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Supporting Information for

In Situ Measurements of an Energetic Wave Event in the Arctic Marginal Ice Zone

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Additional Supporting Information (Files uploaded separately)

none

Introduction

Here we present additional supporting materials: A map with wave and ice model details, information supporting 3 claims in the paper, an alternative explanation of an observation, and, at the suggestion of one reviewer, the available satellite imagery. Text S1 and Tables S1 and S2 support the claim that we measured the largest waves in the Arctic region under ice cover. Text S2 and Figure S1 detail the simple method used to estimate the floe size after the breakup of the ice. Text S3 and Figures S2 and S3 give additional information on the low pressure system which generated the wave event. Text S4 and Figure S4 describe the available satellite imagery. Figure S5 is a synoptic map with ice concentration related to the models used in the study. Text S5 deals with an alternative explanation for the low pass filter behavior observed in Fig. 3 of the article.

Text S1. Review of High Latitude Wave Measurements in Ice

Here, to support our claim to have measured the largest waves in ice in the Arctic region, we have attempted to make an exhaustive review of the literature.

Studies report wave height using a variety of metrics. In studies where the individual maximum wave height, H, or the root-mean-square wave height, H_{rms}, was reported, we use a simple formula to convert to the spectral significant wave height, H_{m0}. Considering typical wave periods and analysis times, the following relationships derived from a Rayleigh distribution are roughly applicable [e.g. Holthuijsen, 2007].

$$H_{m0} \approx 1.4 H_{rms} \approx 0.5 H \tag{S1}$$

When only the energy (or variance) density is reported for a particular spectral band, an attempt is made to estimate a JONSWAP spectrum [Hasselmann et al., 1973] based on the energy level at the peak frequency. This is done in a conservative manner such that the estimation of H_{m0} is an upper limit (or perhaps slightly overestimated).

We tried to be thorough, but invariably there will be studies which were passed over or could not be verified. One that fits into the latter category is work by P. Wadhams, in which the measurement of wave heights was made by an inverted echo sounding from a submarine [Wadhams, 1972; Wadhams, 1978]. Though these citations are indexed (e.g. google scholar, web of science) actual records (proceedings in the first case, an article in the second) could not be located.

As far as the Arctic region (see Table S1) is concerned, our study is by far highest and is similar to wave heights observed in the ice free measurements of Thomson and Rogers, [2014] in the Beaufort Sea. As it may be of interest, we have also tabulated the cases of waves measured in ice in the Antarctic as well (see Table S2).

Text S2. Typical Floe Size after Breakup

To support the statement that the waves were long compared to the typical floe diameter after the ice breaks up, we present the following analysis. We do not have direct estimates of floe size, but we have an image which approximately verifies the differences in scale.

The left side of figure S1 shows the ice field on 03 May 2010 02:47:51 UTC during the wave event. There appears to be long waves propagating through the ice. The right side of figure S1 is an attempt to mark the wave crests. The arrows correspond to the approximate wavelength. Using this crude method, the wavelength of the waves are verified to be at least 1 order of magnitude greater than the typical floe diameter.

To stretch the estimation a bit further we may consider the peak wavelength at the time, ~200 m. Then the half arrow in the foreground of the image on the right is ~100m and we estimate the typical floe size to be 5 – 10 m.

Text S3. Synoptic Weather Conditions

The occurrence of a low pressure system presented in the following analysis corresponds with the timing of the wave event encountered by R/V Lance.

Figure S2 shows the synoptic weather charts for the northern Europe produced by the UK Met Office[1]. The plots are in chronological order starting with the top left at 30 April 2010 00:00 UTC, the top right at 01 May 2010 00:00 UTC, bottom left at 02 May 2010 00:00 UTC, and the bottom right at 03 May 2010 00:00 UTC. The low pressure system is located over Norway in the top left. It deepens from 995 mb to 991 mb on 01 May. The minimum pressure shown was 989 mb on 02 May, creating a large fetch of high winds over the Barents Sea.

In Figure S3, the passive satellite microwave radiometer Special Sensor Microwave Imager (SSM/I) indicated wind speeds up to 24 ms^{-1} over the Barents Sea on the morning of 02 May 2010[2]. The synoptic low pressure system and wind speeds are consistent with a Polar Low (sometimes called Arctic Cyclone), though additional meso- or submeso-scale information would be necessary to make an accurate classification.

[1] Retrieved from http://www.wetterzentrale.de/topkarten/tkfaxbraar.htm

[2] Retrieved from http://www.remss.com/missions/ssmi

Text S4. Satellite Imagery

As suggest by a reviewer, it was logical to look at the available satellite imagery to understand whether or not the fractured-ice-front process could be imaged. In Figure S4, there are four images from the advanced synthetic aperture radar (ASAR) on the ENVISAT satellite which was operated by the European Space Aganecy and were generously retrieved and provided by Ben Holt at NASA’s Jet Propulsion Laboratory. The first image in Figure S4 is also included in Figure 1 in the article.

All images in Figure S4 are wide-swath and medium resolution (150 m). In each image, the southern tip of Svalbard is visible at the top and Hopen Island is pointed out near the bottom center. The timing is relative to wave event which occurred on May 2 (top right image). The first image was of very good quality with details of the ice around Hopen Island clearly visible. Even as such, the resolution was not sufficient to identify the floes which were visible from the ship. In addition, the three following images, including the one captured during the event (top right) were of relatively poor quality. Combining the first three images, the large scale retreat of the ice as a result of the event is visible. In the last image it appears that the ice may be growing slightly in extent.

We can think of two mechanisms by which a fractured ice front may be imaged: (1) a change in average backscatter intensity where one side of the front would appear darker than the other side and (2) change in floe size distribution (as inferred by a reviewer). We suppose (2) would require a very good quality image at a very high resolution. In the image taken during the event, a fractured ice front is not obvious. The image quality is so poor, the possibility of process occurring cannot be ruled out nor can we say it cannot be imaged. We hope that this type of process may be found either in archived or future images.

Text S5. Ice as a Low Pass Filter: An Alternative Explanation

For completeness, we consider another alternative: the effect was an artifact of a slow change in the relative angle between the ship heading and wave direction, so that the ship was acting as the filter which effectively increased its range of response with time. We doubt this possibility because 1) we intentionally chose a period when the heading of the ship was relatively constant (see Fig. 1, 02 23:24 – 03 03:30) and 2) this effect requires nearly planar waves, when in reality waves are always directionally spread.

Figure S1. Photograph from the "ice cam" on the R/V Lance from 03 May 2010 02:47:51 UTC corresponding to Figure 2g of the article. The left side is the original. On the right side, black lines have been placed approximately in the position of what appeared to be wave crests. Black arrows are wave rays pointing in the direction of propagation of the waves with length equal to the wavelength. The wave ray in the foreground in incomplete because the wave crest is out of frame.

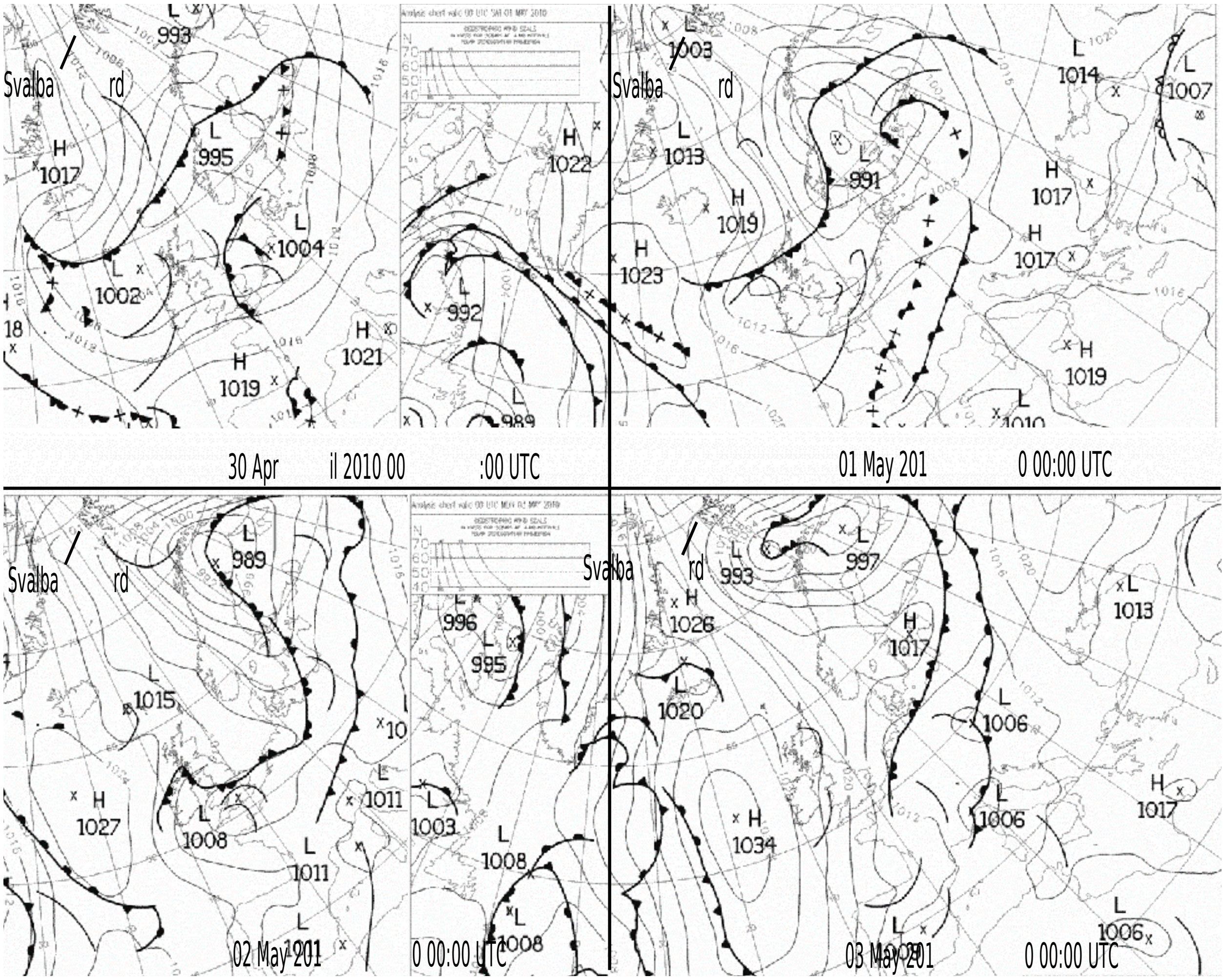

Figure S2 Synoptic weather charts showing the surface pressure at 24 hour intervals starting at 30 April 2010 at 00:00 UTC and ending at 03 May 2010 00:00 UTC going from left to right and top to bottom, respectively. The bottom left, corresponding to May 2, shows the lowest pressure at 989 mb.

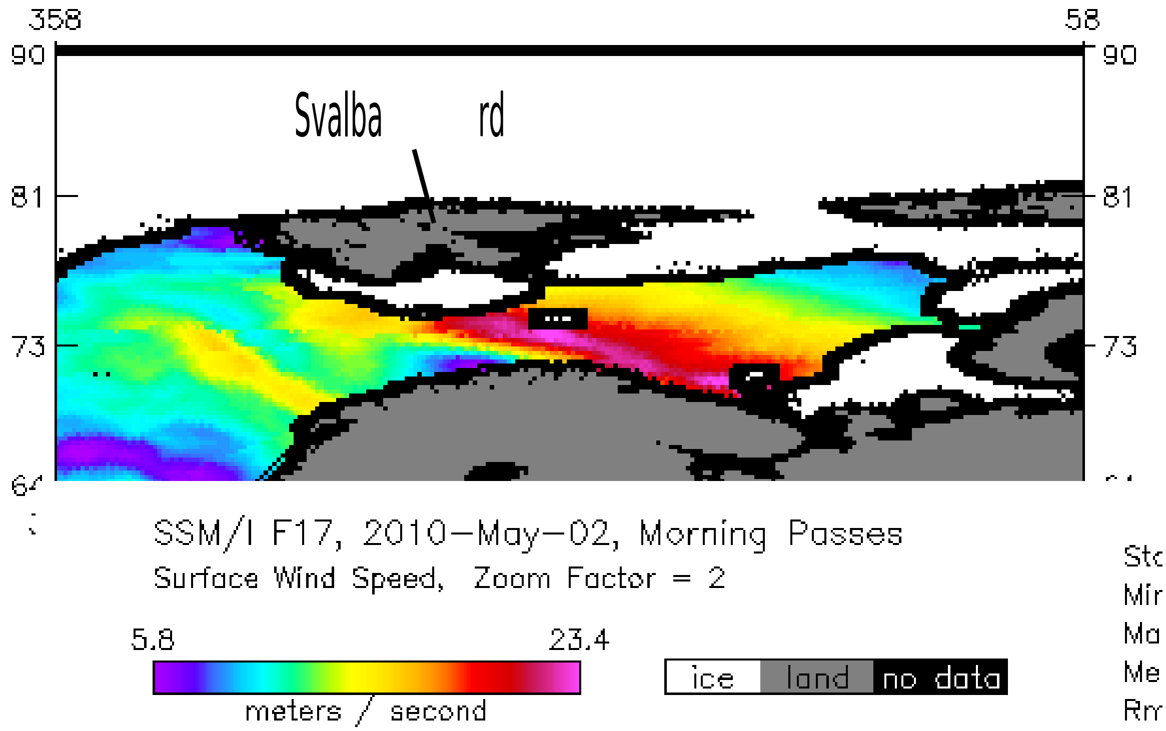

Figure S3 Surface wind speed from SSM/I passive satellite microwave radiometer.

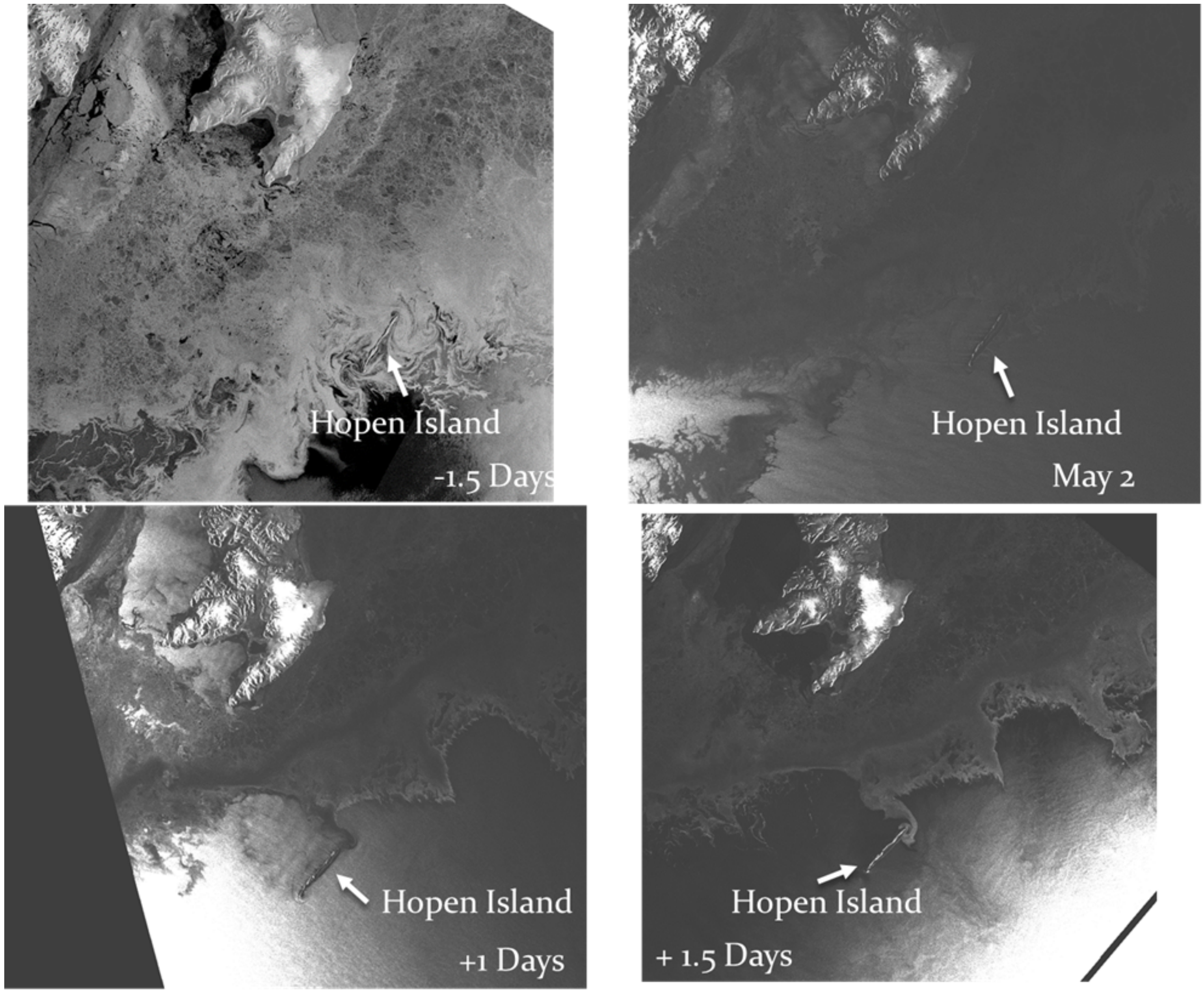

Figure S4 Images from ASAR on ENVISAT which are wide-swath, medium resolution (150 m) provided by Ben Holt (NASA JPL). The southern tip of Svalbard is visible in the top of each image and Hopen Island is pointed out. The timing is relative to May 2 (top right image).

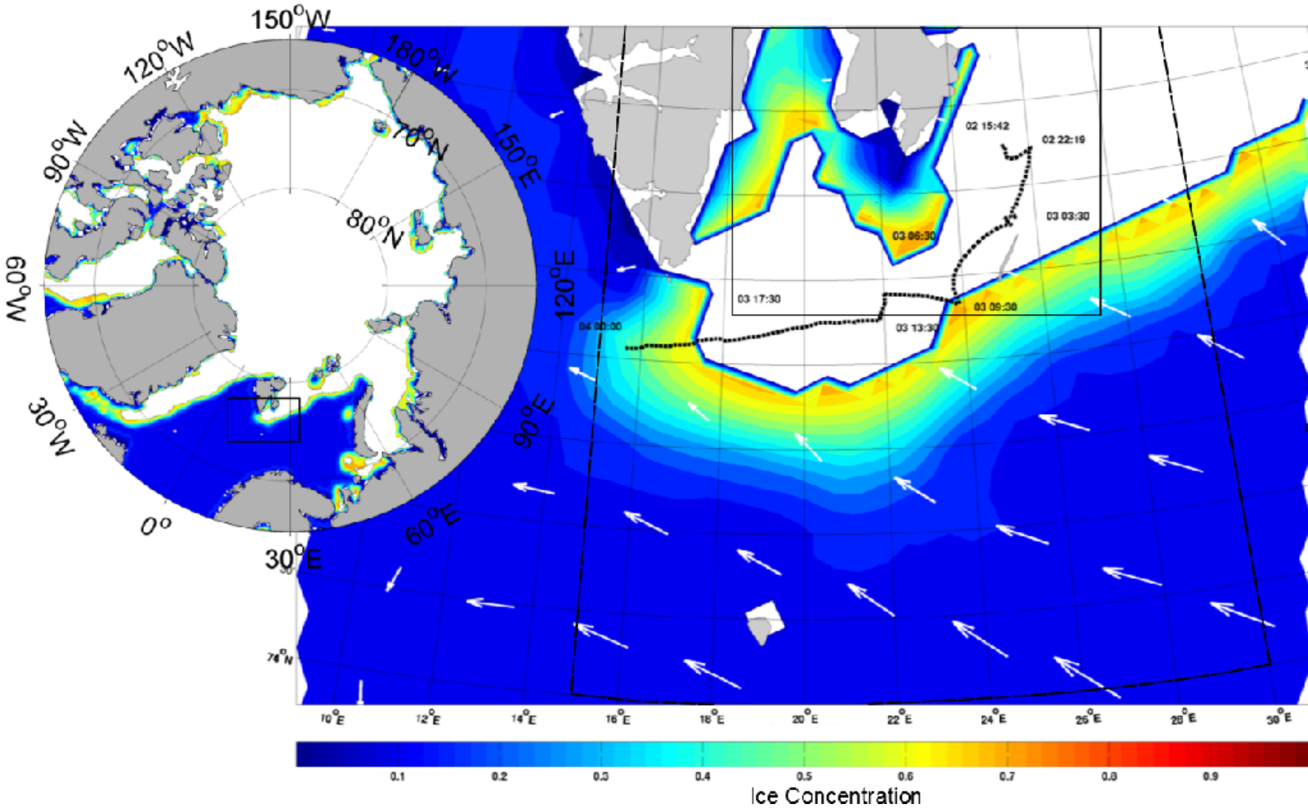

Figure S5 Inset upper left: stereographic projection map of the Arctic polar region. The black square shows the boundaries of the inset map of southern Svalbard and Hopen Island. Ice concentrations from PIPS on May 2nd, 2010 are shown in color corresponding to concentration. The dotted black line is the ship track of R/V Lance with dates and times in UTC. The white arrows point in the peak wave direction with length of arrow proportional to wave height modeled with WW3. The dashed black lines show the boundaries of the inner computational grid in SWAN which extend above the plot to 78°N. The solid black square indicates the boundaries for the map in Fig. 2 of the article.

PUBLICATION	STUDY YEAR	LOCATION	METHOD	WAVE HEIGHT (H_{M0})
[Hunkins, 1962]	1957-1958	Beaufort Sea	"Gravity Meter"[3]	<< 1 m
[Wadhams, 1975]	1972	Canadian North Atlantic[4]	Airborne Laser	~2 m
[Squire and Moore, 1980]	1979	Bering Sea	floe-borne accelerometers	~1.5 m
[Wadhams et al., 1986; Wadhams et al., 1988]	1978, 1979, & 1983	Bering Sea and Greenland Sea	Buoys	~1 m
[Liu et al., 1991]	1989	Labrador Sea	Buoy	~2.6 m
[Marko, 2003]	1998	Sea of Okhotsk[5]	ADCP	~1.5 m
[Asplin et al., 2012]	2009	Beaufort Sea	3-D ship-borne recorder	~0.75 m
This Study	**2010**	**Barents Sea**	**Ship GPS**	**4-5 m**

Table S1. Summary of the published accounts of waves measured in ice in the Arctic region.

[3]There are other studies which analyze the observations of gravity meters, seismometers, or tiltmeters deep in the ice field (see the references in Wadhams, 1975), all of which record small (O(1×10^{-4} m)) vibrations of the ice.
[4]Not within the Arctic region
[5]Not within the Arctic region

PUBLICATION	STUDY YEAR	LOCATION	METHOD	WAVE HEIGHT (H_{M0})
[Robin, 1963]	1959-1960	Wendell Sea	Ship-borne Recorder	~0.5 m
[Liu and Mollo-Christensen, 1988]	1986	Wendell Sea	Visual	~1 m
[Crocker and Wadhams, 1988]	19	Ross Sea	Wire Strainmeter	<< 1 m[6]
[Fox and Haskell, 2001]	1998	Ross Sea	Floe-borne recorder	?[7]
[Doble and Bidlot, 2013]	2000	Wendell Sea	Buoy	~10 m
[Meylan et al., 2014; Kohout et al., 2014]	2012	Antarctic Ocean	Floe-borne recorder	~6 m

Table S2. Summary of the published accounts of waves measured in ice in the Antarctic region.

[6] Measured strain (not amplitude), a conversion depended on Young's modulus (not measured)
[7] They show measurements only in terms of acceleration and acceleration spectra

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