Short surface waves in the Canadian Arctic in 2007 and 2008

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Received 18 September 2012; revised 6 June 2013; accepted 12 June 2013; published 30 July 2013.

[1] We have collected time series data of short oceanic waves as a part of the International Polar Year (IPY) 2007–2008. Using a shipboard laser wave slope (LAWAS) system operating at 900 nm, we have obtained wave slopes measurements up to 60 rad m⁻¹ wave number. We have compared our in situ wave slopes with collocated and concurrent high-resolution upwind Normalized Radar Cross Sections (NRCS) collected by QuikSCAT. The LAWAS measured wave slope spectra were consistent with local wind speeds and QuikSCAT measured NRCS. Our measured short wave mean slopes indicate their enhancement by long waves (0–1 rad m⁻¹) at small values of long-wave slope. Concurrent with wave slope measurements, the strength of the reflected LAWAS light beam was analyzed in terms of the light attenuation coefficient at 900 nm. We have observed a correlation between surface elevation and light attenuation. The mechanism of wave modulated beam attenuation was found to be related to the instantaneous long wave skewness.

Citation: Bogucki, D. J., W. M. Drennan, S. Woods, S. Gremes-Cordero, D. G. Long, and C. Mitchell (2013), Short surface waves in the Canadian Arctic in 2007 and 2008, *J. Geophys. Res. Oceans*, *118*, 3712–3722, doi:10.1002/jgrc.20273.

1. Introduction

[2] Our work is focused on field measurements of short oceanic wave slopes. The importance of the short-wave slopes lies in the fact that they are a good proxy for quantifying measurement of how efficiently the ocean exchanges CO₂ with the overlying air. Gas is transferred across the air-water boundary when the diffusive sublayer, the thin layer where molecular diffusivity is the dominant process, is disrupted. Experimental studies reveal that the most important process mediating gas transfer at moderate wind speeds is microscale breaking of short wind waves, i.e., those with wavelengths of 0.03-0.1 m [Zappa et al., 2002; Bock et al., 1999; Peirson and Banner, 2003]. The oceanic observations of Frew et al. [2004] suggest that the short wave slopes corresponding to waves between 40 and 800 rad m⁻¹ are linearly related to gas transfer flux with a correlation coefficient of at least 89%-i.e., the linear fit accounts for at least 89% of the observed variance. Unfortunately, the dynamics of short oceanic waves remain both poorly quantified and understood. Some short wave

dynamics can be gleaned from a few field experiments (e.g., Gasex2001) [McGillis et al., 2004; Jackson et al., 2012] or inferred based on the strength of the microwave backscatter off the oceanic surface. For example, the QuikSCAT Ku-band radar (13.46 GHz) signal is particularly sensitive to the approximately 1.45 cm long surface waves which dominate the return signal via Bragg scattering. Furthermore, satellite scatterometers such as QuikS-CAT (or future Ocean Vector Winds missions) are capable of obtaining a wide snapshot of the oceanic wave field for waves between 360 and 510 rad m^{-1} [Bogucki et al., 2010]. Unfortunately, there are very few oceanic in situ wave measurements collocated with satellite scatterometer overpasses to verify the accuracy of microwave wave measurements. Our research aims to bridge that gap by directly measuring the short wave spectra and relating them to satellite scatterometer ocean wave observations. As a part of the International Polar Year (IPY), we have experimentally investigated the variability of short oceanic surface waves with the ultimate goal of relating them to the local carbon dioxide fluxes as described in Bogucki et al. [2010].

[3] The circumpolar flaw lead (CFL) system study was a Canadian-led IPY initiative with over 350 participants from 27 countries. The CFL study was 293 days in duration and involved the overwintering of the research ice-breaker—Canadian Coast Guard Ship "Amundsen" in the Cape Bathurst flaw lead throughout the annual sea-ice cycle of 2007–2008. The CFL experiment was organized around a variety of objectives, many aimed at understanding basic physical and biogeochemical processes in the changing Arctic. For example, *Else et al.* [2012] reports new findings on the annual cycle of pCO₂ and air-sea CO₂ exchange in Arctic waters. Extensive valuable information

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Figure 1. The location of LAWAS deployments described in this paper, see Table 1 for more detail. (Image© 2012 TerraMetrics ©2012 Google Data SIO, NOAA, U.S. Navy, NGA GEBCO.)

can be found in the IPY-CFL special section of the Journal of Geophysical Research.

[4] The paper begins with description of the experimental system and the experiment site, followed by description of the processing methods. Next, we present results including the observed wave spectra, along with the surface roughness measured during the coinciding overpasses of QuikSCAT. We finish with a discussion of the results.

2. LAWAS Wave Measurements

[5] We have designed and built the laser wave slope (LAWAS) system to measure the short surface waves and deployed it from the CCGS "Amundsen" in Baffin Bay and the Beaufort Sea, see Figure 1. In all, 15 weeks of wave time series were collected, with special attention paid to collecting time series that are concurrent and collocated with QuikSCAT overpasses. Out of over 60 observation stations, after quality control, we have selected five representative LAWAS deployments, see Figure 1 and Table 1.

[6] The surface wave slope data were collected during four daytime LAWAS deployments in July and August 2008. The data from the LAWAS 20 October 2007 nighttime station were used to analyze the laser beam attenuation coefficient. This nighttime deployment was carefully selected so as to minimize ambient light contamination. All stations were ice free and characterized by 0.2–1.5 m root mean square (rms) wave amplitude. For a more detailed station description and QuikSCAT measured wind speeds averaged within 30 km from the station location, see Table 1.

[7] The LAWAS system (Figure 2) consisted of four Riegl LD-90 laser range finders (or LIDAR) operating at 900 nm wavelength. Each optical transmitter/receiver assembly (or "laser head") was made up of a laser and receiving telescope optics. Optical heads were placed at the corners of a square of aluminum plate measuring 0.6 m on each side and were pointed toward the sea surface, perpendicular to the square metal plate holding the optical heads. The metal square plate also housed a full tri-axis motion pack (Systron Donner BEI MotionPak).

Table 1. LAWAS Measurement Stations and Description of Concurrent QuikSCAT (QS) Overpasses

Date	File Name	Latitude N (deg, min)	Longitude W (deg, min)	LAWAS Data (UTC)	QS Pass (UTC)	QS Rev #	QS Wind Speed (ms ⁻¹)	
20 Oct. 2007	Oct20	71, 47	126, 33	4.5-5.1 (21 October)				
19 Jul. 2008	Jul19_S2	70, 05.94	120, 02.52	4.88-5.72	4:47	47,298	4.7	
22 Jul. 2008	Jul22_S1	71, 42.27	126, 32.76	4.27-5.37	3:28	47,340	5.6	
22 Jul. 2008	Jul22_S1	71, 42.27	126, 32.76	4.27-5.37	5:09	47,341	4.7	
31 Jul. 2008	Jul31_S1	71, 10.80	133, 33.94	11.92-12.55	11:45	47,459	4.9	
1 Aug. 2008	Aug1	71, 18.189	126, 16.376	4.1-4.68	4:09	47,483	9.1	



Figure 2. LAWAS, four Riegl laser range finders operating at 900 nm, mounted 60 cm apart at the corners of a square and attached to an extendable aluminum beam. The mean distance to the sea surface is around 8 m. Inset: The CCGS Amundsen where LAWAS was installed during 2007 and 2008 experiments.

[8] The square metal plate with laser heads was attached to an extendable 12 cm \times 12 cm \times 7 m aluminum beam. During measurement collection, the beam was extended from the upwind side of the ship. Four receiving units collected data from each Riegl rangefinder and tagged it with a time stamp. Data were then sent over a gigabit ethernet cable to a LabView-based data acquisition system. Concurrently with optical data, an additional acquisition system collected motion data from the MotionPak.

[9] Every second, each of the four range finders (independently of each other) sent 2000 short light pulses toward the sea surface. The gated light reflections from the sea surface were binned and averaged in groups of 30 returns, thus yielding the average distance to the sea surface every 30/2000 s. This corresponds to $\simeq 66.7$ Hz acquisition frequency with an ensemble accuracy of better than 1 mm. We have verified that accuracy in the lab using a variety of reflecting surfaces. For discussion, we have selected sets of 30 valid returns thus eliminating returns from rain particles or small snow flakes suspended in the air.

[10] The laser telescopes were mounted so that each laser head and its spot on the ocean surface created a square with a side of 0.6 m in length, see Figure 3 (top). The nominal distance between the laser telescopes and sea surface was less than 8 m and each of the laser spots on the ocean surface was typically 2 cm in diameter. Collocated with each laser (and mounted within the same laser head) was a receiving telescope with a field of view (FOV) partially overlapping the laser spot as seen in Figure 3 (bottom). The overlap area was smaller than either the laser spot or the receiving telescope FOV yielding an effective spot smaller than 1 cm wide, as shown in Figure 3 (bottom).

[11] The overlap length effectively sets up the shortest resolvable surface wave—less than 2 cm in our configuration. To be able to interpret the results of our measurement, we need to develop a model of laser pulse reflection from the sea surface.

3. Model of Laser Pulse Reflection From the Sea Surface

[12] The 66.7 Hz LAWAS data stream contains time series of distance from the surface and the reflected signal strength. The returned signal strength is measured in 256



Figure 3. (top) The image of the LAWAS laser generated spots at 8 m away from the laser heads. (bottom) Close up of LAWAS laser spots. Partially overlapping with the laser spot is the spot corresponding to the receiving telescope field of view. Note the overlap region between telescope field of view and the laser spot. Each of the spots is approximately 2 cm wide. The overlap region, the source of the received light pulse, is less than 1 cm long.

increments such that zero is the weakest and 255 is the strongest signal.

[13] Light attenuation and surface reflection coefficients were the two main factors affecting the LAWAS returned signal strength. The LAWAS light pulse after leaving the laser and before making its way to the receiver, undergoes attenuation in air, reflection from the water surface and then attenuation in air again.

[14] To the first order, the light beam reflection off the sea surface depends on the value of its Fresnel reflection coefficients and the statistics of the wave facets linking the laser with the detector. For a clean water surface undisturbed by a background swell, the Fresnel reflection coefficients are relatively insensitive to the wind speed up to 12 ms^{-1} and are relatively constant with an incidence angle up to 45° [*Haltrin et al.*, 2000], which is much larger than any encountered wave. Hence, the reflectance of the pure water surface is relatively constant with reflectance (R_s) values between 0.02 and 0.03 for most of the waves and wind conditions encountered in our experiment.

[15] In the case of a water surface covered by foam or whitecaps, the surface reflectance becomes drastically different. The optical properties of white caps at 900 nm are characterized by little absorption and strong reflectance R_s of around 0.4–0.6 [*Koepke*, 1984]. We have used the white caps' large light reflectance and their relative insensitivity to environmental conditions as a means to calibrate Riegl returns and ultimately to calculate the light attenuation between ocean surface and Riegl receiver. Typically with no wind, background whitecaps have been observed to cover less than 0.01% of the sea surface [*Goddijn-Murphy et al.*, 2011]. During the deployment on 20 October 2007, the wind speed was around 8 m s⁻¹, corresponding to the whitecap coverage of around 0.2%, equivalent to few seconds long-time interval containing whitecaps over a 30 min long deployment.

[16] The light beam reflection coefficient of a clean ocean surface is further complicated by effects of the time varying curvature of the ocean surface. The surface curvature created by long waves results in reflection at wave troughs being somewhat larger then at wave crests [*Srokosz*, 1986]. The difference between reflection at the wave trough and the wave peak is linked to nonGaussian wave slope statistics.

[17] As the LIDAR works by specular reflection, it senses the elevation of wave facets with zero slope relative to the incoming light beam. For realistic wave slopes, to the leading order, the zero-slope wave statistics, as a function of wave displacement, is a Gaussian function multiplied by an odd (third) order polynomial [*Srokosz*, 1986; *Jackson*, 1979]. The presence of the odd third-order polynomial mathematically implies different light beam reflectance at wave troughs and peaks. The peak/trough reflectance difference in turn, depends on the skewness of the sea surface elevation distribution [*Srokosz*, 1986]. Physically, this is related to the peakier crests and flatter troughs of nonlinear waves and is a measure of the nonlinearity.

[18] We illustrate the effect of these processes on a LIDAR beam in terms of beam attenuation—a quantity independent of the LIDAR radiated power.

4. Measured Light Beam Attenuation at 900 nm

[19] In general, we can express the received pulse intensity reflected off the water surface with beam reflectance R_s and attenuated in air as:

$$I(z) = I_0 R_s \exp\left(-2\int_0^z \alpha(z') dz'\right) = I_0 R_s \exp\left(-2\overline{\alpha}(z)z\right), \quad (1)$$

where z is the distance to the ocean surface, I_0 is the LAWAS initial pulse strength, $\alpha(z)$ is the distancedependent absorption in air, and $\overline{\alpha}$ is the mean absorption, in the integral sense, over distance z, i.e., $\overline{\alpha}(z) = 1/z \int_0^z \alpha(z') dz'$.

 $\begin{bmatrix} 20 \end{bmatrix}$ When the beam reflects from a bright target such as a white cap, then equation (1) can be rewritten as:

$$I_{\max}(z_{\max}) = I_0 R_{s_{\max}} \exp\left(-2\overline{\alpha}_{\max}(z) z_{\max}\right), \qquad (2)$$

where indices ()_{max} correspond to the target distance, water reflectance, and air attenuation when observing the reflective target.

[21] Combining equations (1) and (2) yield the expression for the mean attenuation as:

$$\overline{\alpha}(z) = \frac{\ln\left[I_{\max}/I(z) + A\right]}{2z},\tag{3}$$

where the constant A is estimated to be $A \simeq -0.06$ based on laser 1 measurements carried out on 20 October 2007. Note that the presence of any obstruction on the water surface such as foam, whitecaps, and so on results in *lowering* of the mean absorption $\overline{\alpha}$, as the clean water surface is a very weakly reflective target.

[22] In the air, the main source of pulse absorption at 900 nm is the presence of the water vapor [*Walker*, 1994]. The pure water absorption coefficient at 900 nm is 7 m⁻¹ [*Mobley*, 1994], which results in the light beam losing 72% of its energy over a distance of 14 cm when propagating in liquid water.

[23] We have used the 20 October 2007 LAWAS data set collected during Arctic night. The data spans 30 min and are the laser 1 measurements. A subset of the full record, a 30 s time series of attenuation is presented in Figure 4a. The black dots are the instantaneous surface elevation (the mean elevation is zero), while the connected red dots represent the calculated (equation (3)) beam attenuation at 900 nm. In the time interval 1570-1600 s, see Figure 4a, the measured attenuation varies between 0.02 and 0.16 m^{-1} and the surface elevation about the mean varies between -2.5 and 2.5 m. At the first wave peak (t = 1573 s), the laser 1 maximum sensed attenuation lags slightly behind the wave peak, while the last wave peak coincides with the maximum air attenuation (t = 1595 s). Note that the presence on the surface of any features (foam, etc.) or reflection from a passing snowflake should decrease the measured attenuation.

[24] We have observed several instances when the wave peak is associated with observed increased mean absorption, see Figure 4b. The scatterplot of all measured absorption values as a function of the surface elevation for the nighttime deployment of 20 October clearly shows the



Figure 4. (a) Long-time series (30 s) of LAWAS, laser 1 attenuation as estimated from equation (3). The red connected dots: The light pulse attenuation the black dotes denote the ocean surface location (the mean surface location is at z = 0 m). (b) Scatter plot (20 October 2007) of measured light attenuation, equation (3) versus the surface displacement from the mean. (c) The scatterplot of skewness of the long-wave component versus observed attenuation for waves larger that 2.5 m amplitude.

correlation. Note the asymmetry of the scatterplot with enhanced absorption when the surface displacement exceeds 2.5 m.

[25] Light attenuation when plotted as a function of the long and large wave's skewness is presented in Figure 4c. The long-wave component was obtained by filtering the



Figure 5. (top) A 30 s subset of 1 August 2008 time series of LAWAS measured surface elevation (Laser 1). (bottom) The high frequency (>1 Hz) part of the above elevation time series. Note the effect of the linear interpolation between missing data points.

surface displacement record by a 1 Hz low pass filter and retaining only waves of 2.5 m or larger, Figure 4c.

[26] The skewness of the long-wave component is related to observed light beam attenuation such that only waves with increasingly negative skewness (i.e., "forward leaning" waves) are associated with increased attenuation, Figure 4c. This is consistent with the wave trough/peak reflectance asymmetry as discussed earlier, albeit the insensitivity of the absorption to large and positive wave's skewness is puzzling. A possible explanation for that could be paucity of data with larger wave displacement.

5. LAWAS Measured Surface Displacement

[27] Each Riegl unit is a range finder (LIDAR) which senses the distance to the water surface by converting the transmitted short light pulse from the time of flight to the distance from the obstacle, i.e., the water surface. The distance to the water surface is then calculated as the time taken for the reflected light to return to the laser head. The LAWAS had the lowest amount of dropouts when the water surface was populated with strongly scattering capillary waves with wavelengths smaller than 1 cm—typically encountered when the wind speed exceeds 5 m s⁻¹ [*Zhang*, 1995].

[28] During the experiment, we discovered that each Riegl unit with its acquisition system had a significant time drift, i.e., the time stamps of measured distances had some variation when compared to the other Riegl units. The first stage of processing was then to align the readings from all four Riegl units in time. We have accomplished this by correlating readings of a selected Riegl unit (laser 1) with the remaining three units. For the cross correlation, we used a 1 min long time series subset (typically containing 5–10 waves). The largest observed time lag was around 20 s at the end of a 30 min long data set.

[29] An example of a surface elevation time series for a selected Riegl unit is presented in Figure 5. Each of the Riegl units acquired 66.7 samples per second with corre-

sponding Nyquist frequency 33.35 Hz. Some of the RIE-GEL LIDAR returns have dropped out and these missing data points were obtained by linear interpolation from nearest neighbors. The time series all Riegl units were then resampled on a common time series with a fixed interval $\simeq 1/66.7s$.

[30] In the last step, each of the Riegl unit elevation timer series was split into 10 min long segments and then analyzed for number of dropouts and spikes. For the final analysis, we have only retained the segments with minimal number of dropouts. This approach resulted in reducing by a factor of two the number of good segments available for analysis.

[31] The subsequent statistical spectral analysis was then carried out on an ensemble average of four Riegl units within a 10 min long window.

6. Spatial Omnidirectional Wave Slope Spectra

[32] The Bragg scattering of QuikSCAT microwave signal by the ocean surface depends on waves from a specific wave number range for a given incidence angle. For OuikS-CAT, the range encompasses waves of wave numbers between 360 and 510 rad m^{-1} . In order to convert our LAWAS frequency-based wave surface elevation observations to the spatial domain, we need to assume a relationship between wave parameters such as wave number and frequency. Such a connection is provided in the form of the wave dispersion relation. For deep water, small amplitude, gravity waves (i.e., "linear" surface waves), the dispersion relation between the magnitude of the wave number k and the frequency ω can be expressed as: $\omega^2 = gk$, where g is the gravitational acceleration. Laboratory and field observations demonstrate that as we approach the short gravity waves limit, the observed dispersion relation begins to differ from the linear dispersion relation. Following observations of Wang and Hwang [2004], we assume that the linear dispersion relation for frequency-based measurements is exactly valid up to a wave number of 15 rad m⁻¹ For larger wave numbers, the linear dispersion relation becomes a $k \propto \omega$ like relationship, see Figure 7 of Wang and Hwang [2004] for frequency-based measurements. Wang and Hwang [2004] also document that the linear dispersion relation is valid up to 60 rad m^{-1} when based on spatial surface wave measurements.

[33] Following *Phillips* [1977] and *Hwang et al.* [2000] for a stationary observer, the omnidirectional surface displacement spectrum $\Phi(\omega)$ (see Appendix A), can be converted to omnidirectional wave number wave slope spectrum *S*(*k*) using the following relationship [*Phillips*, 1977]:

$$S(k) = \pi/g \cdot \left[\frac{\omega^3}{2}\Phi(\omega)\right]_{k=\omega^2/g.}$$
(4)

[34] This relationship is valid as long as the observer remains stationary with respect to the water surface which is the case for the analyzed data sets. In the presence of slow ship motion with the speed U, the dispersion relation is modified to become: $\omega_d = \omega + U \cdot k \cos \theta$ (ω and ω_d are, respectively, the real and the Doppler shifted angular frequencies, θ represents the ship angle in respect to the waves, which is assumed to be zero) [Drennan et al., 1994].



Figure 6. Frequency $\Phi(f)$ and slope wave number spectra S(k) acquired during 30 min long LAWAS deployment on 1 August 2008 (Table 1). (top) The frequency displacement spectra. The blue line corresponds to f^{-4} spectral dependence. (bottom) The spatial slope spectra. The f^{-4} in the frequency domain corresponds to $k^{-1/2}$ dependence in the wave number domain. Note slight leveling of the frequency spectra for f > 2 Hz and corresponding S(k) change at k > 10 rad m⁻¹ m. The red line represents the averaged spectra.

[35] The relative accuracy of the wave number estimated from frequency measurements becomes then: $|\Delta k/k| = |2U(\frac{k}{g})^{1/2}|$, when determined from a Doppler shifted wave frequency. Our estimated accuracy of ship drift is $U \simeq 0.1 \text{ms}^{-1}$ implying that the maximum relative wave number error $\Delta k/k \simeq 50\%$ is at k = 60 rad m⁻¹, which also is the upper domain limit for S(k) spectra in Figure 6.

[36] The observed surface elevation spectra $\Phi(f)$ shown in Figure 6 exhibit the expected f^{-4} or equivalent of $k^{-1/2}$ for the wave slope spectra, S(k), down to the wave number of k = 2.5 rad m⁻¹, within the equilibrium subrange. Note some leveling of the frequency spectra for f > 2 Hz and corresponding S(k) change at k > 10 rad m⁻¹. The S(k) slope change at around k > 10 rad m⁻¹ reflects the dynamics of observed surface waves [*Hwang*, 2005] and also is partially an artifact of linear interpolation of missing points as in Figure 5.

[37] This last point can be understood when considering the effect of linear interpolation on missing LAWAS data points in Fourier space. The linear interpolation corresponds in physical space [*Vaseghi*, 1996] to convolving the "real" surface elevation spectra $\Phi(f)$ with a filter function, sin $(f/f_0)/f$, with f_0 being the effective filter width. This convolution in the case of monotonically decreasing surface elevation spectra $\Phi(f)$ effectively results in transferring the low-frequency spectral components to higher frequencies.

[38] The additional factor affecting the variability of S(k) spectra is the apparent change of the dispersion relation (from $\omega^2 = gk$ to $\omega \propto k$, Figure 7 of *Wang and Hwang*

[2004]) for k > 15 rad m⁻¹, when the wave slopes are obtained from frequency measurements. Our estimate of this effect on the S(k) spectra is around a factor of 0.2 at k = 60 rad m⁻¹. For consistency with other researchers, we use the linear dispersion relation throughout this paper, keeping in mind that it may contribute up to 20% to overall spectral S(k) error at 60 rad m⁻¹ and less than 10% when considering the S(k) integral in the 20–60 rad m⁻¹ range. The effect of missing LAWAS data points and their subsequent linear interpolation for k > 10 rad m⁻¹ permits only qualitative evaluation of the wave contribution to mean square slopes (mss) in the 20–60 rad m⁻¹ range.

[39] We have minimized the effect of missing data interpolation, which results in spectral transfer of S(k) from shorter wave numbers to longer wave numbers, by constructing a new spectral slope estimator, $\overline{S}(k)$ defined as: $\overline{S}(k) = S(k)/S(k = 20 \text{ rad m}^{-1})$ for k > 20 rad m⁻¹. Normalizing the slope spectra S(k) to a fixed value at k = 20 rad m⁻¹ effectively removes the effects of short wave numbers aliased to longer wave numbers, but precludes us from using the $\overline{S}(k)$ spectra to obtain the absolute values of the mss in the 20–60 rad m⁻¹ range.

[40] In the final step, we compare our wave slope measurements to high resolution concurrent QuikSCAT observations.

7. High Resolution QuikSCAT Observations

[41] In our presentation, we use two quantities derived from QuikSCAT measurements. The upwind Normalized



Figure 7. The high-resolution QuikSCAT data: (a) The wind direction in degrees from north, (b) sigma-0, and (d) wind speed distribution. The data presented here are acquired on 1 August 2008 concurrently with LAWAS measurements. The LAWAS measurements location is denoted by a dot in the Amundsen Gulf. (c)The ice distribution on 1 August 2008 (http://www.ec.gc.ca/). The light blue denotes open water, white denotes the ice free waters, and brown denotes the old ice. The arrow points North.

Radar Cross Section (NRCS, also referred to as σ_0 or sigma-0) and the estimates of wind speeds and directions under the QuikSCAT swath. The QuikSCAT Ku-band radar (13.46 GHz) signal is particularly sensitive to the \approx 1.45cm surface waves which dominate the signal via Bragg scattering. QuikSCAT measures both vertically and horizontally polarized NRCS, i.e., *v-pol* and *h-pol*, respectively [*Spencer et al.*, 2000].

[42] The QuikSCAT instrument design allows for the collection of spatially overlapping measurements of sigma-0 on a fine but irregular spatial grid. The nominal resolution of individual "slice" sigma-0 measurements is

6 km \times 25 km. However, the spatial overlap in the measurements can be exploited to reconstruct the surface sigma-0 at a higher resolution using signal processing techniques [*Early and Long*, 2001]. This enables retrieval of winds on a much finer (i.e., 2.5 km) grid [*Long et al.*, 2003; *Williams et al.*, 2009]. Though noisier than the standard 25 km QuikSCAT wind products, the high-resolution winds reveal mesoscale wind features [*Williams et al.*, 2009; *Plagge et al.*, 2009] and can be used closer to the coast [*Owen and Long*, 2011]. For the details of QuikSCAT data collected simultaneously with LAWAS data, see Table 1.

[43] Figure 7 shows the spatial distribution of sigma-0 wind speed and wind direction concurrently collected with LAWAS observations on 1 August 2008. The data is presented along the QuikSCAT swath, each pixel is 2.5 km wide. The swath (see Figure 7) is oriented approximately the same as the map in Figure 1, with the dark blue color corresponding to approximate land locations.

[44] We can observe in Figures 7b and 7d that the main features of sigma-0 and QuikSCAT estimated wind speed are roughly similar as the wind speed is inferred from the sigma-0 data. Note in Figure 7a that the wind over the LAWAS site is approximately directed toward the North (denoted by red), while the wind on the Western side of the Amundsen Gulf has a predominant Eastward (blue) component, over open water as presented in Figure 7a.

8. The Comparison of Concurrent and Collocated QuikSCAT Observations With LAWAS Data-Long-Wave Effects

[45] Our data set gives insight into complicated interaction of surface wave components. Unfortunately, the paucity of our ship's data set and lack of directionality of wave spectra allows only for simple correlation between wave slope components and preclude us from drawing more advanced conclusions about the evolving wave field.

[46] The times series of wind data measured on the ship is unfortunately incomplete during the LAWAS measurement periods. We have compared available time series of wind speed with QuikSCAT spatial wind distribution and found that mean wind speed relative difference were within 10%.

[47] Here, we have compared spatial sigma-0 fields and temporal wave slope data from LAWAS. All observations are concurrent and collocated, see Table 1. To get a handle on their variability, we have averaged them either in time—over the 30 min for LAWAS time series—or over a 15 km radius around the LAWAS deployment site, in case of QuikSCAT data. The radius of 15 km corresponds to approximately 1/2 h time span of sigma-0 when considering local winds.

[48] The error bar length (see Figure 8) is equal to a standard deviation from the mean for either spatially averaged data from QuikSCAT observations or temporally averaged data from the LAWAS time series over the radius of 15 km or over 30 min interval, respectively, and is a measure of either spatial or temporal variability.

[49] We have grouped the contributions of mean square slopes measured by LAWAS in two wave number ranges: Contribution from wave numbers up to 1 rad m⁻¹ and a normalized contribution from short gravity waves (beyond the equilibrium range) between 20 and 60 rad m⁻¹. The additional third measure of wave slopes is related to the QuikSCAT measured sigma-0 as it carries information about short capillary waves in the range 360–510 rad m⁻¹ [*Bogucki et al.*, 2010].

[50] The comparison of QuikSCAT sigma-0 and wind speed for the analyzed days (Table 1) exhibits (see Figure 8a) an expected increase of surface roughness sigma-0 with increased wind speed. The relationship between LAWAS normalized mss 20–60 rad m⁻¹ and QuikSCAT wind speed shows mss increase with increasing wind speeds and some-

what larger scatter. From a wind-wave interaction perspective, this increase in scatter in the scatterplot of QuikSCAT sigma-0 versus wind speed could be attributed to the fact that QuikSCAT sigma-0 measurements relate to the capillary waves amplitude and thus are representative of nearly instantaneous ocean response to the local wind, see Figure 8b, while the waves from 20 to 60 rad m⁻¹ range respond more slowly to changes in the local wind speed.

[51] In the scatterplots Figures 8c and 8d, we have compared effect of long-wave slopes $(0-1 \text{ rad } m^{-1})$ on partitioned slopes 20–60 rad m^{-1} or 360 and 510 rad m^{-1} wave components. In general, we expect a linear monotonic relationship between long-wave and short-wave slopes reflecting the fact that for unlimited fetch and a steady-state situation larger wind stresses correspond to more steep long-wave components; for review see *Elfouhaily et al.* [1997].

[52] Somewhat unexpectedly the scatterplot of long $(0-1 \text{ rad } m^{-1})$ mss versus the LAWAS normalized mss 20–60 rad m⁻¹ reveals effects of enhanced shortest waves slopes (20–60 rad m⁻¹) at small value of background long-wave slopes, Figure 8c. The larger long-wave slopes in Figure 8c exhibit the expected dependence on long-wave slopes with increasing mss 20–60 rad m⁻¹.

[53] This anomalous behavior at small waves slopes (point 5 in the Figure 8c) can have number of explanations.

[54] An increase of wave growth with decreasing longwave slope component been observed in tank experiments of *Peirson and Garcia* [2008], where long background waves with small steepness were observed to be most efficient in generating slow short waves.

[55] Another possible explanation can be related to unsteadiness of the wind stress and presence of mixed seas [*Hwang et al.*, 2011] during that measurement. Closer analysis of QuikSCAT spatial wind field corresponding to point 5 in Figure 8c reveals very interesting spatial wind structure, see Figure 7a. The wind stress direction over the measurement site was around 300° from North, while on the eastern site of the image the wind stress direction is nearly opposite. Analysis of QuikSCAT spatial wind field for point 4 shows similar to point 5 spatial wind field structure (nearly counter-propagating wind fields) albeit not as pronounced.

[56] Either of the postulated mechanisms can be potentially responsible this increase of short wave mss. Due to limited amount of data, we can not here quantitatively test both hypotheses.

[57] Interestingly both points 4 and 5 in Figure 8c exhibit large scatter for short wave mss reflecting larger variability of the short-wave field. As observed in experiments of *Peirson et al.* [2003], the wave attenuation due to opposing wind is relatively large and this could contribute to the large scatter in 20–60 rad m⁻¹ mss corresponding to points 4 and 5 in Figure 8c.

[58] Figure 8d presents the QuikSCAT observed wave slopes as a function of long-wave slope. Here, similarly to the Figure 8c, the QuikSCAT wave slopes (point 5) are large at small value of long-wave slope $(0-1 \text{ rad m}^{-1})$ and then exhibit the expected increase with increasing larger long-wave slopes. This unexpected large value of short mss at small mean long-wave slope can be attributed to mechanisms discussed earlier.



Figure 8. The comparison of LAWAS measured mean squared wave slopes components, QuikSCAT observed σ_0 and QuikSCAT wind speed. (a) σ_0 versus QuikSCAT wind speed. (b) LAWAS short-wave slope versus QuikSCAT wind speed. (c) LAWAS short-wave slope versus Long-wave slope. (d) QuikS-CAT observed σ_0 versus LAWAS long-wave slope. The error bar corresponds to standard deviation from the mean over for 30 min LAWAS time series or deviation from the mean over a 15 km radius around the LAWAS deployment for the QuikSCAT data. Numbers 1–5 correspond to 19 July, 22 July, 22 July (5:09), 31 July, and 1 August, QuikSCAT overpasses, see Table 1.

[59] Interestingly, the sigma-0 scatter for points 4 and 5 is relatively small. This is consistent with the fact that QuikSCAT observed waves are much shorter and in 360–510 rad m⁻¹ range thus are very responsive to local wind speed. The local wind speeds had similar variability of around 2 m s⁻¹ and this is then reflected in comparable sigma-0 scatter.

[60] Our observations and literature review suggest indirect effects of long waves on short capillary wave field when analyzing QuikSCAT sigma-0. This likely contributes to increased scatter when plotting sigma-0 versus wind speed. Thus, from the air-sea gas exchange point of view, future improved wind parameterization of gas transfer should include effects of the background state of the long waves.

9. Conclusions

[61] LAWAS proved to be a good tool for short-wave slope measurements and enabled us to estimate the sea-surface roughness associated with wave slopes down to 60 rad m^{-1} .

[62] We also have observed the enhancing effect of small values of long-waves slopes (from wave numbers up to 1 rad m^{-1}) on short gravity waves in the 20–60 rad m^{-1} and 360–510 rad m^{-1} ranges.

[63] The effect of long-wave slopes on the QuikSCAT measured surface roughness was observed to be more pronounced—when considering the associated error bars. This effect, if observed in other data sets, could impact calculations of CO_2 gas transfer from local wind speed.

[64] In our data, the LAWAS measured light attenuation at 900 nm was correlated with large wave amplitude (> 2.5

m) skewness and consistent with long waves modifying the local surface curvature.

Appendix A: Surface Wave Omnidirectional Slope Spectra

[65] The two-dimensional ocean surface $\xi(\mathbf{x},1)$ (bold font denotes a vector) is usually represented in terms of the directional wave number spectrum $\psi(\mathbf{k}, t = 0) = \psi(\mathbf{k})$ such that:

$$<\xi(\mathbf{x},t=0)^{2}>=\int_{0}^{+\infty}\int_{-\pi}^{+\pi}\psi(k,\phi)k\mathrm{d}k\,\mathrm{d}\phi=\int_{0}^{\infty}\chi(k)\mathrm{d}k,$$
(A1)

$$\langle \xi(\mathbf{x}=0,t)^2 \rangle = \int_0^\infty \Phi(\omega) \mathrm{d}\omega,$$
 (A2)

where the angle bracket $\langle \rangle$ denotes the ensemble average operator, $\langle \xi^2 \rangle$ is the mean square surface elevation displacement, and $\chi(k)$ is the omnidirectional elevation spectrum such that the total mean square slope (mss) is:

mss =<
$$(\nabla \xi)^2$$
 >= $\int_0^{+\infty} S(k) dk = \int_0^{+\infty} k^2 \chi(k) dk$, (A3)

where S(k) is the omnidirectional wave slope spectrum. The frequency spectrum of the surface wave displacement is denoted as $\Phi(\omega)$, following the approach of *Phillips* [1977].

[66] **Acknowledgments.** We acknowledge the assistance of Tom Snowdon in preparation and assembly of the LAWAS system and Miguel Izaguirre with LabView programming. We also thank the Captains and crews of the CCGS Amundsen, our fellow CFL scientists, and in particular CFL PI Dave Barber. D.J.B. and W.M.D. acknowledge the support of the NASA Physical Oceanography program. We thank the editor anonymous reviewers for their constructive comments, which helped us to improve the manuscript.

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