Estimating Sea Spray Volume with a Laser Altimeter

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ABSTRACT

Down-looking laser altimeters are commonly used to measure the sea surface elevation. However, because the laser radiation is attenuated by spray droplets suspended along the transmission path, it is presumed that altimeters may also provide an indirect measure of the sea spray volume. Here, this conjecture is discussed by means of laboratory experiments, which have been conducted in a wind-wave flume. A large number of wind conditions were considered between equivalent 10-m wind speeds of 20 and 60 m s^{-1} in order to generate different spray volumes above the water surface. The facility was equipped with a laser and side-looking camera system to estimate the spray volume as well as a nearby down-looking laser altimeter. Results confirm that there is a robust degradation of the laser intensity for increasing wind speed and hence the amount of spray droplets above the water surface. A simple regression model to extract spray volume from the average intensity of the laser radiation is presented, demonstrating the promise of laser altimeters for making in situ spray observations. Additional observations will be required to calibrate the altimeters for applications in the open ocean marine environment.

1. Introduction

One of the effects of wind stress at the ocean surface is the formation of sea spray droplets. For low wind conditions, sea spray may arise from a bubble-bursting process in the whitecap generation (Andreas 1998). This results in an aerosol concentration of tiny droplets with size of a few microns, which may influence the earth's radiative balance and biogeochemical cycles (Melville and Matusov 2002). At higher wind speeds, however, the direct tearing of wave crests results in bigger droplets with sizes from tens to hundreds of microns. This notably contributes to the transfer of water vapor, latent heat, and momentum between the atmosphere and the ocean (Andreas et al. 1995; Andreas 1998). Recent studies (Andreas 2002; Emanuel 2003) have also suggested that reentrant sea spray (i.e., droplets that fall back into the ocean before losing much of their mass) may substantially affect the thermodynamics and intensity of tropical storms, although the magnitude of these effects is not well known in very high winds (Haus et al. 2010). For recent developments on the mechanisms of spray production, see also Andreas (2004) and Kudryavtsev and Makin (2009).

An accurate measure of sea spray concentration is thus relevant in many physical, chemical, and biological processes at the air–sea interface (O'Dowd and de Leeuw 2007). In this respect, during the past decades, a number of laboratory and field experiments have been conducted to derive parameterizations of the air–sea spray fluxes (see, e.g., Andreas 1998; O'Dowd and de Leeuw 2007). Although a broad consensus has not been achieved yet (differences can be as large as six orders of magnitude; Andreas 1998), sea spray estimates are reasonably valid for wind speed lower than about 30 m s^{-1}. For extreme wind conditions such as during tropical storms, unfortunately, measurements become far more complicated (Anguelova et al. 1999). Also, extrapolations from current parameterizations may be inconsistent with theoretical analysis (Emanuel 1995). In response to this issue, here we present a new method for the measurement of sea spray volume, which can potentially become effective during tropical storms if used from stationary, in situ platforms.

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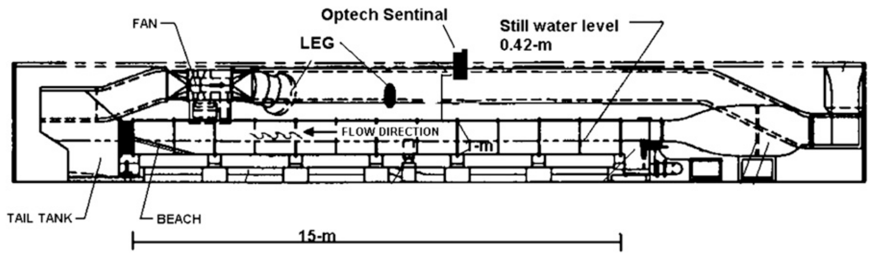

FIG. 1. Setup of spray measurement tests in the University of Miami Rosenstiel School of Marine and Atmospheric Science (UM/RSMAS) ASIST, acrylic test section 15 m × 1 m × 1 m. Optech mounted on rail 3 m above floor with beam passing through porthole on upper lid of tank, fetch at Optech 6 m from wind inlet. Wind moving right to left as shown.

In harsh seas, oceanic features can be gathered by instruments mounted on offshore rigs (see, e.g., Forristall 2000). In this respect, radar and laser altimeters have been used to track the sea surface elevation for a long time (see, e.g., Hauser et al. 2005). These devices operate in vertical mode and rely on the fact that the distance between the instrument and the sea surface can be measured as a function of the time of flight of a short pulse of infrared laser radiation (about 1-μm wavelength), which returns to the instrument of origin after being reflected at the sea surface.

The intensity of the returned signal is affected by the environmental conditions along the transmission path. Basically, there are two factors that can influence the laser radiation: the surface roughness and aerosol content. In this respect, it is well established that rough surfaces tend to enhance the backscatter of the incident signal and hence increase the intensity of the returning laser radiation (see, e.g., Macaskill 1991). Note that the backscatter may also be enhanced by the presence of foam and bubbles as a result of wave whitecaps and breaking (Walker et al. 1996; Ericson et al. 1999). On the other hand, a fraction of the laser radiation is absorbed by fog and sea spray aerosols, which are mainly composed of droplets with size comparable to the laser wavelength (see, e.g., Bateson et al. 2008; Fischer et al. 2009). Note that rain droplets are normally too large compared with the laser's wavelength to influence optical transmissions significantly (Majumbar and Ricklin 2008). Despite the backscatter due to surface roughness in high winds, it is suspected that sea spray may be responsible for a substantial attenuation of the intensity of the laser radiation and thus result in an overall degradation of the signal (cf. Hauser et al. 2005; Dysthe et al. 2008). It is therefore reasonable to assume that a measure of the laser intensity can provide an indirect estimate of the sea spray volume that the laser is forced to cross.

To verify this conjecture, we conducted a number of laboratory tests in a wind-wave flume. Experiments were intended to evaluate the performance of a down-looking laser altimeter under a variety of extreme wind conditions that, consequently, produce different sea spray concentrations above the water surface. Specifically, here we discuss measurements of the laser intensity in relation to the amount of the suspended spray volume. The purpose is to confirm the hypothesis that there is a clear and robust correlation between the degradation of the laser returned signal and the increase of spray volume.

The paper is organized as follows. A description of the experimental tests is presented in section 2. In section 3, we compare experimental observations of sea spray volume against an empirical estimate (Andreas 1998) to test the consistency of laboratory measurements. In section 4, we discuss the effect of spray droplets on the intensity of the laser radiation. For an increasing spray volume, it is verified that there is a robust degradation of the laser radiation. A regression model is thus derived to convert the measurement of the laser intensity into spray volume. Concluding remarks are presented in section 5.

2. Laboratory experiments

Laboratory experiments were conducted at the air–sea interaction laboratory [Air–Sea Interaction Salt-Water Tank (ASIST); Fig. 1] of the University of Miami (http://www.rsmas.miami.edu/groups/asist/). The tank has dimensions of 15 m × 1 m × 1 m. It was filled with freshwater with depth of 0.42 m. Waves can be generated with either a fully programmable wave-maker or wind. For the latter, the tank is equipped with a closed wind circuit that can generate centerline wind with maximum speed equivalent to 10-m wind speed (U_{10}) of 60 m s^{-1}. A minimum-reflection beach was also deployed to dissipate the wave motion at the opposite side of the wave-maker.

The methodology of the experiment is fairly simple. Wind was blown over the water surface to generate the

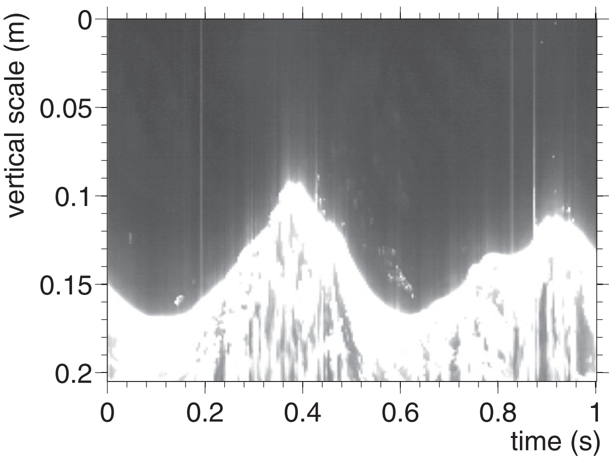

FIG. 2. Sample image from the digital line scan camera: U_{10} = 30 m s^{-1}. The image is composed by 250 line scans stacked into a 1-s image.

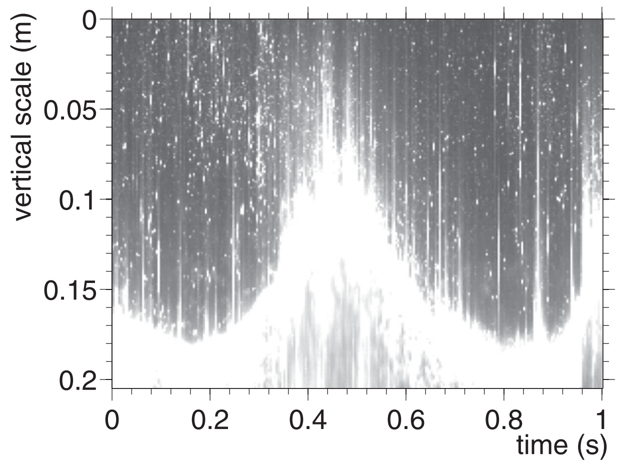

FIG. 3. Sample image from the digital line scan camera: U_{10} = 60 m s^{-1}. The image is composed by 250 line scans stacked into a 1-s image.

wave motion. Tests were performed with U_{10} between 20 and 60 m s^{-1} at increments of 5 m s^{-1}. The wind stress at the water surface forced the formation of spray, which remained confined between the water surface and the ceiling (mean distance 0.58 m). A few tests were also performed with monochromatic, mechanically generated waves in order to gather measurements without wind. Note, however, that not only does the absence of wind eliminate the spray, but it also reduces the surface roughness. At a distance of 6 m from the wave-maker, an Optech Sentinel 3100 laser (http://www.optech.ca/i3dprodline-lvlmonitors.htm) was installed at a height of 1.2 m from the still water surface. The unit consists of a rangefinder, which uses a laser diode to make noncontact range measurements in both dark and well-lit environments without using retroreflectors or mirrors. A narrow-footprint laser beam with wavelength of 905 nm is used. The laser can be reflected from a diffuse surface at virtually any angle and still return to the unit to produce a range measurement. To evaluate the range, the time of flight of the laser pulse to and from the target is measured by a high-precision counter and then converted into a range reading by a microprocessor (see Optech 2004 for details). The instrument is also capable of recording the intensity of the laser radiation, which returns from the surface after the optical transmission passes through and is attenuated by the spray droplets. The laser was configured to pulse at a frequency of 200 Hz. An average returned intensity value of 200 emitted pulses was recorded every second (factory default; Optech 2004) to reduce random errors. Each test lasted 400 s, with averages over this period being of primary interest. A 0.25-m-diameter port in the ceiling was opened for the infrared beam to reach the water surface with minimal disturbance to the flow. For each wind speed, three independent runs were performed.

To obtain an independent estimate of the spray concentration, with which to compare the altimeter observations, we employed an optical technique using a digital line scan camera and a continuous blue laser beam [Digital Laser Elevation Gauge (DLEG)]. The DLEG was installed 2 m downwind of the laser altimeter. The laser operates at 450 nm, and it was directed downward from the top of the tank so that it occupied a vertical cut from the water surface to the lid of the tank. A digital line scan camera (2048 $\times$ 1 pixels) was oriented vertically along the laser beam. Spray particles passing through this beam were illuminated and imaged by the camera. The advantage of this technique is that it provides observations along a comparable path to the infrared laser altimeter in contrast to techniques that draw air mixed with spray out from a single location (e.g., Fairall et al. 2009). The camera was set to sample at 250 Hz. Data were recorded continuously but saved in 1-s blocks. Two sample images are shown in Figs. 2 and 3 for 10-m wind speed of 30 and 60 m s^{-1}, respectively. These images have the appearance of being a snapshot of the water surface but are actually a series of stacked line scans.

3. Estimate of spray volume from line scan camera images

Because the water particles scatter part of the incident light in all directions, spray droplets appear in the form of bright spots in the high-resolution images (see, e.g., Anguelova et al. 1999; Fairall et al. 2009). Here, we make the assumption that the brightness of the portion of image above the water surface is mainly controlled by the spray. An increase in brightness, therefore, corresponds to an increase of the concentration of suspended water droplets (see Figs. 2 and 3). The overall brightness of the images taken in the absence of spray (mechanically generated waves) is used as a reference measurement to evaluate the increment of brightness induced by the aerosol and, consequently, provide an estimate of the spray concentration above the water surface. An estimate of this concentration is calculated for each composite image (i.e., every second). For each test, an average over all recorded images was considered. For convenience, we converted the spray concentration into the spray volume produced per square meter of surface per second. It is important to mention that this estimate considers all suspended droplets over the water surface and is not capable of discriminating the size distribution of droplets.

Postprocessing of the line scan camera image output was performed with standard graphical functions available in MATLAB. The grayscale images were converted into two-dimensional arrays, where each element corresponded to the grayscale intensity of a single pixel in the image. At the water surface, pixels are much brighter (almost white) than at the spray droplets. This feature allowed the identification of the air–water interface and, consequently, the separation of the air column, which is the only part of the image of interest for the estimation of spray volume. An average gray intensity was thus estimated over all air elements (pixels) of the arrays. To calculate the increase of the brightness, the pixel intensity was then evaluated in conditions of no spray. This was retrieved from a series of measurements with gently sloping mechanically generated waves (i.e., no wind). Under these circumstances not only is spray eliminated, but also the occurrence of whitecaps and breaking is avoided. The relative increment of the average pixel intensity between the case with and without spray is interpreted as the percentage of air volume occupied by suspended water droplets. Considering that the line scan camera monitors a vertical slice of the air volume at a finite sampling interval (250 Hz), an estimate of the total air volume that passes through the sample scan depends on the width of a single pixel in the image (i.e., ~0.2 mm), and the speed of air passing through the sample scan. The estimation of the total spray volume per squared meter per second was then straightforward.

In Fig. 4, laboratory estimates of spray volume are presented as a function of U_{10}. This represents an average over the three independent runs; the concurrent 95% confidence interval (i.e., 2 times the standard deviation) is also presented. For wind speeds lower than about 30 m s^{-1}, an estimate of the overall spray volume can be calculated from the integration of the spray generation function, commonly denoted as dF/dr_0 (see, e.g., O'Dowd and de Leeuw 2007), where r_0 is the radius of a droplet at its formation. Many spray generation formulations have been previously developed with very different results. To test the consistency of our measurements, here we used the source functions proposed by Andreas (1998), which is a modified form of the empirical formulation by Smith et al. (1993) that can be applied to predict the production of spray droplets with radii from 2 to 500 μm. An estimate of the spray volume per squared meter per second can thus be calculated as the integral over the range of radii. This estimate is presented as a function of U_{10} in the form of a dashed line in Fig. 4.

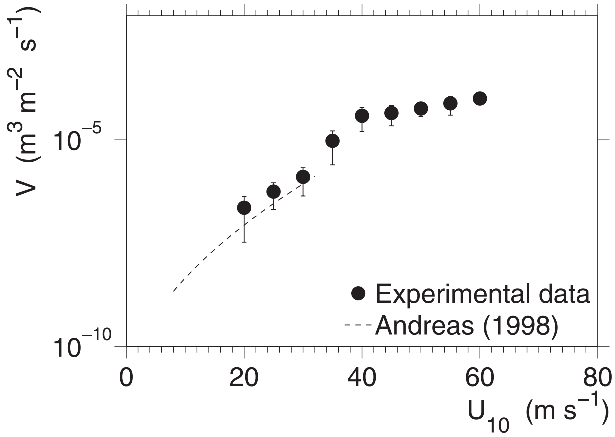

FIG. 4. Spray volume as a function of wind speed. Observations of spray volume are estimated from the digital line scan camera.

On the whole, the spray volume shows a general monotonic increase with the increase of the wind speed. For low wind speed ($U_{10} \leq 30$ m s^{-1}), the amount of spray is rather variable as indicated by a relatively large confidence interval. Nonetheless, the measurements are consistent with the formulation in Andreas (1998), even though they tend to be slightly higher. Note that this agreement is notable despite the use of freshwater in the experiments. For higher winds ($U_{10} > 30$ m s^{-1}), on the contrary, the uncertainty is substantially reduced (i.e., measurements from the different runs are more consistent). Furthermore, there is also a notable deceleration of the growth of spray volume, which seems to reach an asymptotic limit; this may indicate a saturation of the boundary layer. It is also interesting to note that a qualitative approximation of the observed values of spray volume can be obtained, to some extent, by forcing the formulation in Andreas (1998) beyond the boundary of its validity (i.e., $U_{10} > 32.5$ m s^{-1}).

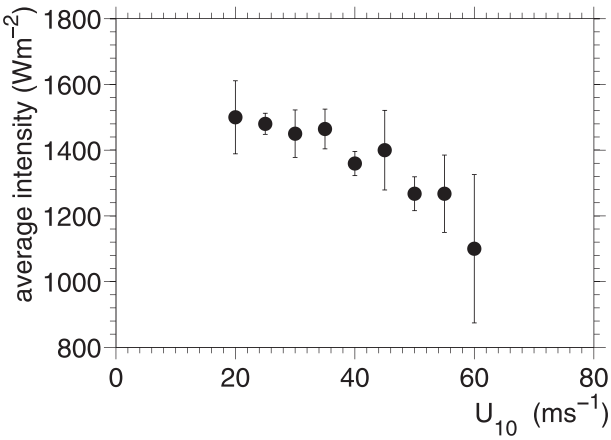

FIG. 5. Average intensity of the infrared laser radiation as a function of the wind speed.

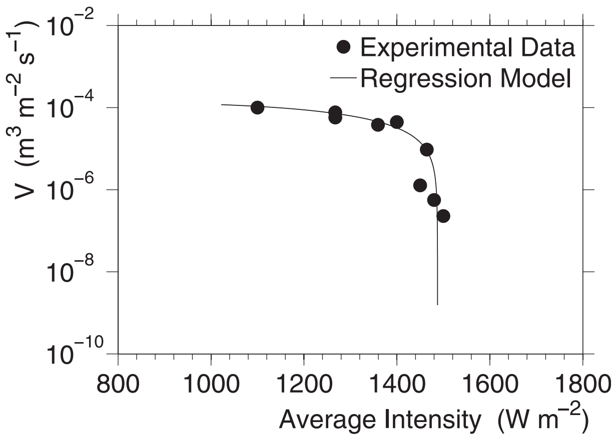

FIG. 6. Spray volume vs average intensity; data are fitted by a quadratic polynomial function [Eq. (1)].

4. Effects of spray droplets on laser intensity

For increasing wind speed, there is an enhancement of the surface roughness and suspended spray volume. Whereas spray absorbs a fraction of the laser energy, resulting in lower backscattered intensity, a rough surface causes more backscatter, leading to a higher recorded intensity (Bateson et al. 2008; Majumbar and Ricklin 2008). Note that foam and bubbles, which form on the water surface at high wind due to wave whitecaps and breaking, may also increase the laser backscattered intensity (Walker et al. 1996; Ericson et al. 1999). In this section, we discuss the variability of the magnitude of the laser radiation for increasing spray volume (and hence wind speed). In Fig. 5, the intensity of the optical transmission is presented as a function of U_{10}; an average intensity over the three independent realizations for each wind speed is presented; the concurrent 95% confidence interval is also displayed.

Tests for gently sloping mechanically generated waves indicate that the laser intensity is on average equal to about 1100 W m^{-2}. In the presence of a moderate wind (e.g., $U_{10} = 20$ m s^{-1}) the intensity was observed to increase up to about 1500 W m^{-2}. As spray concentration is rather low under these circumstances, the enhancement is likely to be related to the surface roughness. As wind speed and, consequently, spray volume further increase, however, the laser radiation was observed to consistently reduce its intensity despite the increase of surface roughness and wave breaking probability (Fig. 5). Thus, this seems to confirm the initial hypothesis that the absorption of the optical radiation by spray droplets dominates the backscatter of the surface roughness. It is important to mention that laboratory measurements are rather uncertain, especially for $U_{10} > 40$ m s^{-1}. This statistical variability may be attributed to the random occurrence of wave breaking, which may result in an arbitrary increase of the backscattered intensity (cf. Walker et al. 1996; Ericson et al. 1999). Interestingly enough, however, the statistical uncertainty does not seem to alter the overall degradation of the intensity of the optical signal for increasing wind forcing and hence spray volume.

The relationship between the magnitude of the optical transmission and the volume of spray droplets is highlighted in Fig. 6. Note that this finding does not depend on the fact that waves are small or short fetched or the vertical spray distribution is limited by the upper lid. This is simply a connection of the reflected laser intensity with the amount of suspended droplets, regardless the cause of spray. The present result can therefore be used to infer a regression model, which can provide an estimate of the amount of spray volume crossed by the laser radiation. In this respect, we mention that an exponential law, in line with the Beer–Lambert law for radiation absorption (e.g., Ingle and Crouch 1988), would predict an asymptotic behavior at high wind speeds, which is not consistent with the observations. Despite some scatter, the relationship between spray and laser intensity shows in fact an evident quadratic pattern. A regression model based on a power law can conveniently be used to fit the observations (see Babanin 2011). However, the analysis of the residuals shows a systematic tendency to overpredict the volume of spray droplets for strong winds. A more accurate model can be achieved by a quadratic polynomial function. Using a least squares method (for details, see, e.g., Emery and Thomson 2001), its form is as follows:

$$y = -3 \times 10^{-10} x^2 + 5 \times 10^{-7} x - 8 \times 10^{-5}, \quad (1)$$

where x is the average laser intensity and y is the spray volume. For Eq. (1), the norm of the residual is about

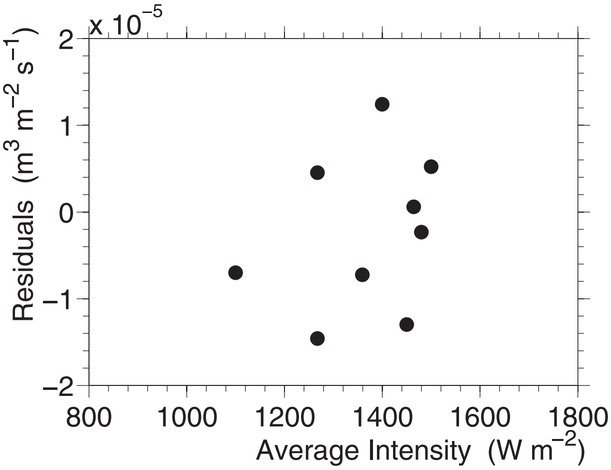

FIG. 7. Residuals of the polynomial fit.

four orders of magnitude lower than the values of spray volume. Moreover, the residuals appears to be uncorrelated (see Fig. 7), thus excluding the presence of systematic deviations from the regression model.

5. Conclusions

Laboratory tests in a wind-wave flume were presented. Experiments were carried out to investigate the effect of suspended spray droplets on the degradation of a downward-looking infrared laser altimeter signal under extreme wind conditions (up to 10-m wind speed of 60 m s^{-1}). The spray volume was evaluated from a digital line scan camera output looking sideways at a slice of the tank that was intersected by a continuous blue laser. Results were then used to develop an empirical method to estimate the spray volume from direct measurements of the laser intensity.

In general, our observations of spray indicate that the total volume of suspended spray droplets grows monotonically with increasing wind speed from moderate to strong winds. For very strong wind, however, the growth of spray volume substantially attenuates as the volume tends to reach an asymptotic limit. Because the suspended spray remains confined between the water surface and the flume's upper lid, this behavior may be related to a possible saturation of the air column.

In the presence of wind, the formation of suspended spray droplets becomes responsible for the absorption and scattering of a fraction of the laser radiation during its propagation to and from the water surface, which results in a reduction of the returned signal's intensity. For increasing wind, however, the enhancement of surface roughness, as well as foam and bubbles that generate from wave whitecapping and breaking, tends to enhance the backscatter of the altimeter signal with a consequent increase of the returning intensity. It is therefore unclear a priori to what extend the spray and surface roughness can modify the overall intensity of the laser radiation. In this respect, the experimental observations show that there is a robust degradation of the laser for increasing wind. This suggests that the intensity of the optical radiation is dominated by the absorption due to spray droplets, despite the backscatter of surface roughness and wave breaking. This results in a clear inverse correlation between the spray volume and the intensity of the laser. This relation was parameterized by a quadratic polynomial function (1). Because laser altimeters can normally be operated during tropical storms, this relation can thus provide an indirect method to observe spray volume in yet unexplored wind conditions.

It is important to mention that laboratory conditions differ from the ocean environments, where waves can be larger and subjected to longer fetches and spray droplets may spread over a deeper atmospheric layer. Also, the use of freshwater instead of saltwater significantly reduces the amount of surface foam and small bubbles and produces a very different droplet size distribution. However, we stress the fact that this study simply refers to the connection of the intensity of the optical signal with the amount of suspended spray droplets crossed during its propagation, regardless the stage of evolution of the wave field or the cause of the spray generation. For quantitative application to the open ocean marine environment, additional measurements will be required to calibrate the returned laser altimeter intensity to extract spray volumes.

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REFERENCES

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.

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

——, 2004: Spray stress revisited. *J. Phys. Oceanogr.,* **34,** 1429–1440.

——, 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, doi:10.1007/BF00712389.

Anguelova, M., R. P. Barber Jr., and J. Wu, 1999: Spume drops produced by the wind tearing of wave crests. *J. Phys. Oceanogr.,* **29,** 1156–1165.

Babanin, A. V., 2011: *Breaking and Dissipation of Ocean Surface Waves*. Cambridge University Press, 485 pp.

Bateson, L., and Coauthors, 2008: The application of remote-sensing techniques to monitor CO_2 storage sites for surface leakage: Method development and testing at Latera (Italy) where naturally produced CO_2 is leaking to the atmosphere. *Int. J. Greenhouse Gas Control,* **2,** 388–400, doi:10.1016/j.ijggc.2007.12.005.

Dysthe, K., H. E. Krogstad, and P. Müller, 2008: Oceanic rogue waves. *Annu. Rev. Fluid Mech.,* **40,** 287–310, doi:10.1146/annurev.fluid.40.111406.102203.

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.

——, 2003: A similarity hypothesis for air–sea exchange at extreme wind speeds. *J. Atmos. Sci.,* **60,** 1420–1428.

Emery, W., and R. Thomson, 2001: *Data Analysis Methods in Physical Oceanography*. Advanced Series on Ocean Engineering, Vol. 2, Elsevier Science, 638 pp.

Ericson, E. A., D. R. Lyzenga, and D. T. Walker, 1999: Radar backscatter from stationary breaking waves. *J. Geophys. Res.,* **104** (C12), 29 679–29 695.

Fairall, C. W., M. L. Banner, W. L. Peirson, W. Asher, and R. P. Morison, 2009: Investigation of the physical scaling of sea spray spume droplet production. *J. Geophys. Res.,* **114,** C10001, doi:10.1029/2008JC004918.

Fischer, R., A. Ting, G. DiComo, J. Prosser, J. Penano, B. Hafizi, and P. Sprangle, 2009: Absorption and scattering of 1.06 μm laser radiation from oceanic aerosols. *Appl. Opt.,* **48,** 6990–6999, doi:10.1364/AO.48.006990.

Forristall, G., 2000: Wave crests distributions: Observations and second-order theory. *J. Phys. Oceanogr.,* **30,** 1931–1943.

Haus, B. K., D. Jeong, M. A. Donelan, J. A. Zhang, and I. Savelyev, 2010: Relative rates of sea–air heat transfer and frictional drag in very high winds. *Geophys. Res. Lett.,* **37,** L07802, doi:10.1029/2009GL042206.

Hauser, D., K. K. Kahma, H. E. Krogstad, S. Lehner, J. Monbaliu, and L. W. Wyatt, Eds., 2005: *Measuring and Analysing the Directional Spectrum of Ocean Waves*. Cost Office, Brussels, 465 pp.

Ingle, J. D. J., and S. R. Crouch, 1988: *Spectrochemical Analysis*. Prentice Hall, 608 pp.

Kudryavtsev, V. N., and V. K. Makin, 2009: Model of the spume sea spray generation. *Geophys. Res. Lett.,* **36,** L06801, doi:10.1029/2008GL036871.

Macaskill, C., 1991: Geometric optics and enhanced backscatter from very rough surfaces. *J. Opt. Soc. Amer.,* **8A,** 88–96.

Majumbar, A. K., and J. C. Ricklin, Eds., 2008: *Free-Space Laser Communications: Principles and Advances*. Optical and Fiber Communications Report Series, Vol. 2, Springer Science, 418 pp.

Melville, K. W., and P. Matusov, 2002: Distribution of breaking waves at the ocean surface. *Nature,* **417,** 58–63.

O'Dowd, C. D., and G. de Leeuw, 2007: Marine aerosol production: A review of the current knowledge. *Philos. Trans. Roy. Soc.,* **A365,** 1753–1774, doi:10.1098/rsta.2007.2043.

Optech, 2004: SENTINEL 3100 users' manual. Tech. Rep. 290-000142/Rev B, Optech, Inc., 70 pp.

Smith, M. H., P. M. Park, and I. E. Consterdine, 1993: Marine aerosol concentrations and estimated fluxes over the sea. *Quart. J. Roy. Meteor. Soc.,* **119,** 809–824, doi:10.1002/qj.49711951211.

Walker, D. T., D. R. Lyzenga, E. A. Ericson, and D. E. Lind, 1996: Radar backscatter and surface roughness measurements for stationary breaking waves. *Proc. Roy. Soc. London,* **452A,** 1953–1984.