SAR ICE THICKNESS MAPPING IN THE BEAUFORT SEA USING WAVE DISPERSION IN PANCAKE ICE - A CASE STUDY WITH INTENSIVE GROUND TRUTH

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ABSTRACT

Pancake and frazil ice represent an important component of the Arctic and Antarctic cryosphere. In particular, pancake ice is the result of a freezing process that takes place in turbulent surface conditions, typically associated with wind and wave fields. The retrieval of its thickness by remote sensing is, in general, a very difficult task. In this paper the change in dispersion of ocean waves as they penetrate into pancake ice is considered so as to gain insight into ice thickness estimation. The spectral changes in wave spectra from imagery provided by space-borne SAR systems (Cosmo-SkyMed satellites) were used to retrieve pancake ice thickness in conjunction with the Sikuliaq research cruise in the Beaufort Sea during October 2015. Inversion procedures were applied to this aim and results were compared with the rich dataset collected in situ through the use of wave buoys and ice thickness measurements.

1. INTRODUCTION

The concept of using the change in the wavelength of ocean waves on entering a frazil-pancake icefield, as measured by spectral analysis of SAR images, as a way of mapping the thickness of the ice, was originated in a seminal paper of 1991 [1] and was further developed by two of the present authors in [2,3]. In our current work in the EU SPICES project (www.h2020-spices.eu/) we plan to use the results of theory and observations obtained so far in order to develop a processing system for routinely deriving ice thicknesses in frazil-pancake regions of the Arctic and Antarctic, and hence assess the mass and heat balances in these regions. To do this, we require more ground truth than had up to now been available, the only direct comparison between satellite and ship-borne work dating from 2004 [3].
In autumn 2015 (Sep 30 - Nov 10) the University of Alaska research ship *Sikuliaq* carried a team funded by the Office of Naval Research "Sea State Project" to study marginal ice zone processes in the Beaufort Sea, particularly wave-ice interaction. During several experiments, a line of wave buoys was deployed along a pre-declared line, which could thus be covered by simultaneous Cosmo-SkyMed (CSK) images. In particular, the image and experiment of October 11 covered an area where frazil-pancake ice was the dominant ice type along the entire length of the survey line out to open water. The ground truth facilities deployed included: i) directional wave buoys placed in the water between pancakes; ii) *Swift* (Surface Wave Instrumented Float with Tracking) directional wave buoys placed outside of the ice edge; and iii) measurements of pancake ice thickness by recovery of cakes and of frazil ice mass per unit area using a collector (a "frazilometer") giving a sample that is allowed to melt out. Hereafter we briefly report on the analysis methods for both buoy data and satellite images. In the Results section we present a comparison between the wave fields measured by the buoys and the wave spectra derived from the SAR, the final goal being the comparison between the ice thicknesses measured *in situ* and those inferred from SAR wave number analysis with the application of a viscous theory.

2. DATA AND METHODS

The main goal of the *Sikuliaq* cruise, to the western arctic Ocean in the autumn of 2015, was to carry out an extensive study of the forces and processes governing the advance of the Arctic Ocean ice edge in autumn. The month of October in the Arctic Ocean is normally one which receives little scientific attention, as ship cruises tend to take place in summer (July-September) while work on ice stations is done in spring (March-May). In particular, the role of wind and waves in governing the seasonal rates of ice advance and retreat.
To study wave penetration into the extreme edge zone, a wave array, made up of three *Swift* buoys crossing from open water into partial ice cover, plus one UK wave buoy in the ice bands, was deployed. The UK buoy (Fig.1a) measures two tilts, an acceleration and a direction, and thus give the directional spectrum of wave energy; this evolved from models which have been used for over 30 years of wave research in Cambridge. They were built for projects of Prof Peter Wadhams and were operated by Wadhams and Dr Martin Doble, the buoy designer. The *Swift* buoys (Fig.1b) were designed by the research group of Prof

Jim Thomson at University of Washington, and measure the same wave parameters as well as wind, turbulence and noise. They are spar buoys which float vertically in the water, while the UK buoys can either sit on an ice floe in a waterproof case or be inserted into a float for use in the water.

Figure 1. UK buoy (a) and SWIFT buoy (b).

Among the different experiments during the *Sikuliaq* cruise, in this preliminary study we focus on the field operations of 10-13 October. Upon reaching the ice edge on its south-eastern side (looking towards Canada) on 10 October, we began deploying SWIFTs and UK wave buoys to drift in an array aligned with the waves that were forecast to come in from the open water to E and SE during a coming storm. Pancake ice was forming rapidly and waves were approximately 1 m high. A second line of buoys spanned 95 km, from open water to deep within a field of rapidly growing pancakes. The working hypothesis is that the waves provided sufficient mixing to release the ocean heat stored in the “near surface temperature maximum” observed with the underway CTD. This means that pancake ice forms in the first place because of wave action but can also be destroyed by excessive wave action which brings up ocean heat stored during the summer.

In order to cover the 10-13 October experiment, the acquisition of a SAR-X CSK satellite image over the area of the field operations gave us the state of the region for October 11 at 14:34:09 (see the geo-referenced Fig. 2). The image was a CSK ScanSAR Wide, with a swath of 100 km and the pixel = 15 m.

2.1 Satellite images

The analysis of SAR images followed the procedure fully described in [3]. First, a strip of 5 imagettes was extracted across the ice/sea edge in the vicinity of the buoy positions (Fig.3); the size of each imagette was 512x512 pixels, i.e. 7.68x7.68 km. The imagette SAR spectrum was then computed (Fig.4), providing the input to the following SAR/wave spectrum inversion step. The change in shape of the spectrum in window 3, when the waves enter the ice, is very clear.

2.2 Buoy data

The buoy data analysis consisted of two steps: the first one consisted of GPS data (latitude/longitude) analysis in order to track the buoys paths during the time interval of interest, the second one consisted of directional power spectrum computation (following the technique proposed in [4]). The GPS buoy data consisted of latitude/longitude time series acquired with sampling interval of 0.5 sec used to track the buoy path during the time spanning that we decided to use (1 hour from 14:04:00 to 15:04:00 for October 11). GPS data were analyzed to recognize which buoys lay closest to the SAR acquisition area during this interval. Buoys numbered 03, 05, 07 gave the closest match.

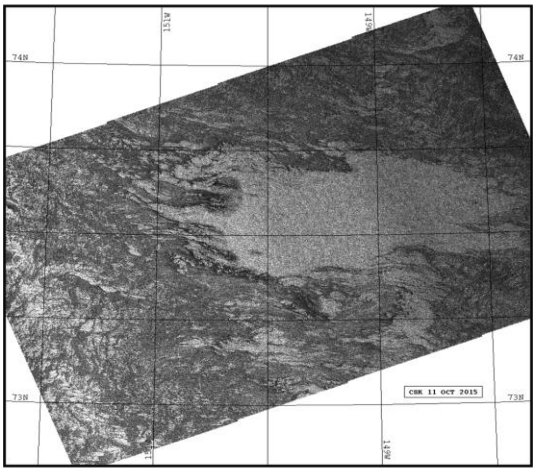

Figure 2. Area of field operations seen from CSK SAR-X on October 11.

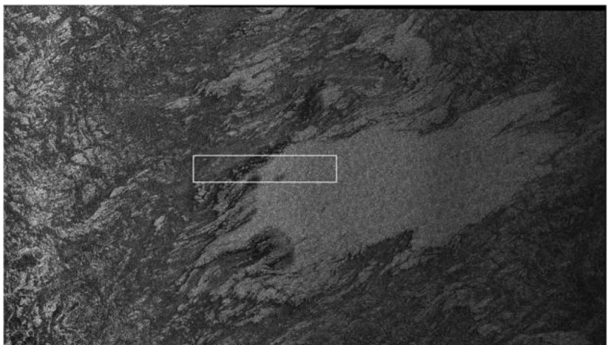

Figure 3. Strip of extracted imagettes.

The vertical displacement (heave) time series for the selected buoys (all placed in the sea ice zone) was hence analyzed according to the statistical method proposed in [4]. The records were acquired with 4Hz sampling rate. First, we looked for the presence of a significant secular trend in the data; if present, this trend was removed. Then, each time series was filtered using a digital band pass filter with Hann window and 4-70 seconds passing band in order to remove high frequency noise and low frequency periodic components, like tides. The filtered time series was then divided into segments of 2048 samples, each one overlapping on 50% of its length. This choice was adopted because data segmentation, with overlapping segments, reduces statistical uncertainties [4]. Each segment was windowed using a 2048-points Hann window before FFT computation in order to reduce the spectral leakage. By averaging the N obtained FFTs, we produced a final, single power spectrum of *m* degrees of freedom [4].

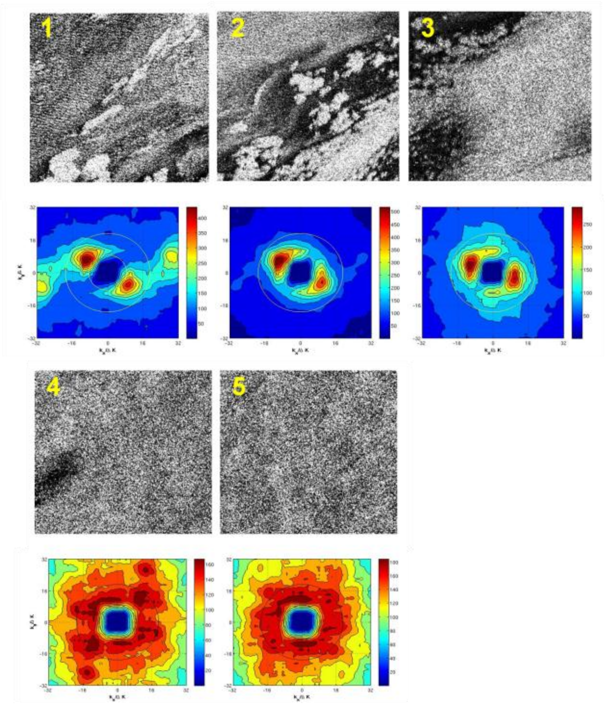

Figure 4. SAR spectrum for each imagette in sea-ice (1,2,3) and open water (4,5).

2.3 Inversion algorithm

Inversion procedures were applied to both the open water and the sea ice SAR spectra derived through the analysis of the CSK image acquired on October 11.

For open water the procedure estimates the wind-sea spectrum as was done in [3], according to the parametrization of [5, 6]. The parameters involved in this procedure are wind speed and wave age, the latter defined as the ratio between wind speed and the phase velocity of the dominant wave. A preliminary estimation of the wind vector is therefore mandatory for a reliable inversion result. In this case the SAR image was used. The wind direction (with 180° ambiguity) was taken from the direction of windrows visible on the open sea area, well in agreement with the meteorological information from the *Sikuliaq* cruise scientific report (which also allowed to resolve the direction ambiguity). Given the wind speed and the SAR incidence angle, the inversion procedure seeks for the wave age value which minimizes the difference between the observed and simulated SAR spectra. The simulation of the SAR spectrum is carried out using the integral transform given by [7]. A further minimization is then carried out with respect to the propagation direction of the peak wave as fully described in [3].

In sea ice, the wave propagation model for wave dispersion and attenuation proposed by [8] was used in order to infer physical properties such as thickness. This model treats the ice layer as a viscous fluid while the water beneath it is assumed to be inviscid. The idea is thus to find the best values of the two parameters which ‘minimize’ the difference between the observed and simulated SAR spectra like in [3].

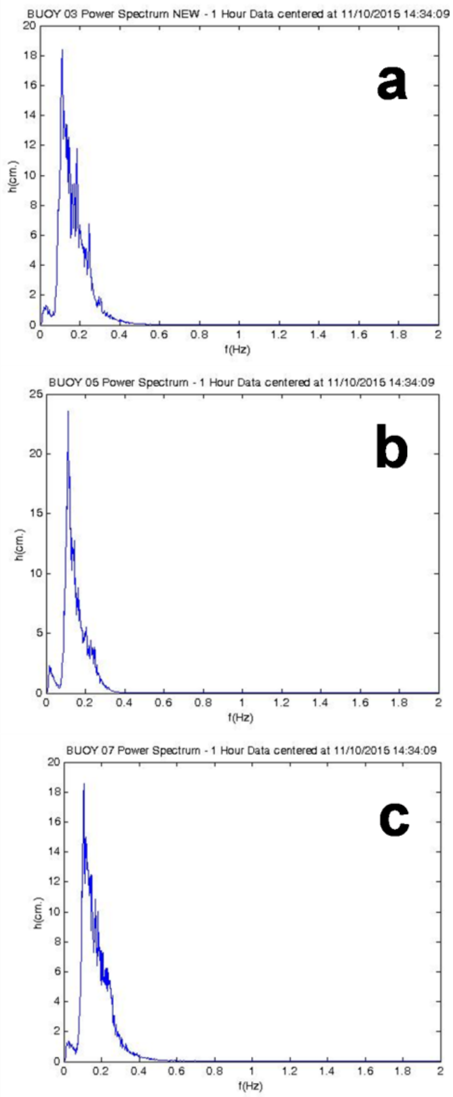

Figure 5. Power Spectrum of data collected by buoys number 03, 05, 07 (a, b , c respectively)

3. RESULTS AND CONCLUSIONS

Aim of this experiment was to obtain SAR observations directly overhead *Sikuliaq* ship as it launched an ice buoy array and carried out direct observations of frazil and pancake ice.

Figure 5 show the directional power spectra computed for buoys 03, 05 and 07 applying the method described above. The three buoys were very close during the time interval of the analysis and hence their power spectra show coherent results. The data collected by buoys 03 and 05 present a significant peak that corresponds to a wave period of about 8.8 seconds, with an amplitude which is larger at the site of buoy 05 than of buoy 03. Buoy 07 shows a slightly different frequency peak corresponding to wave period of 9.3 seconds, with an amplitude similar to that of buoy 03.

The application of the inversion algorithm to the imagettes of Fig. 4 returned significant peaks corresponding to wavelengths of 29 and 32 m in open water and sea ice, with significant heights of about 65 and 51 cm, respectively. From these data, a pancake ice thickness of about 29 cm was retrieved using a kinematic viscosity of 0.05 m^2/s. Even though quite resilient to relatively large changes in viscosity, this value overestimates the pancake ice thickness (11 cm) measured during the Sikuliaq cruise, being also very sensitive to input wind speed. Several factors could have affected our results, i.e. the uncertainties in the wind field estimation, the need of a more accurate model for the wave dispersion theory, etc.

All these aspects should be carefully addressed before using SAR observations of wave dispersion in ice for the estimation of the frazil/pancake ice thickness in large areas of the Arctic and Antarctic regions. The analysis (in progress) of the complete dataset collected during the *Sikuliaq* cruise in fall 2015 is expected to provide useful information to refine this preliminary version of our SAR imaging inversion procedure in order to retrieve reliable results.

4. ACKNOWLEDGMENTS

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