The Impact of Sea Spray on Air-Sea Fluxes in Coupled Atmosphere-Ocean Models

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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 hope to develop simple, physics-based parameterizations for these air-sea fluxes for use in large-scale models, especially those simulating tropical and extratropical storms.

OBJECTIVES

The ultimate goal of this work is to understand the physics and, thus, how to parameterize the air-sea fluxes of momentum and sensible and latent heat at all wind speeds. Since the COARE bulk flux algorithm (Fairall et al., 1996) is successful at winds speeds of 10 m/s or less, I focus on higher wind speeds, where sea spray is present and is a likely transfer agent. My first objective is to learn how to partition the air-sea fluxes between interfacial and spray contributions. Because the sum of the sensible and latent heat fluxes via all routes—the total enthalpy flux—provides the energy for tropical storms, the second objective is to develop a parameterization for the air-sea heat fluxes that includes spray effects and is suitable for large-scale, coupled air-sea interaction models. The third objective focuses on air-sea momentum exchange in high winds and on how spray and other surface disruptions alter this exchange.

APPROACH

This work is theoretical and analytical; it has no experimental component. Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theory also predicts how the sea spray generation function should depend on wind speed. The analytical part involves developing parameterizations for the various processes under consideration 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.

Theory and microphysical modeling suggest that we can estimate the total (i.e., both interfacial and spray) air-sea latent ($H_{L,T}$) and sensible ($H_{s,T}$) heat fluxes as (e.g., Andreas and DeCosmo, 1999, 2002)

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

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14. ABSTRACT
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15. SUBJECT TERMS

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$$H_{s,T} = H_s + \beta\overline{Q}_S - (\alpha - \gamma)\overline{Q}_L \ . \qquad (2)$$

Here, H_L and H_s are interfacial fluxes estimated with the COARE algorithm (Fairall et al., 1996), and $\overline{Q}_L$ and $\overline{Q}_S$ are spray latent and sensible heat fluxes predicted by Andreas's (1992) microphysical model. α, β, and γ are small, nonnegative coefficients obtained by tuning (1) and (2) with data. I have been using my microphysical model and measurements of $H_{L,T}$ and $H_{s,T}$ from HEXOS (Humidity Exchange over the Sea experiment; DeCosmo, 1991) to evaluate α, β, and γ.

WORK COMPLETED

I published two significant papers this fiscal year. The first (Andreas, 2002) is a review of spray production and the sea spray generation function in which, I think, I finally bring some consensus to this field. The spray generation function quantifies the rate at which the sea surface produces spray droplets of initial radius r_0 as a function, for example, of wind speed. We can find, perhaps, two dozen formulations for this important function in the literature. But because these typically span six orders of magnitude for any given radius and wind speed, they cannot all be correct. Using theory and indirect evidence, I identified which functions were plausible and which were obviously wrong. The functions that survived this scrutiny now span less than an order of magnitude at any given droplet radius and wind speed. Two of the surviving functions are applicable even in winds up to 30 m/s. I settle on the function from Fairall et al. (1994) as the best current choice.

In the second significant paper, Andreas and DeCosmo (2002) used (1) and (2) to partition DeCosmo's (1991) HEXOS flux data into contributions from interfacial and spray transfer. That is, we evaluated α, β, and γ in (1) and (2). In effect, this partitioning identified a signature of sea spray in the HEXOS data that had gone undetected (e.g., DeCosmo et al., 1996; Smith et al., 1996; Makin, 1998). On the basis of our analysis, we believe that, for 10-meter winds above 12 m/s, almost all the HEXOS measurements of latent and sensible heat flux contain a 10% spray effect. In other words, the α, β, and γ terms in (1) and (2) sum to at least 10% of the corresponding interfacial terms, H_L and H_s, for winds above 12 m/s.

The obvious conclusion is that spray fluxes must be important in high winds. The microphysical model we used to compute $\overline{Q}_L$ and $\overline{Q}_S$ in (1) and (2), however, is too computationally intensive for routine use in large-scale models. I have, therefore, been developing a bulk flux parameterization for the spray terms in (1) and (2). In this, I write the total fluxes in (1) and (2) as

$$H_{L,T} = H_L + Q_{L,sp} \ , \qquad (3)$$

$$H_{s,T} = H_s + Q_{S,sp} \ , \qquad (4)$$

where the interfacial terms H_L and H_s would come from the COARE algorithm, for example, and the spray terms $Q_{L.sp}$ and $Q_{S,sp}$ would come from this new bulk spray flux algorithm.

Computations with Andreas's (1992) microphysical model suggest that spray droplets with radii near 100 μm carry most of the spray sensible heat, while droplets with radii near 50 μm carry most of the spray latent heat (e.g., Andreas, 1992; Andreas et al., 1995; Andreas and DeCosmo, 1999). I therefore hypothesize that these droplets are the bellwethers of the spray heat transfer and, thus, parameterize the spray fluxes as

$$Q_{L,sp} = \rho_w L_v \left[1 - \left(\frac{r_{eq,50}}{50\,\mu m}\right)^3\right] V_L(u_*), \qquad (5)$$

$$Q_{S,sp} = \rho_w c_w \left(T_s - T_{eq,100}\right) V_S(u_*) \; . \qquad (6)$$

Here, ρ_w is the density of seawater; c_w, its specific heat; L_v, the latent heat of vaporization; T_s, the sea-surface temperature; $r_{eq,50}$, the equilibrium radius (in micrometers) of droplets that started with a radius of 50 μm; and $T_{eq,100}$, the equilibrium temperature of droplets that started at 100 μm. The V_L and V_S terms are functions of the friction velocity u_* and, in essence, tune (5) and (6) to data. Andreas and Emanuel (2001) laid some of the groundwork for this bulk spray flux model.

RESULTS

In most of my microphysical modeling, I used the spray generation function from Andreas (1992). My review of spray generation, however, demonstrates that the Andreas (1992) and Fairall et al. (1994) functions are similar [mainly because the Fairall et al. (1994) function derives from the Andreas (1992) function]. The Fairall et al. function, however, seems to have a better dependence on wind speed and, thus, is reliable for 10-meter winds up to 25 m/s. I therefore began using it instead in my modeling.

With the Fairall et al. (1994) function, I redid Andreas and DeCosmo's (2002) analysis of the HEXOS data. Although the resulting α, β, and γ values in (1) and (2) are now somewhat smaller, my conclusions are the same: Most of the HEXOS heat flux data show at least a 10% spray effect for winds above 12 m/s.

I used these new α, β, and γ values to evaluate the V_L and V_S functions in (5) and (6). The results are

$$V_L = 4.75\times10^{-8}\, u_*^3 \; , \qquad (7)$$

$$V_S = 1.65\times10^{-6}\, u_*^3 \; . \qquad (8)$$

In these, V_L and V_S have units of m/s when u_* has units of m/s. The resulting fluxes in (5) and (6) then have units of W/m^2. Andreas (2003) reports the full details of this new bulk flux algorithm, which also includes a parameterization for spray contributions to the surface stress.

Figures 1 and 2 show this new flux algorithm tested against the HEXOS heat flux data. Each figure shows HEXOS measurements of either the total latent or sensible heat flux divided by the algorithm's prediction of this total flux based on equations (3)–(8). In each figure, the average of these ratios is near 1, and the data markers show no trend with the 10-meter wind speed, U_{10}. In other words, the new algorithm accurately predicts both the magnitude and the wind speed dependence of the HEXOS heat flux data. Neither the COARE algorithm (Fairall et al., 1996) nor another popular algorithm from Zeng et al. (1998) is as accurate in predicting the HEXOS fluxes (Andreas and DeCosmo, 2002).

The filled circles in the two figures show cases when the spray terms in (3) and (4) are at least 10% of the corresponding interfacial terms. As in Andreas and DeCosmo's (1999, 2002) analyses that were based on the full microphysical model, almost all the points for U_{10} values above 12 m/s in both figures are filled. Since the spray fluxes increase as roughly the cube of the wind speed [i.e., see (7) and (8)] while the interfacial fluxes go only linearly with the wind (e.g., Fairall et al., 1996; Andreas and DeCosmo, 2002), the spray fluxes will eventually dominate the interfacial fluxes.

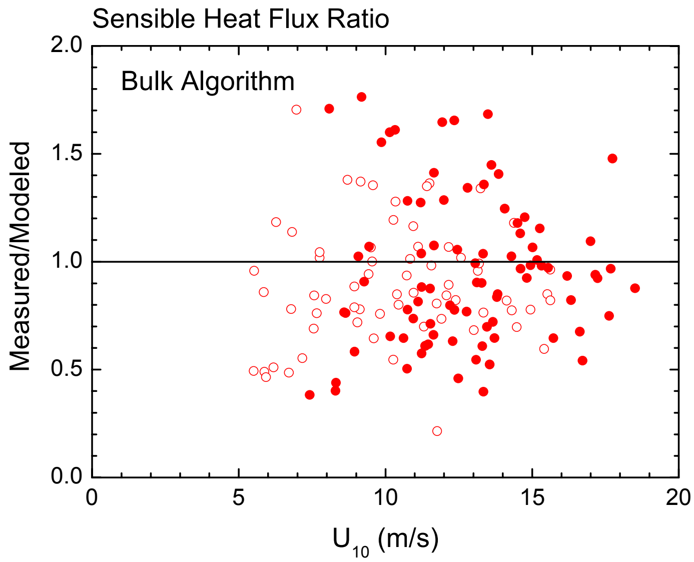

Figure 1. The ratio of HEXOS measurements of sensible heat flux to the corresponding flux modeled with the bulk algorithm. Filled circles denote cases when the modeled spray flux ($Q_{S,sp}$) is at least 10% of the modeled interfacial flux (H_s). The average of the ratios plotted in this figure is 0.945, and their correlation coefficient with wind speed is 0.035.

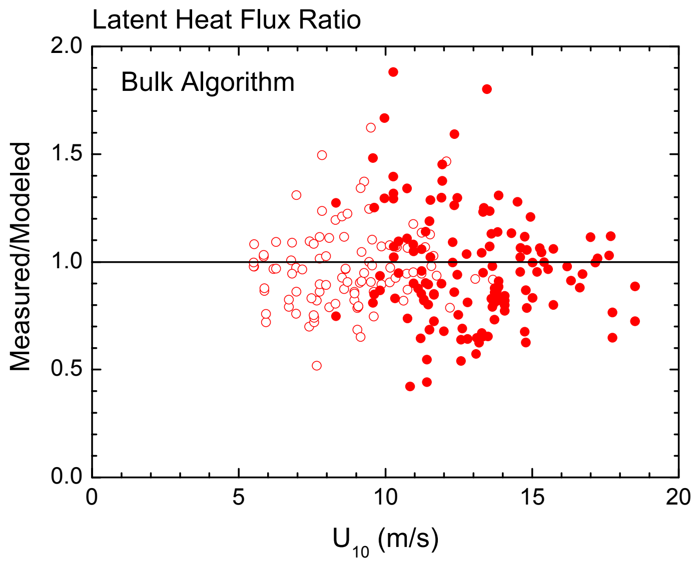

Figure 2. As in Fig. 1 except this shows the latent heat flux ratio. Filled circles denote cases when the modeled spray flux ($Q_{L,sp}$) is at least 10% of the modeled interfacial flux (H_L). The average of the ratios in this figure is 1.010, and their correlation coefficient with wind speed is 0.066.

IMPACT/APPLICATIONS

The role of sea spray in mediating the air-sea fluxes in high winds is a central theme in ONR's Coupled Boundary Layers and Air-Sea Transfer (CBLAST) initiative. Perhaps parochially, I believe this focus is in part due to my research on sea spray over the last decade. I have identified the spray generation function as a crucial unknown and, in particular, have shown that we must understand the production of spume, the largest spray droplets, to improve the spray generation function. My modeling has also shown the potential magnitude and the wind speed dependence of the spray effects.

My reanalysis of the HEXOS data with Janice DeCosmo identified what the signature of spray-mediated heat fluxes looks like for winds up to almost 20 m/s. That is, in winds nominally above 12 m/s, the usual bulk flux algorithms, such as the COARE algorithm (Fairall et al., 1996), tend to underpredict both the surface sensible and latent heat fluxes because they do not account for spray's ability to transfer heat and moisture.

On the basis of this HEXOS analysis, Kerry Emanuel and I developed parameterizations for the spray-mediated enthalpy and momentum fluxes and tested these in Emanuel's simple tropical cyclone model. These parameterizations are the basis for the new bulk spray flux algorithm that I have developed. This is ready for use in other large-scale, coupled models being developed under CBLAST.

TRANSITIONS

Besides the papers I have written to describe my spray research, other, more direct transitions of this research are through my collaborations with Kerry Emanuel at MIT and Will Perrie at Bedford Institute of Oceanography, Halifax, Nova Scotia. We have been developing and testing spray parameterizations in large-scale models (e.g., Andreas and Emanuel, 2001; Li et al., 2003).

RELATED PROJECTS

The Division of Atmospheric Sciences at the National Science Foundation is funding me for three-years to study "Air-Sea Fluxes at High Wind Speeds with Application to Tropical Cyclone Intensity Prediction." I am collaborating in this work with Wade McGillis and Jim Edson of WHOI, Tetsu Hara and Isaac Ginis of the University of Rhode Island, and Kerry Emanuel of MIT. I also have leveraged my ONR funding by collaborating on spray research with scientists outside CRREL who are funded by projects at their own institutions, for example, Janice DeCosmo at the University of Washington.

The original proposal to ONR that led to my funding here included Will Perrie and Charles Tang at Bedford Institute as collaborators. ONR decided to fund only me under that proposal, however. Perrie and I, nevertheless, followed through with those plans to collaborate. I have, thus, provided him the FORTRAN code for my bulk spray flux algorithm, and he and colleagues have implemented it in the Canadian Mesoscale Compressible Community atmospheric model. They are currently investigating spray effects on extratropical storms with this model.

I was a member of the Ph.D. thesis advisory committee for Magdalena Anguelova at the College of Marine Studies at the University of Delaware. She was working on topics related to my own interests: spray and sea-salt. In June, she defended her thesis, "Whitecaps, Sea-Salt Aerosols, and Climate."

REFERENCES

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

Andreas, E. L, 2002: A review of the sea spray generation function for the open ocean. *Atmosphere-Ocean Interactions*, Vol. 1, W. Perrie, Ed., WIT Press, Southampton, UK, 1–46.

Andreas, E. L, 2003: An algorithm to predict the turbulent air-sea fluxes in high-wind, spray conditions. Preprint volume, 12th Conf. on Interaction of the Sea and Atmosphere, Long Beach, CA, 9-13 February 2003, Amer. Meteor. Soc., Boston, to appear.

Andreas, E. L, and J. DeCosmo, 1999: Sea spray production and influence on air-sea heat and moisture fluxes over the open ocean. *Air-Sea Exchange: Physics, Chemistry and Dynamics*, G. L. Geernaert, Ed., Kluwer, Dordrecht, 327–362.

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 K. A. Emanuel, 2001: Effects of sea spray on tropical cyclone intensity. *J. Atmos. Sci.*, 3741–3751.

Andreas, E. L, J. B. Edson, E. C. Monahan, M. P. Rouault, and S. D. Smith, 1995: The spray contribution to net evaporation from the sea: A review of recent progress. *Bound.-Layer Meteor.*, **72**, 3–52.

DeCosmo, J., 1991: Air-sea exchange of momentum, heat and water vapor over whitecap sea states. Ph.D. dissertation, University of Washington, Seattle, 212 pp. [Available from UMI Dissertation Services, P. O. Box 1346, Ann Arbor, MI 48106–1346.]

DeCosmo, J., K. B. Katsaros, S. D. Smith, R. J. Anderson, W. A. Oost, K. Bumke, and H. Chadwick, 1996: Air-sea exchange of water vapor and sensible heat: The Humidity Exchange over the Sea (HEXOS) results. *J. Geophys. Res.*, **101**, 12,001–12,016.

Fairall, C. W., J. D. Kepert, and G. J. Holland, 1994: The effect of sea spray on surface energy transports over the ocean. *Global Atmos. Ocean Sys.*, **2**, 121–142.

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 hurricane. Preprint volume, 12th Conf. on Interaction of the Sea and Atmosphere, Long Beach, CA, 9-13 February 2003, Amer. Meteor. Soc., Boston, to appear.

Makin, V. K., 1998: Air-sea exchange of heat in the presence of wind waves and spray. *J. Geophys. Res.*, **103**, 1137–1152.

Smith, S. D., K. B. Katsaros, W. A. Oost, and P. G. Mestayer, 1996: The impact of the HEXOS programme. *Bound.-Layer Meteor.*, **78**, 121–141.

Zeng, X., M. Zhao, and R. E. Dickinson, 1998: Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using TOGA COARE and TAO data. *J. Climate*, **11**, 2628–2644.

PUBLICATIONS

Andreas, E. L, 2002: A review of the sea spray generation function for the open ocean. *Atmosphere-Ocean Interactions,* Volume 1, W. Perrie, Ed., WIT Press, Southampton, UK, 1-46.

Andreas, E. L, 2002: Book review: *Wind Stress over the Ocean*. *Atmospheric Research*, **62**, 171-173.

Andreas, E. L, 2003: An algorithm to predict the turbulent air-sea fluxes in high-wind, spray conditions. Preprint volume, 12th Conference on Interaction of the Sea and Atmosphere, Long Beach, CA, 9-13 February 2003, American Meteorological Society, Boston, to appear.

Andreas, E. L, and J. DeCosmo, 2002: The signature of sea spray in the HEXOS turbulent heat flux data. *Boundary-Layer Meteorology*, **103**, 303-333.

Andreas, E. L, and K. A. Emanuel, 2001: Effects of sea spray on tropical cyclone intensity. *Journal of the Atmospheric Sciences*, **58**, 3741-3751.

Li, W., W. Perrie, E. L Andreas, J. Gyakum, and R. McTaggart-Cowan, 2003: Impact of sea spray on numerical simulation of extratropical hurricane. Preprint volume, 12th Conference on Interaction of the Sea and Atmosphere, Long Beach, CA, 9-13 February 2003, American Meteorological Society, Boston, to appear.