3764.
- Li, W., W. Perrie, E. L. Andreas, J. Gyakum, and R. McTaggart-Cowan, 2003: Impact of sea spray on numerical simulation of extratropical hurricanes. Preprints, 12th Conference on Interactions of the Sea and Atmosphere, Long Beach, CA, 9–13 February 2003, American Meteorological Society, CD-ROM 2.5, 9 pp.
- Perrie, W., X. Ren, W. Zhang, and Z. Long, 2004a: Simulation of extratropical Hurricane Gustav using a coupled atmosphere-ocean-sea spray model. *Geophys. Res. Lett.*, **31**, L03110, DOI: 10.1029/2003GL018571.
- Perrie, W., W. Zhang, X. Ren, Z. Long, E. L. Andreas, J. Gyakum, and R. McTaggart-Cowan, 2004b: The role of waves, sea spray and the upper ocean in midlatitude storm development. Preprints, 26th Conference on Hurricanes and Tropical Meteorology, Miami, FL, 3–7 May 2004, American Meteorological Society, CD-ROM 16D.7, 2 pp.
- Perrie, W., E. L. Andreas, W. Zhang, W. Li, J. Gyakum, and R. McTaggart-Cowan, 2005: Sea spray impacts on intensifying midlatitude cyclones. *J. Atmos. Sci.*, **62**, 1867–1883.
- Taylor, P. K., and M. J. Yelland, 2001: The dependence of sea surface roughness on the height and steepness of waves. *J. Phys. Oceanogr.*, **31**, 572–590.

PUBLICATIONS

Andreas, E. L., 2005: Approximation formulas for the microphysical properties of saline droplets. *Atmospheric Research*, **75**, 323–345. [published, refereed]

Andreas, E. L., 2005: Handbook of physical constants and functions for use in atmospheric boundary layer studies. *ERDC/CRREL Monograph*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH. [in press]

Perrie, W., E. L. Andreas, W. Zhang, W. Li, J. Gyakum, and R. McTaggart-Cowan, 2005: Sea spray impacts on intensifying midlatitude cyclones. *Journal of the Atmospheric Sciences*, **62**, 1867–1883. [published, refereed]