Turbulent Air-Sea Exchange in Extreme Winds and Its Effects on Storm Structure

Edgar L Andreas
NorthWest Research Associates, Inc. (Seattle Division)
25 Eagle Ridge
Lebanon, New Hampshire 03766-1900
phone: (603) 448-3555 email: eandreas@nwra.com

Contract Number: N000140810411
http://www.nwra.com/resumes/andreas/

LONG-TERM GOALS

The goal is to investigate, theoretically and through analyzing existing data, sea surface physics and air-sea exchange in extreme winds. The underlying motivations are improving predictions of tropical cyclone intensity and structure and developing guidelines for planning an eventual field experiment to observe the air-sea drag and enthalpy exchange in high winds. Ultimately, these goals require developing physics-based parameterizations and theoretical constraints for turbulent air-sea fluxes in extreme winds. One focus will be on the role that sea spray plays in transferring heat, moisture, momentum, enthalpy, and salt across the air-sea interface in high winds.

OBJECTIVES

1. Continue analyzing data sets collected in high winds (e.g., HEXOS, FASTEX, CBLAST) to deduce surface fluxes and develop parameterizations for the air-sea fluxes of enthalpy and momentum that begin to probe the behavior of the sea surface in hurricane-strength winds.
2. Undertake theoretical work to identify processes near the air-sea interface in extreme winds that affect the air-sea exchange of enthalpy, momentum, and other constituents. Develop physical constraints for these processes and tentative parameterizations for them.
3. Publicize the role that sea spray plays in high winds and the consequent need to explicitly parameterize its effect in models.

APPROACH

This work is theoretical and analytical; it has no experimental component. Andreas is the only NWRA participant. He has been collaborating in some of this work, however, with Kathleen F. Jones (CRREL), Christopher W. Fairall (NOAA/ESRL), and others, who have their own funding.

The main emphasis of this work is on how sea spray mediates the air-sea fluxes. Microphysical theory establishes how rapidly spray droplets exchange heat and moisture in a given environment. Theory also predicts how sea spray production depends on wind speed and how spray droplets are distributed

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Turbulent Air-Sea Exchange in Extreme Winds and Its Effects on Storm Structure**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NorthWest Research Associates, Inc. (Seattle Division),25 Eagle Ridge,Lebanon,NH,03766-1900**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

in the near-surface air. The analytical part involves developing parameterizations for spray transfer processes by simplifying model results or by synthesizing datasets and observations. Checking the parameterizations against available data is also another aspect of what I call analytical work.

In my recently published bulk flux algorithm for high-wind, spray conditions (Andreas et al. 2008; Andreas 2010a), I modeled the total air-sea fluxes of latent heat ($H_{L,T}$), sensible heat ($H_{s,T}$), and enthalpy ($Q_{en,T}$) as follows:

$$H_{L,T} = H_L + Q_{L,sp} \ , \tag{1a}$$

$$H_{s,T} = H_s + Q_{S,sp} \ , \tag{1b}$$

$$Q_{en,T} \equiv H_{L,T} + H_{s,T} = H_L + H_s + Q_{en,sp} \ . \tag{1c}$$

Here, H_L and H_s are the interfacial fluxes of latent and sensible heat, which I compute with the COARE Version (2.6) bulk interfacial flux algorithm (Fairall et al. 1996). The $Q_{L,sp}$, $Q_{S,sp}$, and $Q_{en,sp}$ are theoretically based spray contributions to the total fluxes; I tuned these with data from HEXOS (Humidity Exchange over the Sea) and FASTEX (Fronts and Atlantic Storm-Tracks Experiment) for wind speeds up to 20 m/s.

Much physics and math is hidden in equations (1). In particular, obtaining $Q_{L,sp}$, $Q_{S,sp}$, and $Q_{en,sp}$ requires a good estimate of the so-called sea spray generation function, dF/dr_0 (e.g., Monahan et al. 1986). This function predicts the number of spray droplets of initial radius r_0 that is produced per square meter of sea surface, per second, per micrometer increment in droplet radius. I have thus spent a lot of time trying to improve estimates of this function (Andreas 1992, 1998, 2002), including work this year (Andreas et al. 2010) that I will describe shortly.

WORK COMPLETED

Figure 1 shows the spray generation function that I have been using recently (e.g., Jones and Andreas 2009). An enduring assumption in this field is that dF/dr_0 can be related to the near-surface spray droplet concentration, $C_0(r_0)$ (units of number of droplets of radius r_0 per cubic meter, per micrometer increment in droplet radius), through a velocity scale:

$$dF/dr_0 = V_{eff}(r_0) C_0(r_0) \ . \tag{2}$$

Here, V_{eff} is the effective spray production velocity for droplets of initial radius r_0.

Traditionally, V_{eff} is taken as the dry deposition velocity at height h, V_{Dh}. To evaluate this practice and to see if other velocity scales are better, Andreas et al. (2010) tested (2) with several candidates for V_{eff}: the deposition velocity, V_{Dh}; the wind speed at the wave crests, $U_{A_{1/3}}$, where $A_{1/3}$ denotes the significant wave amplitude; the vertical turbulent droplet diffusion velocity, σ_{wd}; and the ejection velocity of jet droplets, V_{ej}, as measured in the laboratory by Blanchard (1963).

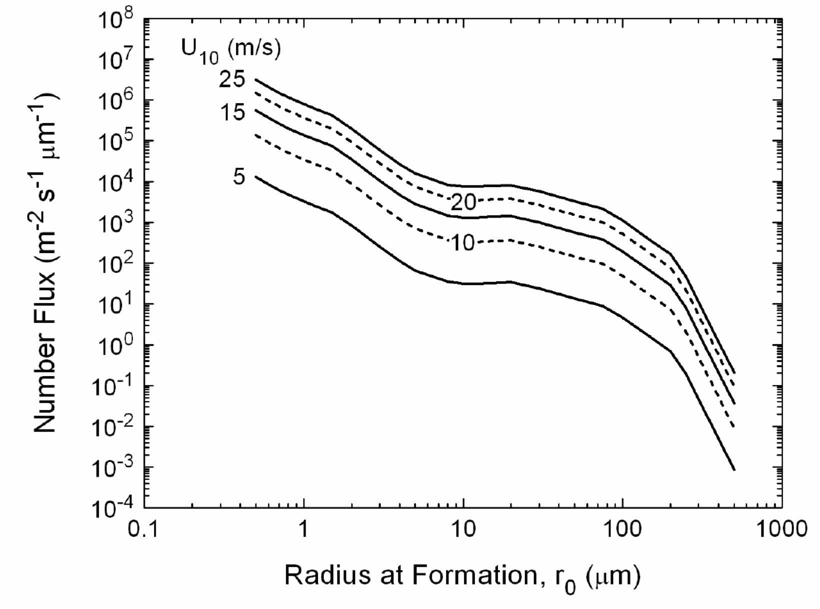

Fig. 1. The spray generation function dF/dr_0 in units of number of droplets produced with initial radius r_0 per square meter of sea surface, per second, per micrometer increment in droplet radius, as a function of r_0. This function merges the small-radius function from Monahan et al. (1986) with the large-radius function from Fairall et al. (1994) in the r_0 interval 1.5–2.0 μm. U_{10} is the wind speed at a reference height of 10 m. dF/dr_0 decreases with r_0 by six orders of magnitude for r_0 between 0.5 and 500 μm but increases as roughly the third power of wind speed at any given radius.

Andreas et al. (2010) give the full details of this analysis, but Figures 2 and 3 give the basic conclusions. After assembling 13 sets of $C_0(r_0)$ measurements from the literature and using the dF/dr_0 function shown in Figure 1, we estimated V_{eff} from (2) and compared it with our four candidate velocity scales. First, we concluded that (2) is not a good model for radii r_0 less than about 20 μm; these droplets are so small that they have atmospheric residence times too long for them to be in equilibrium with the local surface production—the fundamental assumption in (2).

Figure 2 also suggests that the deposition velocity is not a good candidate for V_{eff}: V_{Dh} underestimates our calculated V_{eff} by 1–2 orders of magnitude for all radii. The wind speed at the wave crests, $U_{A_{1/3}}$, however, is a good estimator for V_{eff} in (2). Figure 3 shows that, for droplets with $r_0 > 20$ μm, $U_{A_{1/3}}$ is within a factor of five of our calculated V_{eff} for all radii.

We also found that the turbulent droplet diffusion velocity, σ_{wd}, is too small to represent V_{eff}. The jet droplet ejection velocity, V_{ej}, is another good candidate for V_{eff} in our dataset; but we suspect that it is not as universal as $U_{A_{1/3}}$ because the production of spume droplets will ultimately be the dominant production mechanism as the wind speed increases.

Tropical cyclones exist through a delicate balance between enthalpy exchange across the sea surface and momentum loss at the sea surface to waves and currents (e.g., Emanuel 1995). In models, the enthalpy source is always parameterized as interfacial transfer: for example, as

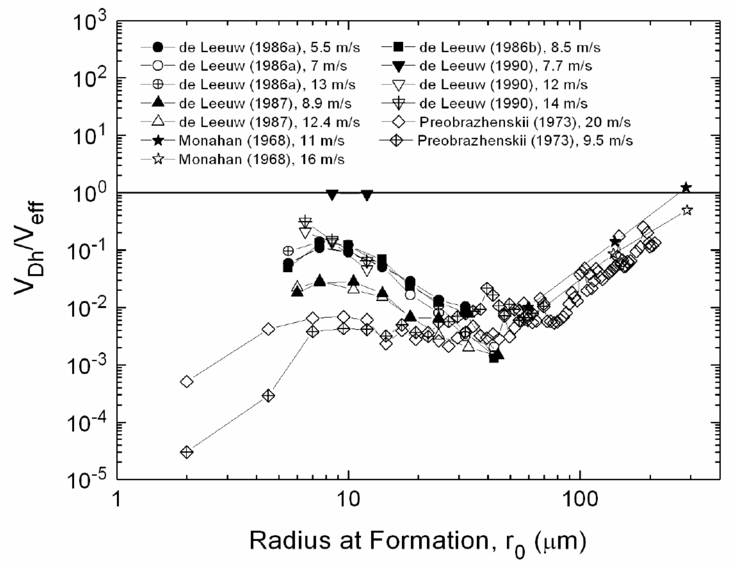

Fig. 2. The ratio of the modeled dry deposition velocity, V_{Dh}, to the effective spray production velocity, V_{eff}, calculated from (2) using the dF/dr_0 function shown in Figure 1 and 13 sets of near-surface droplet concentration measurements from the literature. If V_{Dh} were a good estimate of V_{eff}, the ratio V_{Dh}/V_{eff} would be near 1. But V_{Dh}/V_{eff} is typically 0.01–0.1 for all radii r_0 between 0.5 and 300 μm.

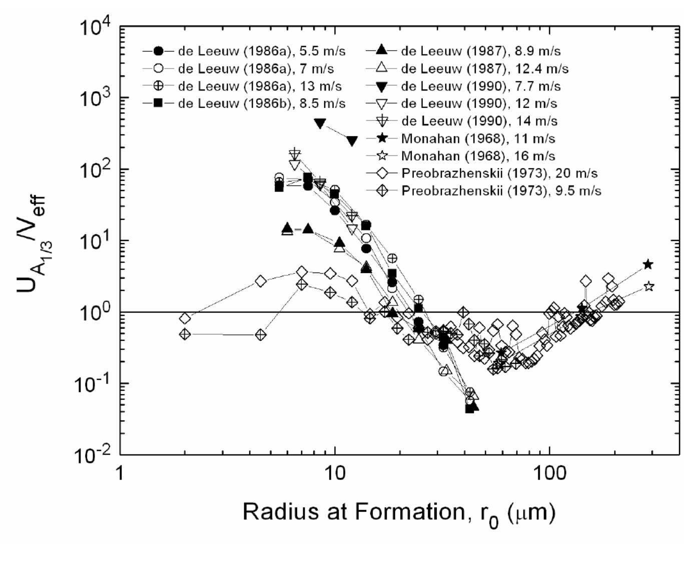

Fig. 3. As in Figure 2, but this shows the ratio of the wind speed at the wave crests, $U_{A_{1/3}}$, to V_{eff}. Here, $U_{A_{1/3}}/V_{eff}$ is typically between 0.5 and 5 for all radii r_0 from 20 to 300 μm.

$$Q_{en,T} = \rho_a C_{Kr} S_r \left[c_{pd} \left(\Theta_s - \Theta_r \right) + L_v \left(Q_s - Q_r \right) \right] . \tag{3}$$

Here, S_r, Θ_r, and Q_r are the effective wind speed, potential temperature, and specific humidity at reference height r; Θ_s and Q_s are the temperature and specific humidity at the sea surface; and ρ_a, c_{pd}, and L_v are, respectively, the air density, the specific heat of dry air at constant pressure, and the latent heat of vaporization.

Finally, C_{Kr} is the enthalpy transfer coefficient appropriate at height r. The associated neutral-stability value at a standard reference height of 10 m, C_{KN10}, is often assumed to be constant or, perhaps, a single-valued function of wind speed. When sea spray contributes to the enthalpy transfer, however, these assumptions are fallacious (Andreas 2010b).

Because my bulk flux algorithm can compute both the interfacial and spray contributions to $Q_{en,sp}$ through (1c), I can invert (3) to demonstrate that C_{KN10} is not as simple to treat as most models assume. That is, from the specified mean meteorological quantities S_r, Θ_r, Q_r, Θ_s and Q_s, I can compute $Q_{en,sp}$ from (1c) and then find

$$C_{Kr} = \frac{Q_{en,T}}{\rho_a S_r \left[c_{pd} \left(\Theta_s - \Theta_r \right) + L_v \left(Q_s - Q_r \right) \right]} . \tag{4}$$

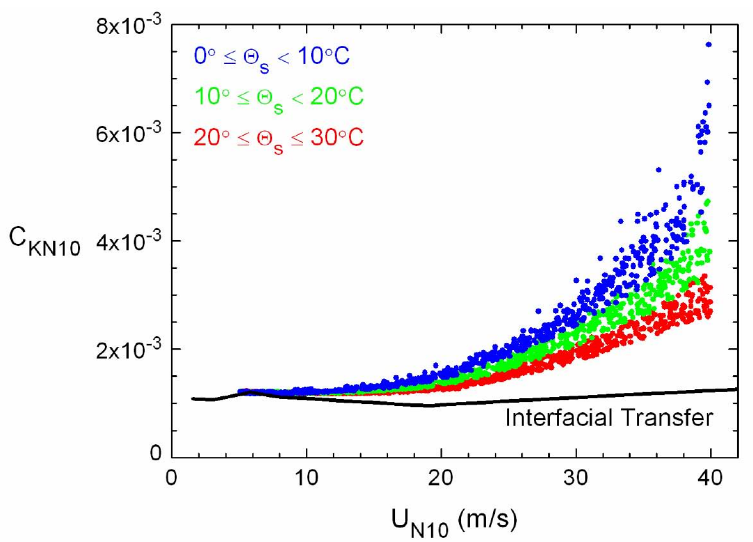

Fig. 4. The neutral-stability, 10-m enthalpy transfer coefficient, C_{KN10}, computed from the artificial dataset and plotted as a function of the neutral-stability, 10-m wind speed, U_{N10}. The solid curve shows what C_{KN10} would be if only interfacial transfer operated. Θ_s is the sea surface temperature. C_{KN10} is always above the curve for interfacial transfer: Spray-mediated processes augment the interfacial transfer. Moreover, the spread in the C_{KN10} values increases with increasing wind speed; and the values cluster according to sea surface temperature, where the coolest temperatures (0° to 10°C) produce the largest C_{KN10} values.

For comparison purposes, I convert C_{Kr} to C_{KN10}.

Using a random number generator, I produced 2000 sets of S_r, Θ_r, Q_r, Θ_s and Q_s values and computed the resulting fluxes from (1) (Andreas 2010b). I then converted these fluxes to the associated neutral-stability, 10-m transfer coefficients for enthalpy, latent heat, sensible heat, and momentum—C_{KN10}, C_{EN10}, C_{HN10}, and C_{DN10}, respectively—under the assumption that all transfer was by interfacial processes alone. This is the practice in all current mesoscale and large-scale ocean storm models—a practice that fails to recognize spray effects.

Figure 4 shows my calculations of the enthalpy transfer coefficient from this artificial, though realistic, dataset. The black curve shows what C_{KN10} would be if the transfer were strictly by interfacial processes. This curve is a single-valued function of wind speed. When I include spray-mediated transfer, however, it is clear that C_{KN10} cannot be represented as a constant or even as a single-valued function of wind speed.

Emanuel (1995) identified the ratio C_{KN10}/C_{DN10} as the key to understanding hurricane intensity. Figure 5 shows my computations of this ratio for surface temperatures typical of tropical cyclones, $20° \le \Theta_s \le 30°C$. This figure also shows Emanuel's presumed lower limit for C_{KN10}/C_{DN10} in the high-speed core of hurricanes, 0.75; the curve for strict interfacial transfer; and aircraft measurements of C_{KN10}/C_{DN10} during CBLAST (the Coupled Boundary Layers and Air-Sea Transfer project).

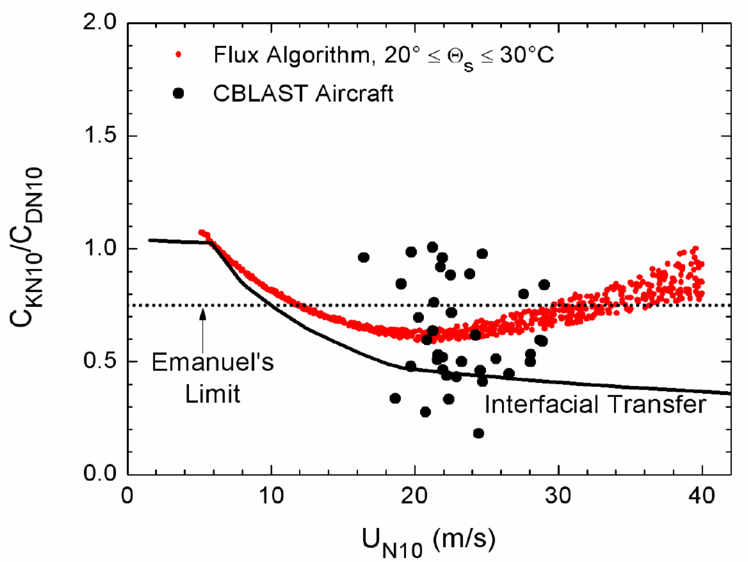

Fig. 5. The ratio of enthalpy transfer coefficient to drag coefficient, C_{KN10}/C_{DN10}, as computed from the artificial data and plotted as a function of U_{N10} for surface temperatures typical of tropical cyclones, $20° \le \Theta_s \le 30°C$. The solid curve shows what this ratio would be if the exchange were controlled by interfacial processes. Clearly, when spray is a transfer agent, C_{KN10}/C_{DN10} is significantly larger than interfacial transfer can explain. The CBLAST aircraft measurements of C_{KN10}/C_{DN10} (J. A. Zhang et al. 2008) did not reach hurricane-strength winds but support my theory of spray-mediated transfer for wind speeds between 16 and 30 m/s. My theory also predicts that C_{KN10}/C_{DN10} is larger than 0.75 for hurricane-strength winds, as Emanuel's (1995) analysis requires.

Three features stand out in Figure 5. First, because most of the CBLAST data (J. A. Zhang et al. 2008) are above the curve for interfacial transfer, these data document significant spray-mediated transfer. Second, my theoretical predictions pass right through the middle of the CBLAST data cloud and are, thus, compatible with measurements up to wind speeds of 30 m/s. Third, my predictions for C_{KN10}/C_{DN10} are above Emanuel's (1995) limit of 0.75 for hurricane-strength winds, as his sensitivity analysis requires.

Figures 6 and 7 show two more results from this analysis. Figure 6 shows the 10-m, neutral-stability transfer coefficient for latent heat, C_{EN10}, that I computed under the assumption of strict interfacial transfer. Figure 7 is a similar plot for the sensible heat transfer coefficient, C_{HN10}. Again, both coefficients are quite variable because of spray-mediated transfer.

RESULTS

Our finding a good candidate for the effective production velocity in (2) for larger spray droplets—that is, $U_{A_{1/3}}$—has several implications. First, it provides a means for linking measurements of the near-surface droplet concentration, $C_0(r_0)$—which is relatively easy to measure—with the spray generation function, dF/dr_0—which is very difficult to measure for droplets with radii larger than 20 μm. This connection may provide new insights into the nature of dF/dr_0 and, thus, benefit all spray modeling.

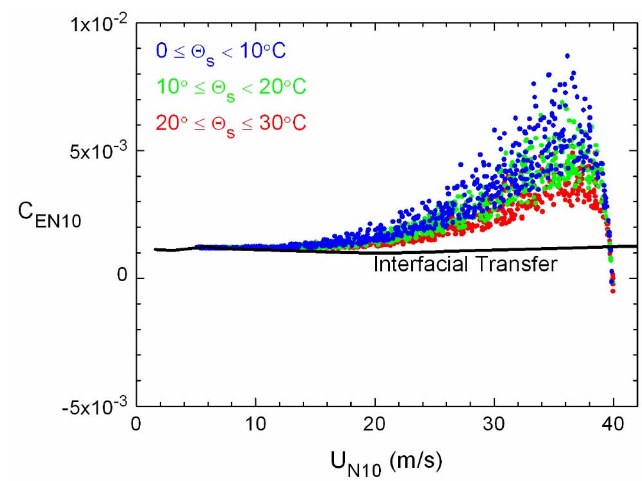

Fig. 6. As in Figure 4, except this shows the 10-m, neutral-stability transfer coefficient for latent heat, C_{EN10}, as a function of U_{N10}. The C_{EN10} values spread and the values increase with wind speed; whereas if the transfer were strictly interfacial (solid line), C_{EN10} would not spread and would change little with wind speed. Cooler sea surface temperature tends to produce larger C_{EN10} values than warmer surface temperature for Θ_s between 0° and 30°C. The curious dipping tail at high wind speed is an artifact of how I specified relative humidity in the dataset.

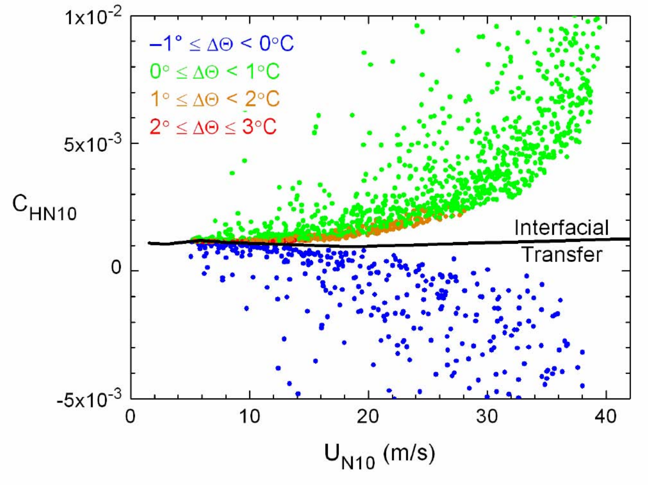

Fig. 7. As in Figure 6, except this plot shows C_{HN10}, the 10-m, neutral-stability transfer coefficient for sensible heat. The colored symbols indicate ranges in the sea-air-temperature difference, $\Delta\Theta$. For the blue symbols, $-1° \leq \Delta\Theta < 0°C$, the near-surface air is stably stratified, and C_{HN10} is always below the curve for strict interfacial transfer. In fact, some values are negative, indicating a counter-gradient sensible heat flux. For the other symbols, $\Delta\Theta \geq 0°C$, the near-surface air is unstably stratified, and the C_{HN10} values are above the curve representing interfacial transfer.

More importantly for my work, though, is that the near-surface vertical spray concentration profile is often represented as (e.g., Goroch et al. 1980; Hoppel et al. 2002)

$$C(z, r_0) = C_0(r_0)\left(z / A_{1/3}\right)^{-V_g(r_0)/ku_*} . \tag{5}$$

Here, z is the height; $A_{1/3}$, the significant wave amplitude; $V_g(r_0)$, the terminal fall speed of droplets with radius r_0; k, the von Kármán constant; and u_*, the friction velocity. If enough spray is present, the near-surface air may be stabilized against turbulent exchange. Equations (2) and (5) could provide a way of quantifying this effect.

One of the hottest debates in air-sea interaction research is on how C_{DN10} behaves in winds above 30 m/s. Hurricane models seem to require that it stop increasing as fast with wind speed as it does for lower wind speeds. This stabilization by spray may allow the turbulence to be decoupled from the surface and explain how C_{DN10} can level off at high wind speed.

Figures 6 and 7 provide an explanation for observations heretofore only poorly understood. Measurements of C_{HN10} over the ocean are often more scattered than measurements of C_{EN10} (e.g., Large and Pond 1982; DeCosmo et al. 1996; Dupuis et al. 2003; Persson et al. 2005). These differences in the precision of C_{HN10} and C_{EN10} measurements are often explained as an effect of signal-to-noise ratio: Because the sensible heat flux over the ocean is often smaller than the latent heat flux, C_{HN10} values should be more uncertain that C_{EN10} values. Figures 6 and 7, however, also explain these observations as a consequence of spray-mediated processes. Because transfer coefficients based on strict interfacial transfer are poorly posed for wind speeds above about 10 m/s, the coefficients are highly variable because the spray effects do not obey interfacial scaling.

In fact, Figure 7 suggests that C_{HN10} would, on average, be evaluated to be smaller in stable stratification than in unstable stratification. This result is exactly what Large and Pond (1982) found, and there has been no explanation of it until now.

IMPACT/APPLICATIONS

The turbulent air-sea flux algorithm that I have developed has four 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 flux measurements; and it is theoretically based and, therefore, can be extrapolated to high-wind conditions. Furthermore, evaporating spray can also add salt to the ocean surface; my developing a parameterization for this flux (Andreas 2010a) is a fourth feature that no other air-sea flux coupler has.

Although I have tested this algorithm against in situ data, we still need to see if it improves predictions of ocean storm structure and intensity. Will Perrie and his colleagues at Bedford Institute of Oceanography have done the most storm modeling with my spray flux algorithm (Perrie et al. 2004, 2005, 2006; W. Zhang et al. 2006; Zhang and Perrie 2008). But they focused on midlatitude storms and used an early version of my flux algorithm. More recently, I have been working with Isaac Ginis at the University of Rhode Island and Shuyi Chen at the University of Miami to test my flux algorithm in their tropical cyclone models.

TRANSITIONS

Besides the journal articles and conference presentations that describe my work on air-sea exchange in high winds, I have developed a software "kit" that contains the instructions and FORTRAN programs necessary to implement my bulk flux algorithm. Version 3.3 is the current version of that kit, and it is posted on the web site www.nwra.com/resumes/andreas/software.php, where it can be freely downloaded.

Another vehicle for transitions is my membership on the American Meteorological Society's Committee on Air-Sea Interaction. I have served on that committee for almost five years and am the current chairperson of this committee. Through this membership, I was the program co-chair for both the 2007 (in Portland, OR) and 2009 (in Phoenix, AZ) Conferences on Air-Sea Interaction and oversaw the planning for our September 2010 Conference in Annapolis, MD, as the committee chair. In these roles, I arranged for several sessions at each of these conferences that were relevant to the subject of my current research for ONR. Namely, all three conferences featured sessions on sea surface physics (waves, whitecaps, and spray generation), tropical and extratropical storms, and flux parameterizations.

RELATED PROJECTS

About 20 months ago, I finished a one-year project funded by the Mineral Management Service. Kathleen F. Jones of the U.S. Army Cold Regions Research and Engineering Laboratory was the PI and funded me as a subcontractor. We are still producing results from work started under that project. Our objective was to develop guidelines for predicting spray icing on permanent platforms (usually drilling platforms) in the waters around Alaska. Spray icing is a hazard to both personnel and equipment during high-wind events with sub-zero temperatures. That is, the conditions of interest in the spray icing project overlap some of the conditions that are important in this ONR project. The two projects, thus, mutually leveraged each other. For the spray icing project, we developed equations for predicting the near-surface vertical profile in spray concentration as a function of droplet radius from what I know about the sea spray generation function. Jones and Andreas (2009) published our final report; but Jones and Andreas (2010) and, to a lesser extent, Andreas et al. (2010) are products of that collaboration.

Less than a year ago, I started a three-year project funded under the National Ocean Partnership Program. This project is on "Advanced Coupled Atmosphere-Wave-Ocean Modeling for Improving Tropical Cyclone Prediction Models," with Isaac Ginis at the University of Rhode Island and Shuyi Chen at the University of Miami as lead PIs. I am a subcontractor to the University of Rhode Island and will supply expertise, code, and analyses to help the project understand how sea spray affects hurricane intensity.

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, 1998: A new sea spray generation function for wind speeds up to 32 m s^{-1}. *J. Phys. Oceanogr.*, **28**, 2175–2184.

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, U.K., 1–46.

Andreas, E. L, 2010a: Spray-mediated enthalpy flux to the atmosphere and salt flux to the ocean in high winds. *J. Phys. Oceanogr.*, **40**, 608–619.

Andreas, E. L, 2010b: The fallacy of the enthalpy transfer coefficient in high winds. Extended abstract, 17th Conference on Air-Sea Interaction, Annapolis, MD, 27–30 September 2010, American Meteorological Society, 2.2, 11 pp.

Andreas, E. L, P. O. G. Persson, and J. E. Hare, 2008: A bulk turbulent air-sea flux algorithm for high-wind, spray conditions. *J. Phys. Oceanogr.*, **38**, 1581–1596.

Andreas, E. L, K. F. Jones, and C. W. Fairall, 2010: The production velocity of sea spray droplets. *J. Geophys. Res.*, doi: 10.1029/2010JC006458, to appear.

Blanchard, D. C., 1963: The electrification of the atmosphere by particles from bubbles in the sea. *Prog. Oceanogr.*, **1**, 71–202.

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.

de Leeuw, G., 1986a: Vertical profiles of giant particles close above the sea surface. *Tellus*, **38B**, 51–61.

de Leeuw, G., 1986b: Size distribution of giant aerosol particles close above sea level. *J. Aerosol Sci.*, **17**, 293–296.

de Leeuw, G., 1987: Near-surface particle size distribution profiles over the North Sea. *J. Geophys. Res.*, **92**, 14,631–14,635.

de Leeuw, G., 1990: Profiling of aerosol concentrations, particle size distributions and relative humidity in the atmospheric surface layer over the North Sea. *Tellus*, **42B**, 342–354.

Dupuis, H., C. Guerin, D. Hauser, A. Weill, P. Nacass, W. M. Drennan, S. Cloché, and H. C. Graber, 2003: Impact of flow distortion corrections on turbulent fluxes estimated by the inertial dissipation method during the FETCH experiment on R/V *L'Atalante*. *J. Geophys. Res.*, **108**, C3, 8064, doi: 10.1029/2001JC001075.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.*, **52**, 3969–3976.

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 Syst.*, **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.

Goroch, A., S. Burk, and K. L. Davidson, 1980: Stability effects on aerosol size and height distributions. *Tellus*, **32**, 245–250.

Hoppel, W. A., G. M. Frick, and J. W. Fitzgerald, 2002: Surface source function for sea-salt aerosol and aerosol dry deposition to the ocean surface. *J. Geophys. Res.*, **107** (D19), 4382, doi: 10.1029/2001JD002014.

Jones, K. F., and E. L Andreas 2009: Sea spray icing of drilling and production platforms. *ERDC/CRREL Tech. Rep. TR-09-3*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 54 pp.

Jones, K. F., and E. L Andreas, 2010: Sea spray icing of fixed offshore structures. *Quart. J. Roy. Meteor. Soc.*, submitted.

Large, W. G., and S. Pond, 1982: Sensible and latent heat flux measurements over the ocean. *J. Phys. Oceanogr.*, **12**, 464–482.

Monahan, E. C., 1968: Sea spray as a function of low elevation wind speed. *J. Geophys. Res.*, **73**, 1127–1137.

Monahan, E. C., D. E. Spiel, and K. L. Davidson, 1986: A model of marine aerosol generation via whitecaps and wave disruption. *Oceanic Whitecaps and Their Role in Air-Sea Exchange Processes*, E. C. Monahan and G. Mac Niocaill, Eds., D. Reidel, Dordrecht, 167–174.

Perrie, W., X. Ren, W. Zhang, and Z. Long, 2004: Simulation of extratropical Hurricane Gustav using a coupled atmosphere-ocean-sea spray model. *Geophys. Res. Lett.*, **31**, L03110, doi: 10.1029/2003GL018571.

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.

Perrie, W., W. Zhang, X. Ren, Z. Long, and J. Hare, 2006: Midlatitude storm impacts on air-sea CO_2 fluxes. *Atmosphere-Ocean Interactions, Volume 2,* W. Perrie, Ed., WIT Press, Southampton, U.K., 143–153.

Persson, P. O. G., J. E. Hare, C. W. Fairall, and W. D. Otto, 2005: Air-sea interaction processes in warm and cold sectors of extratropical cyclonic storms observed during FASTEX. *Quart. J. Roy. Meteor. Soc.*, **131**, 877–912.

Preobrazhenskii, L. Yu., 1973: Estimate of the content of spray-drops in the near-water layer of the atmosphere. *Fluid Mech.–Soviet Res.*, **2**, 95–100.

Zhang, J. A., P. G. Black, J. R. French, and W. M. Drennan, 2008: First direct measurements of enthalpy flux in the hurricane boundary layer: The CBLAST results. *Geophys. Res. Lett.*, **35**, L14813, doi: 10.1029/2008GL034374.

Zhang, W., and W. Perrie, 2008: The influence of air-sea roughness, sea spray, and storm translation speed on waves in North Atlantic storms. *J. Phys. Oceanogr.*, **38**, 817–839.

Zhang, W., W. Perrie, and W. Li, 2006: Impacts of waves and sea spray on midlatitude storm structure and intensity. *Mon. Wea. Rev.*, **134**, 2418–2442.

PUBLICATIONS

Andreas, E. L, 2009: Relating the drag coefficient and the roughness length over the sea to the wavelength of the peak waves. *Journal of Physical Oceanography*, **39**, 3011–3020. [published, refereed]

Andreas, E. L, 2010: Spray-mediated enthalpy flux to the atmosphere and salt flux to the ocean in high winds. *Journal of Physical Oceanography*, **40**, 608–619. [published, refereed]

Andreas, E. L, 2010: Reply to Hwang. *Journal of Physical Oceanography*. [in press, refereed]

Andreas, E. L, 2010: The fallacy of the enthalpy transfer coefficient in high winds. Extended abstract, 17th Conference on Air-Sea Interaction, Annapolis, MD, 27–30 September 2010, American Meteorological Society, 2.2, 11 pp. [published]

Andreas, E. L, K. F. Jones, and C. W. Fairall, 2010: The production velocity of sea spray droplets. *Journal of Geophysical Research*, doi: 10.1029/2010JC006458. [in press, refereed]

Brooks, I. M., E. L Andreas, G. McFiggans, M. D. Anguelova, and C. O'Dowd, 2011: Primary marine aerosol fluxes: Progress and Priorities (Meeting Summary). *Bulletin of the American Meteorological Society*. [in press, refereed]

de Leeuw, G., E. L Andreas, M. D. Anguelova, C. W. Fairall, E. R. Lewis, C. O'Dowd, M. Schulz, and S. E. Schwartz, 2010: Production flux of sea-spray aerosol. *Reviews of Geophysics*. [submitted, refereed]

Jones, K. F., and E. L Andreas, 2010: Sea spray icing of fixed offshore structures. *Quarterly Journal of the Royal Meteorological Society*. [submitted, refereed]