WAVE DISPERSION BY ANTARCTIC PANCAKE ICE FROM SAR IMAGES: A METHOD FOR MEASURING ICE THICKNESS

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ABSTRACT

A synthetic aperture radar (SAR) image of the advancing winter marginal ice zone (MIZ) in the Antarctic, composed of frazil-pancake ice, has been analysed in a new way in order to test the predictions of a recently developed theory of wave dispersion in pancake ice which treats the ice as a viscous layer (Keller, 1998). In the image, obtained in April 2000, the structure of the wave spectrum in the MIZ and its change from the open-water spectrum are consistent with a pancake layer thickness of 0.2-0.3 m. Intensive in situ measurements of the pancake ice in the MIZ some 280 km W of the image location were made from FS Polarstern during a period covering the satellite imaging, and yielded a mean ice thickness of 0.24 m. We conclude that this technique is giving realistic results for ice thickness, whereas earlier work based on a different dispersion theory (mass loading) tended to over-estimate thickness. After further validation, it is therefore possible that the SAR wave technique can become an accepted method for remotely sensing ice thickness in pancake icefields.

INTRODUCTION

The technique of extracting valid directional wave spectra from subscenes of satellite SAR imagery is now well-established. After initial studies which extracted the SAR spectrum without correction (Wadhams and Holt, 1991), more recent studies have employed a variety of techniques to convert a raw SAR spectrum into a valid sea surface directional spectrum. Using two of these techniques, the Hasselmann inversion (Hasselmann et al., 1996) and the cross-spectra inversion (Engen and Johnsen, 1995), we have used SAR spectra to derive the change in wave dispersion as a wave train enters frazil and pancake icefields (Wadhams et al., 2002). By tracking the peak of the spectrum through a succession of subscenes as the waves move into the icefield, and measuring the change in wave number of this component on crossing the ice edge, we were able to estimate the ice cover thickness through use of thickness-dependent dispersion theory. In all of these studies we found that mass-loading theory, the simplest and apparently most plausible model for wave dispersion in pancake icefields (Wadhams, 1986), predicts greater ice thicknesses than are actually observed.

A recently developed model by Keller (1998), in which the frazil-pancake ice cover
is treated as a layer of highly viscous fluid, offers a better description of wave dispersion and attenuation which could give us a new means of obtaining more accurate thickness estimates. To test this new theory, a new inversion procedure was developed and applied to an ERS-2 SAR image (orbit 26128, frame 5013) obtained from the winter Antarctic ice edge in the region of 68°S 25°W on April 19, 2000. Field data were obtained by FS Polarstern, at an ice edge region 280 km to the west of the SAR image, during April 16-19. Fig. 1 shows the image used, spanning a clear ice edge, where the bright part of the image is the rough open sea and the darker part is frazil and pancake ice.

SPECTRAL INVERSION OF THE SAR IMAGE

New inversion procedures were applied to both the open water and sea ice spectra. For the open water region the procedure estimates the wind-sea spectrum according to a parameterisation involving wind speed and the wave age, the latter defined as the ratio of the phase velocity of the dominant wave to the wind speed. A preliminary estimation of the wind vector is therefore mandatory for a reliable inversion result. In this case the wind vector was estimated from the SAR image itself, with the 180° ambiguity resolved by QuikSCAT wind data collected approximately two hours after the SAR passage (Fig. 2).

Open water

The best fit wind-generated wave spectrum in the open sea gives the following parameters:

Peak wavelength: 78 m;
Peak direction: 42°;
$H_s$: 1.95 m (significant wave height)

the angle being measured with respect to the range direction.
Fig 1.
Sea ice

Keller’s (1998) model treats the ice layer as a viscous fluid of a given thickness and the water beneath it as inviscid. For deep waters, the model has only two free parameters: ice thickness and viscosity. Again, the inversion procedure becomes parametric as two parameters (thickness \( h \) and kinematic viscosity \( \nu \)) are to be retrieved. The algorithm is thus similar to the one implemented for wave spectrum retrieval in open sea. In this case, the retrieved ice parameters are:

\[
ch = 24 \pm 1 \text{ cm} \quad \text{(where } c \text{ is ice concentration)}
\]

\[
\nu = (5 \pm 1) \times 10^{-2} \text{ m}^2 \text{ s}^{-1}
\]
Besides, the following parameters relevant to the wave spectrum in sea ice were found:

Peak wavelength: 80.6 m;
Dominant wave direction: 41°;
H_s: 1.65 m.

These values are spatial averages over a distance up to 10-15 km from the ice edge. It must be stressed how the best fit for the kinematic viscosity is of the same order as the value found by Newyear and Martin (1999) in their tank experiments.

Fig. 3 shows the observed SAR spectra obtained from 4 of the 8 subscenes. The change in shape of the spectrum after window 3, when the waves enter the ice, is very apparent, while at windows 6 and 8, about 16 km and 29 km, respectively, inside the icefield, the high wave number components have almost disappeared.
SAR spectrum 19 APR 2000, $\Delta K = \pi/8 \times 10^{-2}$ (rad m$^{-1}$)

Fig. 3
COMPARISON WITH IN SITU DATA

The intention of this experiment was to obtain SAR imagery directly overhead FS Polarstern as she launched an ice buoy array and carried out direct observations of frazil-pancake ice (Doble et al., 2003). In the event, because of ice conditions, Polarstern was forced to carry out this work some 300 km to the west of the intended position, in the vicinity of 68° 40’S, 32° 30’W. However, the dates of the work (April 16-19) spanned the SAR overflight, and the composition of the MIZ appeared to be similar along the whole set of longitudes visited by Polarstern, being more a function of penetration from the ice edge than of geographical location. We therefore tentatively conclude that the ice sampled by Polarstern had the same characteristics as that seen on the SAR.

The ice analysis was done as follows. Whole pancakes were lifted onto the deck and their dimensions measured; they were also cut up for salinity analysis. Frazil ice in the interstices between pancakes was sampled by a tube covered at one end by a plankton net being lifted up through the suspension from beneath. Excess water was allowed to drain away then the ice sample was melted and the volume measured. The assumption was made, based on the observed ratios between measured ice volume and suspension depth seen in the original tube, that while in the water the frazil ice crystals within the suspension occupied a volume fraction of 0.4. Fig. 4 shows the results of the sampling. The distributions of pancake and (corrected) frazil layer thicknesses are shown for all the stations, and for the outer and inner (greater than 70 km penetration) parts of the MIZ separately. Overall, 35 pancakes and 58 frazil samples were analysed. On the assumption of a 70% pancake fraction by area in the mix, the remainder being frazil, an overall mean thickness for the composite icefield was estimated at 24 cm. If the zones are considered separately the mean for the outer MIZ was 18 cm and for the zone at deeper penetration 32 cm.
CONCLUSIONS

An excellent agreement between the optimised ice thickness and the mean of pancake ice thickness observations, carried out concurrently in the marginal ice zone by FS Polarstern, was obtained: in both cases ice thickness was in the range 0.2-0.3 m. Also, wave data from buoys deployed by Polarstern gave wave heights which agreed well with those derived from the SAR spectra. The relevant optimal kinematic viscosity was $5 \times 10^{-2}$ m$^2$ s$^{-1}$, which is in the range of laboratory values from Newyear and Martin (1999).
These results suggest that the SAR waves technique combined with the Keller theory offers a powerful new tool for the remote sensing estimation of pancake icefield thicknesses.

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REFERENCES


