Sea Spray and Icing in the Emerging Open Water of the Arctic Ocean

Kathleen F. Jones
Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, NH 03755
phone: (603) 646-4417   fax: (603) 646-4644   email: kathleen.f.jones@usace.army.mil

Award Number: N0001412MP20085

and

Edgar L Andreas
NorthWest Research Associates, Inc.
25 Eagle Ridge
Lebanon, NH 03766
phone: (603) 448-3555   fax: (603) 448-3555   email: eandreas@nwra.com

Award Number: N00014-12-C-0290
http://www.nwra.com/resumes/andreas/

LONG-TERM GOALS

The goal of this project is to develop the capability to quantify both the concentration of sea spray over the open ocean and the severity of sea spray icing on fixed offshore structures. We will use information on the relationship of the spray concentration distribution to wind speed (e.g., Lewis and Schwarz 2004; Andreas et al. 2010; Jones and Andreas 2012) to estimate the sea spray climatology in ice-free northern oceans from reanalysis data and the time-varying extent of the sea ice cover. Our field campaigns in the second and third years will focus on measuring sea spray parameters and relevant meteorological conditions to characterize spray drop distributions at high wind speeds and cold temperatures. Sea spray data at high wind speeds are sparse, and there are no measurements of the spray drop concentration at air temperatures below freezing. This effort directly addresses two of the focus areas in the core ONR Arctic program:

- Improving understanding of the physical environment and processes in the Arctic Ocean;
- Developing integrated ocean-ice-wave-atmosphere Earth system models for improved prediction on time scales of days to months.

OBJECTIVES

Our objectives are as follows:

- Use reanalysis data to estimate spatially and temporally distributed sea spray concentrations over the northern oceans. This estimate is currently limited by the sparse information on sea

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**
4. TITLE AND SUBTITLE **Sea Spray and Icing in the Emerging Open Water of the Arctic Ocean**		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) **U.S. Army Corps of Engineers,Cold Regions Research and Engineering Laboratory,72 Lyme Road,Hanover,NH,03755**		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 **Same as Report (SAR)**	18. NUMBER OF PAGES **15**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

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

spray at high wind speeds. Adapt the Andreas et al. (2008, 2010, 2014) spray algorithms for high wind speeds and subfreezing temperatures.

- Use these estimates of sea spray concentration to characterize the icing risk for offshore structures in northern regions by adapting the heat balance calculation for freezing rain in Jones (1996) to saline drops and by modifying the Finstad et al. (1988) collision efficiency algorithm to account for the larger mass of saline drops compared to freshwater drops.

- Determine the properties of sea spray in high wind speeds by making drop concentration measurements on fixed offshore structures or at well exposed coastal or island sites at air temperatures below freezing.

- Measure the density of ice accreted from sea spray on fixed structures and develop a relationship between spray ice density and weather parameters.

- Use our sea spray measurements to revise the Jones and Andreas (2012) spray concentration distribution for high wind speeds; update our initial icing risk analysis.

- Rapidly disseminate all data and metadata.

APPROACH

Our goal is to quantify sea spray concentrations from wind-generated sea spray and the resulting spray icing on offshore structures, such as wind turbines and exploration, drilling, and production platforms. Our approach combines 1) simulating sea spray and icing from reanalysis data and data from moored buoys and coastal stations, 2) a field campaign to measure the liquid water content and concentration of sea spray in high winds, 3) developing a spray concentration density function for high wind speeds, 4) estimating the spatial distribution of sea spray in all seasons, and 5) determining icing risk when the air temperature is below freezing in northern oceans.

The key CRREL personnel for this project are Kathy Jones, Chris Williams, and Kerry Claffey. Ed Andreas of NWRA is the co-PI with Jones. We borrowed Chris Fairall's cloud imaging probe for the Winter Rock Experiment (WREx) in January 2013 on Mt. Desert Rock. Personnel from College of the Atlantic, which owns the lighthouse and associated facilities on the Rock, provided logistics for the experiment. The data for the spray climatologies come from the National Data Buoy Center (NDBC), the National Snow and Ice Data Center (NSIDC), and the National Centers for Environmental Prediction (NCEP).

CRREL
For the year 3 field experiment, Jones and Claffey deployed to Mt. Desert Rock from 18 January to 18 February 2014, with logistics again provided by College of the Atlantic. The weather and wave conditions for WREx2 are plotted in Figure 1. High winds (~20 m/s) occurred on a number of days, with the windiest conditions in a nor'easter that affected the region from 13 to 16 February. Temperaures were below freezing for over half the time, and the water temperature decreased from 6°C to 4°C during the experiment. Our measurements focussed on the vertical variation in sea spray concentration and liquid water content both for open ocean conditions and in locally generated spray.
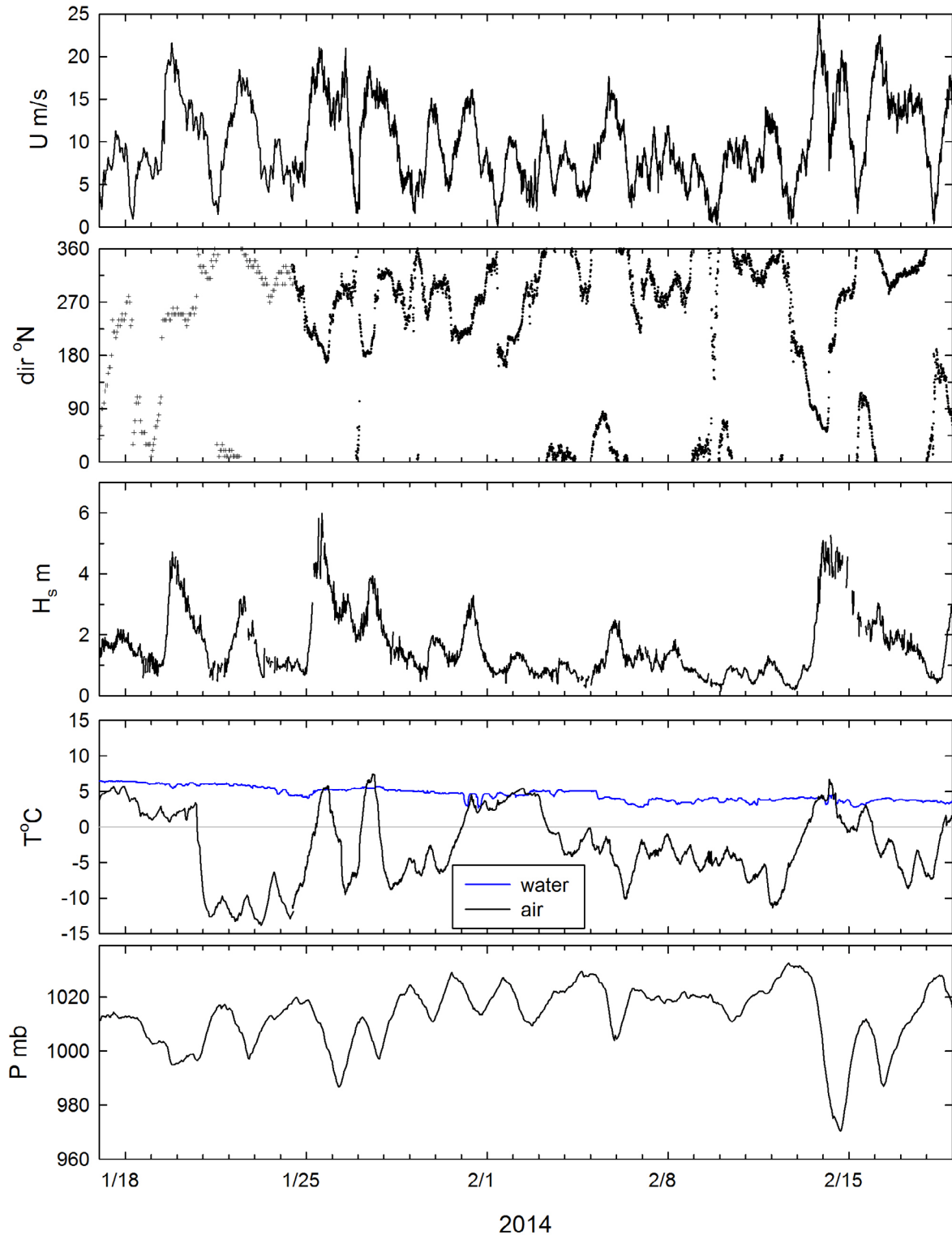
Figure 1. Weather and ocean data for WREx2 in 2014. Atmospheric pressure data is from the NDBC station on the Rock. Wind and air temperature data prior to 24 Jan at 1100, when CRREL installed a weather station on the lighthouse, are from Matinicus Rock to the southwest. Ocean data are from NERACOOS buoy I01 to the north.

Figure 2. Rotating multicylinder observation on the lower catwalk on the lighthouse, 22 Jan 2014. The wind and the mass of ice on each cylinder are analyzed to determine the best fit parameters of an assumed drop concentration distribution.

To test the spray concentration gradient formulation by Fairall et al. (2009) we exposed drop slides nearly simultaneously from the lower catwalk of the lighthouse (19 m asl) and from the foghorn platform (7.5 m asl). And because drop slides can sample only a small volume of air (~ 0.08 to 0.8 m^3), decreasing with increasing wind speed and spray drop concentration, we also carried out multicylinder observations (Figure 2) at those two elevations. The rotating multicylinder was developed to characterize drop distributions in supercooled clouds. It samples 10s to 100s of cubic meters of air in each observation (Jones et al. 2014) and exploits the decrease in the collision efficiency with decreasing drop diameter of the wind-blown drops with cylinders. We adapted it for the sometimes above-freezing conditions during WREx2 by using absorbent paper covers for each of the cylinders. This method provides useful results when the sea spray liquid water content is relatively high, that is, when it is windy, but the cylinder covers sometimes did not survive in those conditions.

A mast located on at waters edge on the west side of the Rock, with good exposure to wind and waves from the west and north acts like an offshore structure, with spray generated by waves impacting and running up the near-vertical rock wall at its base. The spray ice on the mast (Figure 3a) has a profile similar to that on a wind turbine mast in the Baltic Sea (Figure 3b), with spray icing near the sea surface limited by the warm sea water (~5°C at MDR) washing the mast and the ice thickness decreasing with height consistent with the expected spray concentration gradient. We documented the spray icing profile on the mast using time lapse photos and videos, initially from the lighthouse catwalk and later from a tripod installed near the mast above the high water level. When the mast was accessible, typcially at low tide, we collected samples of the accumulated ice from various heights and orientations and measured the salinity of the melted samples.

The major focus of our work to date has been on characterizing sea spray over the open ocean. This is appropriate for determining spray icing on fixed offshore structures with little area at the waterline. However, on structures with large diameter legs or with vertical sides extending below the waterline, spray caused by run-up of waves on the legs or sides may be significant. If access to the platform is by boat to a ladder on the legs, then any ice on the leg may deny access, as is the case in Figure 3b. The

overall contribution of locally generated spray to icing on an offshore drilling and production platform will depend on width of the structure at the waterline relative to the overall width and the height of the deck and equipment above sea level. More structure area at the waterline provides more area for waves to run up and create spray. However, if the deck is relatively high, then the trajectory of the locally generated spray may be primarily under the platform, with only small drops with low liquid water content impinging on the equipment at deck level and above. The semi-submersible drilling rigs *Ocean Bounty* and the *Sedco 708* had little area at the waterline and therefore experienced significant icing only in winds over 20 m/s (Jones and Andreas 2012). At 19 m/s observers on the *Sedco 708*, noted that spray ice accretion was greater on the lee side trusses below the deck than on trusses on the windward side of the platform. This is likely from spray generated by wave interaction with the windward legs. There was no spray icing at deck level or above. However, for platform designs with solid sides or large diameter legs like those shown in Figure 4, run-up and locally generated spray may be significant. The Molikpaq in Figure 4a was originally designed for pack ice conditions, but has been deployed in open water where it would be vulnerable to spray icing.
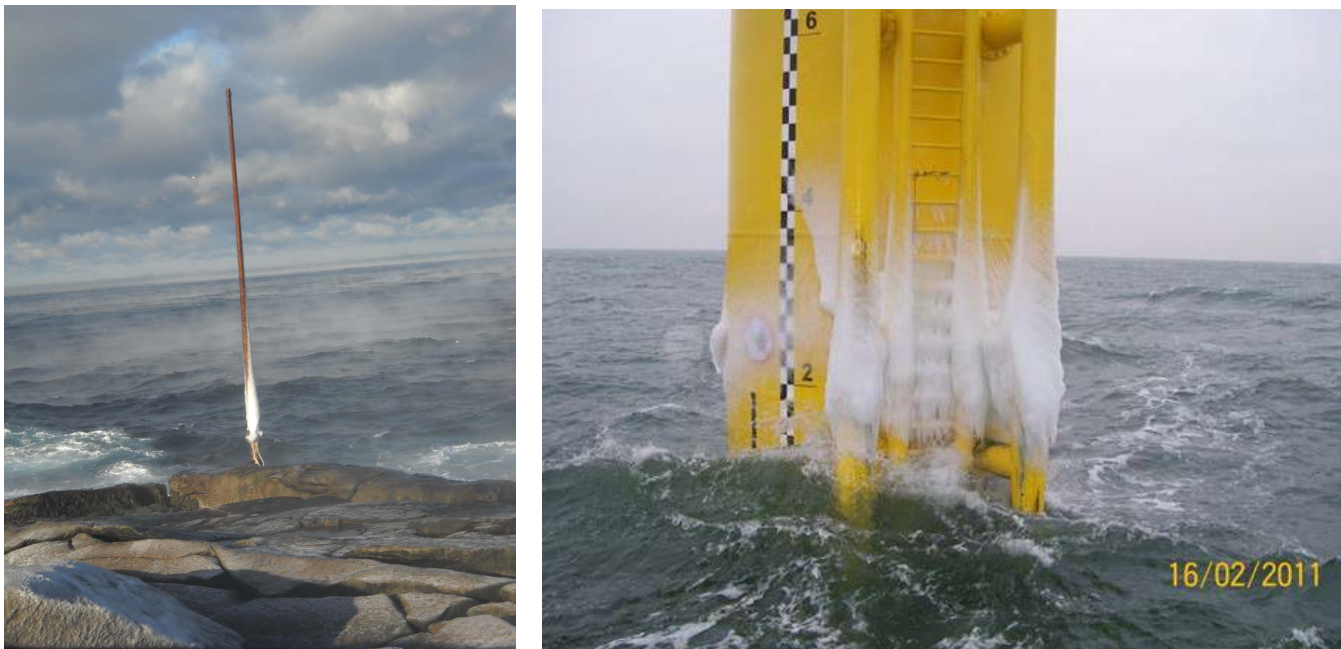
Figure 3. Spray ice a) on the mast on Mt. Desert Rock, 23 January 2014. The ice accreted during the previous day in winds between 15 and 20 m/s and air temperatures ranging from -10 to -12°C , and b) on the leg of a wind turbine platform in the Baltic Sea. The ice is covering the ladder, preventing access to the platform by boat.

To address this issue Jones compiled information from papers analyzing physical models of run-up and splash from wave interaction with a cylindrical pile and field observations of the height of spray generation by wave interaction with a breakwater. The papers on physical models of the interaction of waves with cylinders (de Vos et al. 2007, Lykke Andersen et al. 2011, Ramirez et al. 2013) analyzed the data using velocity head stagnation theory assuming that the kinetic energy of the water particles is converted into potential energy, resulting in run-up R_u on the pile given by

$$R_u = \eta_{max} + m\frac{u^2}{2g}, \qquad (1)$$

where η_{max} is the wave crest height, u is the water particle velocity at the wave crest, and m is determined from the test data. Ramirez et al. (2013) used video to determine values of m as a function of wave steepness for the 2% run-up heights of green water (level A), mixed water and air (level B), and spray (level C). The spray level often had to be estimated and that estimate appears to be limited to relatively low values by the structure holding the pile in place. Yamashiro et al. (2012) documented sea spray generated by wave interaction with a vertical-sided breakwater outside the harbor of a fishing village in Japan. From videos of the spray, they determined the mean and maximum spray height and occurrence rate of spray for each measurement period, along with the prevailing wind speed and significant wave height and period. The value of m from the physical models with no wind significantly underestimates the spray heights observed at the breakwater. However, if we use the wind speed rather than the water particle velocity in (1), the calculated 2% spray height is not unreasonable compared to the reported maximum spray height from the breakwater observations. For estimating spray icing on offshore structures we have determined m for level C for the mean spray height from the Yamashiro et al. (2012) data. At that height we assume the spray concentration associated with spindrift from Jones and Andreas (2012) and a vertical variation in concentration using Fairall et al. (2009) both above and below this level, limited below by the height of level B where the spray merges with the ocean. This spray cloud is generated only where there are vertical surfaces of the offshore structure at the waterline, so in modeling sea spray on a structure the locally generated concentration is scaled by that fraction of the structure width and the spray frequency and superposed over a background of open ocean spray concentration.

Figure 4. Offshore exploration, drilling and production platforms for which local spray generation may be significant a) Molikpaq platform northeast of Sakhalin Island in the Sea of Okhotsk (http://www.ckb-rubin.ru/en/projects/offshore_structures/russias_far_east_shelf/sakhalin_2/) and b) Mars tension leg platform (http://forcechange.com/2137/the-tides-are-turning-obama-to-increase-taxes-on-offshore-drilling/).

To estimate the severity of sea spray icing Jones has compiled relevant parameters from North American Regional Reanalysis (NARR) data (Mesinger et al. 2005; NCEP reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from http://www.esrl.noaa.gov/psd/) for 1979-2014 into three-month blocks. The plan is to analyze those data to estimate the spray icing climatology typical for that time of year, assuming both open ocean spray conditions, and locally generated spray for a platform like Molikpaq.

NWRA

A crucial piece of information necessary for many studies of sea spray is the spray generation function dF/dr_0 where r_0 denotes the drop radius at formation (e.g., Andreas 2002). dF/dr_0 quantifies the number of spray drops of radius r_0 that are produced per square meter of sea surface per second per micrometer increment in drop radius. It has units of $m^{-2} s^{-1} \mu m^{-1}$. The near-surface spray concentration $C_0(r_0, U_{10})$ is all we can measure, however. C_0 has units of the number of spray drops of radius r_0 per cubic meter of air per micrometer increment in drop radius, $m^{-3} \mu m^{-1}$. U_{10} is the wind speed at the standard reference height to 10 m.

At Mt. Desert Rock we measured $C_0(r_0, U_{10})$ during WREx by capturing spray drops on Vaseline-coated microscope slides and with a cloud imaging probe (Figure 5). The cloud imaging probe automatically counts and sizes drops as they pass through an array of laser diodes. The probe that we used sizes drops in 12.5 μm bins in radius from near zero to 755 μm. We observed very few drops as large as 200 μm in radius at Mt. Desert Rock. From such concentration measurements, it is typical to infer the spray generation function by invoking an effective spray production velocity, V_{eff}, such that

$$\frac{dF}{dr_0} = C_0(r_0, U_{10}) V_{eff}(r_0). \tag{2}$$

Andreas et al. (2010) review the various velocity scales that have been used for V_{eff}; the most common one is the dry depostion velocity (e.g., Smith et al. 1993). Andreas et al. concluded, however, that the wind speed at the wave crests, $U_{A_{1/3}}$ ($A_{1/3}$ indicates the significant wave amplitude), is the best velocity scale for the relatively large spray drops that the cloud imaging probe can measure.

Figure 5. The cloud imaging probe (gold instrument) and its associated sonic anemometer/thermometer (thin instrument with several short arms near it) on the foghorn platform at Mt. Desert Rock in January 2013. The laser array is on the far end of the probe on the thin, gold arm that is barely visible. The sonic anemometer is crucial for evaluating spray concentration from the cloud imaging probe's measurements because it provides the direction and speed of the drops through the laser array.

A parallel track in our work has been developing a so-called bulk flux algorithm. Andreas et al. (2014) recently completed describing the current version, Verison 4.0, of this algorithm. Generally, bulk flux algorithms permit coupling the ocean to the atmosphere through flux boundary conditions because such algorithms predict the surface fluxes of momentum (τ, also called the surface stress) and latent ($H_{L,T}$) and sensible ($H_{s,T}$) heat. In our applications, though, we will typically be using the bulk flux algorithm as the "front end" for sea spray calculations because the algorithm also yields quantities that, for example, let us compute wind speed, temperature, and spray concentration profiles as functions of height. In outline form, our bulk flux algorithm is

$$\tau \equiv \rho u_*^2 = \rho \left[f\left(U_{N10} \right) \right]^2, \tag{3a}$$

$$H_{L,T} = H_{L,int} + H_{L,sp}, \tag{3b}$$

$$H_{s,T} = H_{s,int} + H_{s,sp}. \tag{3c}$$

Equation (3a) is a totally new drag relation that does not require specifying a drag coefficient C_D or an aerodynamic roughness length z_0 (Andreas et al. 2012). Rather, it predicts the friction velocity u_* directly from a hyperbolic function of the 10 m wind speed at neutral stability U_{N10}. A unique feature of this algorithm is that it recognizes two routes by which latent and sensible heat cross the air-sea interface: the *interfacial* route (subscript int) that is controlled by molecular processes right at the sea

surface and the *spray*-mediated route (subscript sp) that is controlled by microphysics at the surface of spray drops. When added together, these two contributions produce the total latent and sensible heat fluxes (subscript T) that eddy-covariance measurements generally yield and that atmospheric and ocean models need for flux boundary conditions.

WORK COMPLETED

CRREL
Jones has analyzed the multicylinder observations from WREx2, and confirmed the model results in Jones and Andreas (2013), showing that in wind speeds less than about 20 m/s exposure durations to obtain a useful mass of ice/water on the cylinders is excessive, significantly more than two hours. The highest winds we experienced, during the nor'easter, were accompanied by snow. Salinities of ice/snow samples from antennas and cables on the lower catwalk of the lighthouse were a few o/oo indicating that sea spray contributed about 10% of the mass. Liquid water contents from the half-dozen multicylinder observations in relatively high winds, particularly those on 22 January at -10°C, will be compared to the results of the drop slide analysis, still to be completed.

Jones downloaded 35 years of NARR data and processed and compiled it into 3 month blocks to use as input for modeling the sea spray icing climatology for both open ocean and local spray conditions. For the local spray conditions we will assume a solid-sided structure like the Molikpaq platform.

NWRA
Version 4.0 of the new bulk flux algorithm is complete, and Andreas et al. (2014) have described developing it in a paper that is in press. The algorithm is written in Fortran, and that code is freely available to download at http://www.nwra.com/resumes/andreas/software.php.

We have over 20 days of sea spray drop observations from the cloud imaging probe that we deployed on Mt. Desert Rock in WREx. We are still analyzing these data, but Figures 6 and 7 show some preliminary results. Figure 6 shows many drop concentration spectra—that is, $C_0(r_0)$ in (2) as a function of radius—that we measured in various wind speed ranges. Figure 7 shows drop concentrations for four radius bins as a function of wind speed. The radius noted on each plot is the center of a bin that is 12.5 μm wide. The red line in each figure is the best fitting line through data for which the wind speed is at least 5 m/s, approximately the lowest wind speed at which whitecaps form and sea spray, thus, also forms.
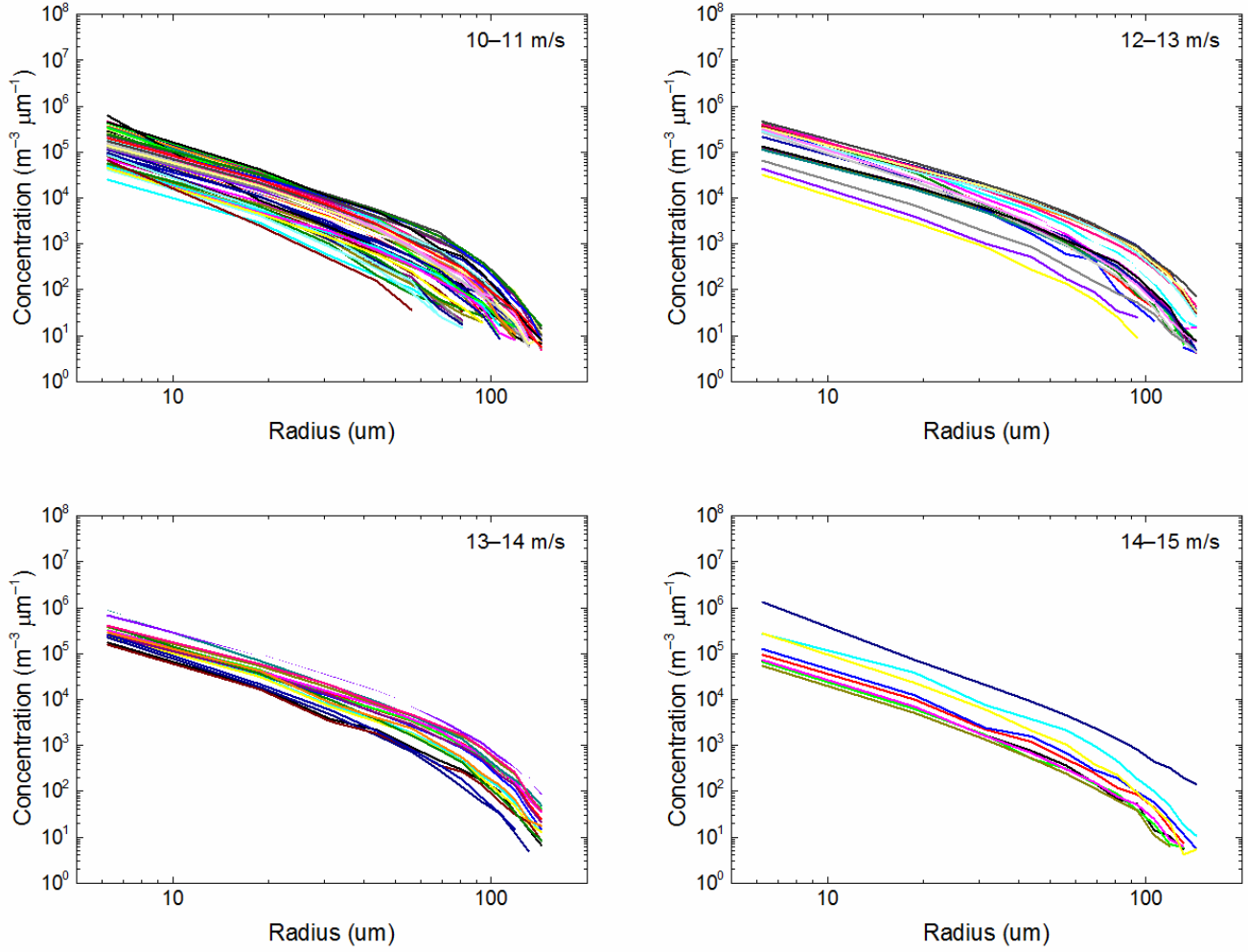
Figure 6. Spray drop concentrations as a function of ambient drop radius as measured by the cloud imaging proble on Mt. Desert Rock. Each of the four panels collects all quality-controlled drop spectra measured during 30 minute averaging intervals in each of four wind speed ranges, 10–11 m/s, 12–13 m/s, 13–14 m/s, and 14–15 m/s. Although the average levels of the spectra are different from plot to plot, the spectral shapes are surprisingly similar.
*Where the spectra are nearly linear in these log-log plots, drop concentration is approximately proportional to the inverse cube of radius.*

RESULTS

CRREL
Spray liquid water contents calculated from the multicylinder observations on the lighthouse at wind speeds approaching the ~20 m/s required for spindrift generation over the open ocean are consistent with the relatively low values expected in those conditions.

Preliminary results from a model of local spray generation using the measurements of Yamashiro et al. (2012) in an extrapolation of the formulation of Ramirez et al. (2013) show the significant contribution to spray icing of some structure configurations from local water run-up and spray generation.
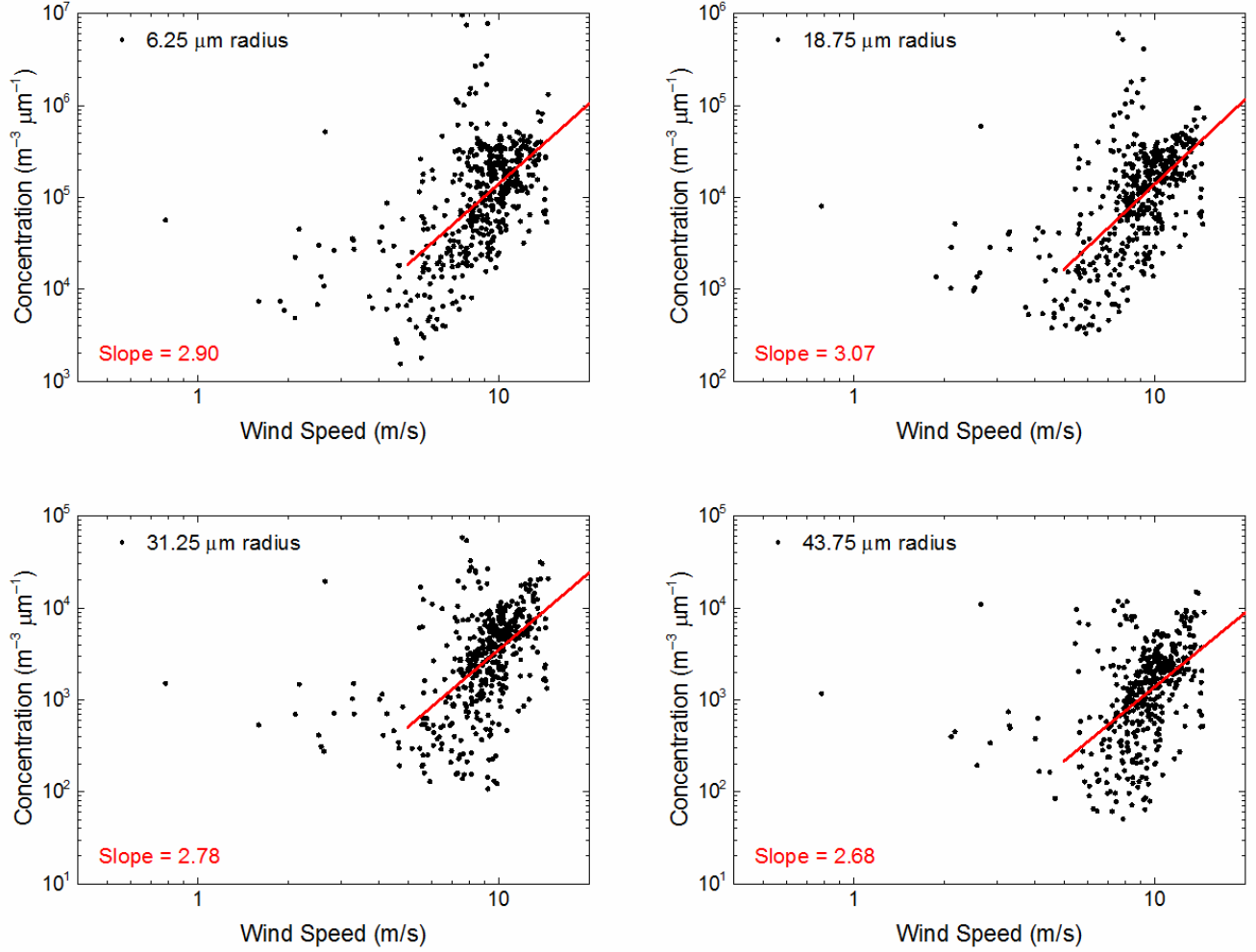
Figure 7. Thirty minute averages of quality-controlled spray drop concentrations from the cloud imaging probe are plotted against wind speed for four different radius bins, each 12.5 μm wide: 6.25, 18.75, 31.25, and 43.75 μm. In each panel, the red line shows the best fit through the points for wind speeds above 5 m/s, the nominal threshold for whitecap formation. In each of these log-log plots, the slope of this best-fit line is near 3. That is, for these drop sizes, concentration goes approximately as the cube of the wind speed.

NWRA

The four panels in Figure 6 suggest that, although the spectral levels increase with wind speed, the spectral shapes are consistent from wind speed to wind speed. Therefore, for the radius range shown in these plots, 6.25 to 143.75 μm, we will try parameterizing drop concentration for use in (2) as multiplicative functions of radius and wind speed. That is,

$$C_0\left(r_0, U_{10}\right) = g\left(r_0\right)h\left(U_{10}\right). \tag{4}$$

We will deduce $g(r_0)$ from plots such as those in Figure 6. For the four radius bins plotted in Figure 7, the best-fit lines have slopes near 3 in these log-log plots. These results imply that the $h(U_{10})$ function in (4) will look something like

$$h\left(U_{10}\right) \sim U_{10}^3.\tag{5}$$

This is a satisfying result because whitecap coverage is generally believed to go as the third power of wind speed (e.g., Monahan and O'Muircheartaigh 1980; Wu 1988). In turn, the spray generation function is presumed to follow the wind speed dependence of the whitecap coverage (e.g., Monahan et al. 1986; Fairall et al. 1994). Consequently, spray generation should go, approximately, as the cube of wind speed.

For putting the importance of this work in perspective, realize that, in Lewis and Schwartz's (2004) encyclopedic review of spray generation, they said next to nothing about drops with r_0 above 40 to 50 µm. The recent review by de Leeuw et al. (2011) also limited its discussion to drops for which $r_0 \leq 50$ µm. But the large spume drops—radii from about 20 µm up to 500 µm—that are produced when high winds tear water right off the wave crests are the ones most important for spray icing because these carry most of the water (Jones and Andreas 2012). Although we did not see high enough winds and the cloud imaging probe was not close enough to the sea surface for us to observe the biggest spume drops, our work on the spray generation function may serve as a bridge. In other words, our drop spectra extend from the smaller radii that Lewis and Schwartz (2004), de Leeuw et al. (2011), and many others have investigated into the mid-region of the spume range where the spray generation function is very uncertain (Andreas 2002).

IMPACT/APPLICATIONS

- We are developing a sea spray climatology over the northern oceans. Sea spray generated over the open ocean in high winds and subfreezing air temperatures can accumulate as ice on fixed offshore structures, including exploration, drilling, and production rigs and wind turbines. Wind and wave interaction with fixed offshore structures that have significant area at the waterline can result in ice accumulations on these structures at lower wind speeds. We expect the sea spray climatology in the Arctic Ocean to change with the declining sea ice cover.

- The declining sea ice cover also affects spray icing on coastal infrastructure. On 27 December 2010 a storm caused spray icing on power distribution lines in the village of Savoonga on St.Lawrence Island in the Bering Strait. Galloping of the ice covered wires and shorts caused by saline ice on the insulator strings resulted in a loss of power to the entire village. The initial outage lasted a few days and pipes that froze because of the outages burst. Winter storms are not unusual in this region, but this kind of damage was unprecedented in the 42-year experience of the Alaska Village Electric Cooperative. The utility concluded that the absence of the usual sea ice cover was a major contributor to the outage.

- The evaporation of the drops in the marine boundary layer affects the heat and mass transfer across the air-sea interface, which in turn influences climatology. Global climate models are sensitive to changes in the surface heat flux that are as small as 1 W/m^2. Spray-mediated heat fluxes are estimated to be much larger than this (Andreas et al. 2008, 2014).

TRANSITIONS

Andreas has developed a software "kit" that contains instructions and the Fortran programs necessary to implement a bulk air-sea flux algorithm. Version 3.4 of this algorithm was the last one described in the literature (Andreas et al. 2008; Andreas 2010). Andreas has, however, recently posted Version 4.0 at http://www.nwra.com/resumes/andreas/software.php, where it can be freely downloaded. This new version is built around the new air-sea drag relation that Andreas et al. (2012) developed, is tested with ten times as much data as was Version 3.4, and is fully described in Andreas et al. (2014).

RELATED PROJECTS

NWRA
Andreas is in the fourth year of an ONR project funded by the Marine Meteorology Program: "Predicting the Turbulent Air-Sea Surface Fluxes, Including Spray Effects, from Weak to Strong Winds." In that project, he has been collaborating with Larry Mahrt and Dean Vickers, who is a subcontractor, to develop a bulk flux algorithm from a large air-sea flux dataset that they have assembled as part of the project. That bulk flux algorithm can be used in large-scale models to couple the atmosphere to the sea by providing the flux boundary conditions on the air-sea exchanges of momentum and sensible and latent heat. Among other parties, Andreas has been working with the modelers at the Naval Research Lab in Monterey to test this algorithm in the Navy's global model, NAVGEM. The spray concentration measurements that we have made under the current project can augment information about the spray generation function that is also relevant to the Andreas-Mahrt project.

In June 2014, Andreas began a collaborative project with Penny Vlahos and Ed Monahan at the University of Connecticut to study spray-mediated air-sea gas transfer. The National Science Foundation is funding this work. Briefly, ocean scientists have been investigating bubble-mediated air-sea gas transfer for over 30 years, but no one has yet looked at the mirror-image process of spray-mediated air-sea gas transfer. This NSF project will complement and build on our current work for ONR because, to estimate the rate of spray-mediated gas transfer, we will also need to know the spray generation function.

REFERENCES

Andreas EL. 2002. A review of the sea spray generation function for the open ocean. *Atmosphere-Ocean Interactions, Volume 1*, WA Perrie, Ed., WIT Press, Southampton, U.K., 1–46.

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

Andreas EL, Persson POG, Hare JE. 2008. A bulk turbulent air-sea flux algorithm for high-wind, spray conditions. *J. Phys. Oceanogr.* **38**: 1581–1596.

Andreas EL, Jones KF, Fairall CW. 2010. Production velocity of sea spray droplets. *J. Geophys. Res.* **115**: C12065, doi:10.1029/2010JC006458.

Andreas EL, Mahrt L, Vickers D. 2012. A new drag relation for aerodynamically rough flow over the ocean. *J. Atmos. Sci.* **69**: 2520–2537.

Andreas EL, Mahrt L, Vickers D. 2014. An improved bulk air-sea surface flux algorithm, including spray-mediated transfer. *Quart. J. Roy. Meteor. Soc.*, **140**, in press.

de Leeuw G., Andreas EL, Anguelova MD, Fairall CW, Lewis ER, O'Dowd C, Schulz M, Schwartz SE. 2011. Production flux of sea-spray aerosol. *Rev. Geophys.* **49**: RG2001, doi:10.1029/2010RG000349).

de Vos L, Frigaard O, De Rouck J. 2007. Wave run-up on cylindrical and cone shaped foundations for offshore wind turbines. *Coastal Engineering*. **54**: 17-29.

Fairall CW, Kepert JD, Holland GJ. 1994. The effect of sea spray on surface energy transports over the ocean. *Global Atmos. Ocean Syst.* **2**: 121–142.

Fairall CW, Banner ML, Peirson WL, Asher W, Morison RP. 2009. Investigation of the physical scaling of sea spray spume droplet production. *Journal of Geophysical Research* 114: C10001.

Jones KF, Andreas EL. 2012. Sea spray concentrations and the icing of fixed offshore structures. *Quart. J. Roy. Meteor. Soc.* **138**: 131–144.

Jones KF, Andreas EL. 2013. Winter measurements of sea spray at Mt. Desert Rock. *Proc. 15th International Workshop on the Atmospheric Icing of Structures (IWAIS XV)*, St. John's Newfoundland, 8–11 September 2013, 3-48–3-53.

Jones KF, Thompson G, Claffey KJ, and Kelsey EP. 2014. Gamma Distribution Parameters for Cloud Drop Distributions from Multicylinder Measurements. *Journal of Applied Meteorology and Climatology*, **53**, 1606–1617. [published, refereed]

Lewis ER, Schwartz SE. 2004. *Sea Salt Aerosol Production: Mechanisms, Methods, Measurements, and Models—A Critical Review*. Geophysical Monograph 152, AGU, Washington, DC, 413 pp.

Lykke Andersen T, Frigaard P, Damsgaard ML, De Vos L (2011) Wave run-up on slender piles in design conditions-Model tests and design rules for offshore wind, *Coastal Engineering*. **58**: 281-289.

Mesinger F, DiMego G, Kalnay E, Mitchell K, Shafran P, Ebisuzaki W, Jovic D, Woollen J, Rogers E, Berbery EH, Ek MB, Fan Y, Grumbine R, Higgins W, Li H, Lin Y, Manikin G, Parrish D, Shi W. 2006. North American Regional Reanalysis. *Bulletin of the American Meteorological Society*. **87**(3): 343-360.

Monahan EC, O'Muircheartaigh I. 1980. Optimal power-law description of oceanic whitecap coverage dependence on wind speed. *J. Phys. Oceanogr.* **10**: 2094–2099.

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

Ramirez J, Frigaard P, Lykke Andersen T, de Vos L. 2013. Large scale model test investigation on wave sun-up in irregular waves at slender piles. *Coastal Engineering*. **72**: 69-79.

Smith MH, Park PM, Consterdine IE. 1993. Marine aerosol concentrations and estimated fluxes over the sea. *Quart. J. Roy. Meteor. Soc.* **119**: 809–824.

Wu J. 1988. Variations of whitecap coverage with wind stress and water temperature. *J. Phys. Oceanogr.* **18**: 1448–1453.

Yamashiro M, Yoshida A, Nishi Y. 2012. Effects of wave-dissipating blocks on reduction of salinity in the air generated at a vertical breakwater based on field observations. *Coastal Engineering Journal.* **54**(3) 1250019, 24 pp.

PUBLICATIONS

Andreas EL. 2014. Perspectives on estimating the spray-mediated flux of gases across the air-sea interface. Extended abstract, *16th Conference on Atmospheric Chemistry*, Atlanta, GA, 3–6 February 2014, American Meteorological Society, paper 7.1, 11 pp. [published]

Andreas EL, Jordan RE, Mahrt L, Vickers D. 2013. Estimating the Bowen ratio over the open and ice-covered ocean. *Journal of Geophysical Research Oceans*, **118** (9), 4334–4345. doi:10.1002/jgrc.20295. [published, refereed]

Andreas EL, Mahrt L, Vickers D. 2014. An improved bulk air-sea surface flux algorithm, including spray-mediated transfer. *Quarterly Journal of the Royal Meteorological Society*, **140**. [in press, refereed]

Andreas EL, Mahrt L, Vickers D. 2014. An improved bulk air-sea surface flux algorithm, including spray-mediated transfer. Extended abstract, *21st Symposium on Boundary Layers and Turbulence*, Leeds, U.K., 9–13 June 2014, American Meteorological Society, paper 2B.3, 19 pp. [published]

Jones KF, Thompson G, Claffey KJ, and Kelsey EP. 2014. Gamma distribution parameters for cloud drop distributions from multicylinder measurements. *Journal of Applied Meteorology and Climatology*, **53**, 1606–1617. [published, refereed]

Vickers D, Mahrt L, Andreas EL. 2014. Formulations of the sea-surface friction velocity in terms of the mean wind and bulk stability. *Journal of Applied Meteorology and Climatology*. [refereed]

HONORS/AWARDS/PRIZES

Ed Andreas was introduced as a new Fellow of the American Meteorological Society at the AMS Annual Meeting in Atlanta in February 2014.