Interannual Variability in Weddell Sea Ice from ERS Wind Scatterometer

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Abstract - ERS-1/2 SAR and Wind Scatterometer data are analyzed together with SSM/I radiometer data to investigate interannual variability in Weddell Sea ice and summer melt signatures during the period 1992-1997. Simultaneous SAR and Scatterometer images were obtained during a February 1995 cruise of the H.M.S. *Endurance* and aerial photographs collected for validation of the observations. Accompanying field data are used to illustrate observed variability, and to validate the first ever observation of extensive summer melt ponding in the Weddell Sea.

INTRODUCTION

Fundamental differences exist between the Antarctic and Arctic when it comes to spatial and temporal variability in sea-ice conditions in response to seasonal atmospheric and oceanographic forcing. In summer, the Arctic remains largely covered by multiyear ice, surviving each summer melt period by way of its thickness, to accrue incrementally more thickness in winter. Antarctica has no perennial ice counterpart, and for the most part non-landfast sea ice reaches an age of only second-year ice before drifting into high oceanic heat flux regimes and rapidly melting. Sea-ice dynamics regulate the maximum age of the ice cover, particularly in the Weddell and Ross Seas, where the Gyre circulation sweeps sea ice northwards. The relative age and thickness of the residual autumn ice cover is a critical variable to the stability of the upper ocean in these regions, as summer melting helps to freshen and stabilize the mixed layer and together with the residual perennial ice cover prevents complete removal of the summer ice cover.

In the Antarctic, melting largely takes place from beneath the ice, as summer air temperatures rarely rise above 0°C. Consequently, the expression of classical surface melt-ponding has never been observed and thus the surface retains a snow cover year-round. Conversely, Arctic summer melting results in the expression of melt ponds over up to 60% of the surface as the snow cover disappears completely. Meltwater infiltrates the warm, porous sea ice, flushing out its salt content to leave it relatively brine-free. The fact that the Antarctic snow cover is retained throughout summer helps to insulate the ice and protect it [1]. In perennial ice regions, surface flooding can occur with resulting upward meteoric ice growth occurring during autumnal freeze-up [2].

In this paper, we study the combined seasonal effects of sea-ice advection and summer melting upon time-varying microwave signatures extracted from a number of fixed regions in the north-western Weddell Sea. The resulting data set extends from 1992-1997, enabling the long-term mean annual signal to be extracted. The residual interannual anomaly time-series illustrates extreme variations in regional melting and/or sea-ice dynamics.

DATA SETS

Several active and passive satellite microwave data sets were combined with field data from the north-western Weddell Sea. Synthetic Aperture Radar (SAR) images (100x100 km) and wind scatterometer data were collected by the ERS-1 and 2 spacecraft (hereafter EScat). The latter were processed into images at 3d intervals [3, 4] for the period 1992-97. EScat measured the vv-polarized normalized backscatter coefficient σ°_{vv} (dB) along a 500 km-wide swath and the backscatter at a mid-swath incidence-angle of 40° is expressed as *A*. A number of EScat sample boxes are defined and numbered in the North-western Weddell Sea, in Fig. 1. Additional coincident daily SSM/I data were extracted from these regions.

Pairs of overlapping ERS-1 SAR swath data were acquired on 11 and 14 February (orbits 18704 and 18747), and 12 and 15 February, 1995 and mosaicked. In Fig 1 the descending

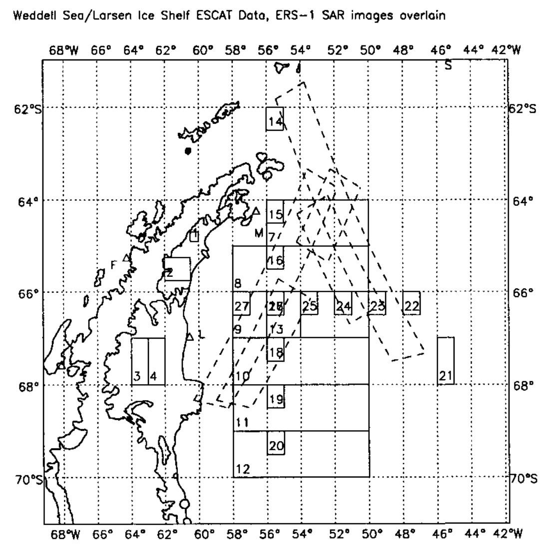

Figure 1. Weddell Sea map indicating numbered sample boxes for EScat and SSM/I data, overlapping ERS-1 SAR mosaics (dashed) on 11 and 14 February, 1995, and meteorological stations (triangles) situated at Faraday (F), Marambio (M), and the Larsen Ice Shelf (L).

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and ascending strips (dashed) span several hundred kilometer long transects. These crossed the open ocean limit of the marginal ice zone (MIZ) at around 65° S into high concentration (>95%) perennial ice south of 67° S.

Coincident field data were acquired between 10-15 February, 1995 from H.M.S. *Endurance* [5]. The British Royal Navy icebreaker positioned herself to collect simultaneous *in-situ* data during ERS-1 overpasses. One helicopter facilitated surface data collection while another was equipped for aerial photography. The 11 and 14th February descending pair of SAR swaths were acquired during local daylight (09:25hrs), thereby enabling detailed air-photo comparisons.

INTERANNUAL VARIABILITY

Time series microwave signatures extracted from the sea-ice boxes in Fig. 1 show variability indicative of seasonal and annual changes in the characteristics of the snow and ice floe surfaces together with the proportions of ice types advected through each region. To rule out dynamic effects, four control regions (1-4) were investigated on the Larsen Ice Shelf (LIS) in conjunction with meteorological station data. Results from box 3 are shown in Fig. 2. The upper panel indicates a large dynamic range in *A* values as a result of austral summer melt as far as 68° S. Decreases of -20 dB or more occur during active surface melting. The middle panel indicates the 5-year mean annual and filtered cycles, and the lower anomaly cycle is the result of removing the mean from the record. Clearly, the summers of 1992/93 and 1994/95 were anomalous, each with earlier and more extended melt seasons. These years coincide with events marking rapid disintegration of the northern section of the Larsen Ice Shelf together with the landfast ice between James Ross Island and the peninsula [7]. Also the calving of a spectacular iceberg occurred in the region of box 2 in early 1995 [7].

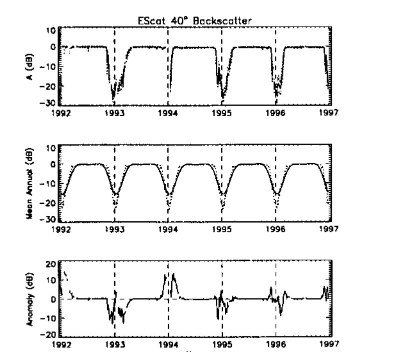

Figure 2. Interannual and anomaly time series from the Larsen Ice Shelf (box 3).

Variability in Escat *A* values is also investigated in two other regions in Fig 3. The advection of varying fractions of seasonal or perennial ice through each box is responsible for the large seasonal amplitude in Fig. 3a and b. Oscillations in *A* during minimum ice extent in box 15 indicate that wind-roughened open water is not responsible for any values exceeding -15 dB in this box. This is typical in stable summer boundary layers in the MIZ. Notably, Fig. 3a shows minima in the summer months. April and May peaks in *A* are typical of high perennial ice concentrations, and show a gradual decline until October. 1992 and 1995 ice seasons suggest large fluxes of old ice (> -10 dB) through this box [3], marking the disintegration of fast ice along local parts of the peninsula. To corroborate this, swarms of large floes of perennial ice with >1m deep snow were observed during WWGS '92 [6]. Figure 3a also shows abrupt melt onsets in late 1992 and '95.

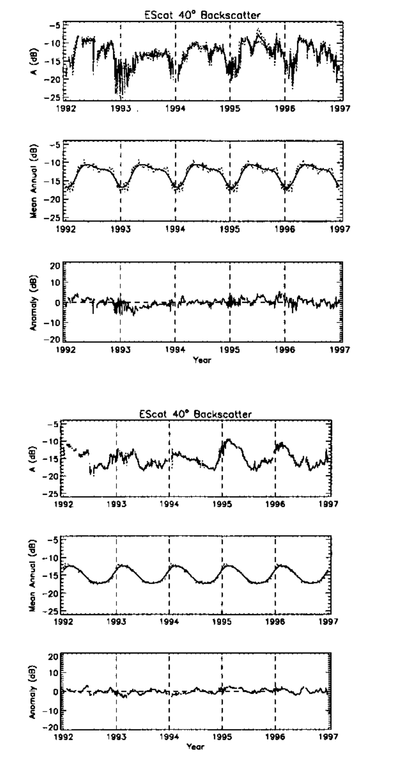

Figure 3. Interannual time series from (a) box 15; and (b) box 20.

Fig. 3b shows an extremely different signal in southern box 20. Peak *A* values now occur in austral summer in contrast to box 15 minima. A seasonal decline in *A* values during winter marks diffusion of residual perennial sea ice and advection of an increasing fraction of seasonal sea ice through this region in response to northwards drift of ice away from the Ronne-Filchner ice shelf polynya [3].

The distinctive seasonal cycle and maxima in Fig. 3b characterize 1992 flooding signatures documented during Ice Station Weddell (ISW) [2]. Snow-covered perennial ice floes surrounding ISW increased their σ°_{vv} values in austral summer as a result of ice-surface flooding beneath the snow. Since air temperatures at this latitude are typically too cold for melting, the snow must insulate the ice sufficiently to become isothermal, by heat supplied from beneath. If the snowcover is deep enough for an isostatic imbalance [1] then it may flood with seawater through open brine drainage channels, causing a widespread increase in σ°_{vv} [2].

SUMMER SCATTERING SIGNATURES

In the southernmost boxes, austral summer results in a signal with opposite sense to boxes experiencing direct surface melting. Dramatic reductions in the summer backscatter in seasonal ice regions can only be associated with the onset of snow-surface melting, particularly in boxes near to the meteorological station Marambio, where air temperatures are well known. SSM/I observations concur by exhibiting blackbody temperatures during periods of warm air temperatures and surface melting.

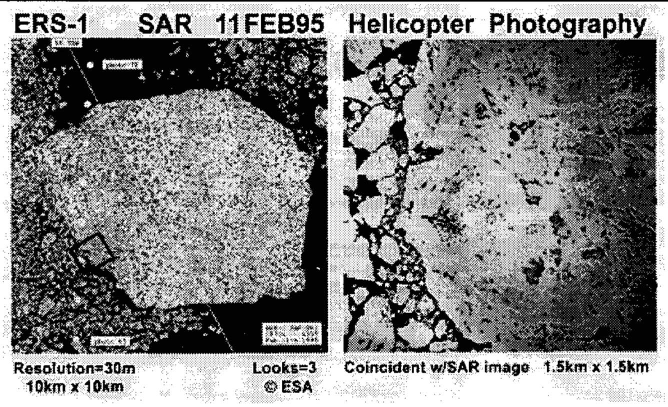

Figure 2. ERS-1 SAR image and coincident aerial photograph from black box indicating melt ponding.

Melt ponding

Surface melt is demonstrated to have a significant effect upon regional signatures in the north-western Weddell Sea. *In-situ* observations of melting made in February 1995 explain the widespread reduction in *A* values in box 7, 8, 15, and 16. Fig. 4 shows a 10 km vignette of an ERS-1 SAR scene obtained coincident to aerial photographs made from Endurance (centered on white spots). The photograph from the highlighted box indicates the lower left edge of the large floe, approximately 6 x 7.5 km in size, situated 100 km inside the ice edge at 65.85°S 55.75°W. The anomalous appearance of large melt ponds up to 50m across is evident on the large floe. Similar ponding is also observed on smaller ice floes (15-200m in diameter) seawards to within 2-3 km of the ice edge before floes were too small to support surface ponds. Measurements also indicated that such perennial floes were typically 2.5-4m thick with a 2-15 cm deep snow cover.

Thus, perennial ice in northern Weddell Sea experiences classical melt-ponding during particularly warm summers. Ponds are expressed in topographic low points on the surfaces of conglomerate ice floes with significant relief. However, the areal extent of melt ponding does not appear to have a significant enough impact at 23° incidence, such that meltponds are clearly expressed in the high-resolution, filtered 16-bit SAR data. As previously explained in [8], this may be due to the fact that rough-surface scattering from high-relief portions of ponded surfaces dominate backscatter signatures.

Flooding

South of the seasonal melt front, the snowcover rarely experiences surface melting, and the snow-ice interface appears to have the more dominant effect on seasonally varying backscatter signatures. As previously explained, high snow loading and basal melting can cause isostatic imbalance, flooding, and upward meteoric ice growth [2]. In 1992 at ISW, resulting slushy, saline and high permittivity basal snow enhanced summer σ°_{vv} values. Presently, there is no evidence to suggest that flooding does not also occur on perennial ice floes further to the north, but at some point snow surface melting masks any ice surface scattering signal.

CONCLUSIONS

EScat trends are explained primarily by changes in air temperature and secondly advection of different ice types into/out of the study regions. Results indicate significant interannual variability in the duration and intensity of the melt season, particularly in the north-western region off the east coast of the Antarctic peninsula. The austral summer warming in 1992/93 and 1994/95 was relatively intense, with the anomalous appearance of Antarctic melt ponds, observed for the first time in February 1995. Summer surface melting is expressed in different ways in the microwave data depending on whether north or south of the seasonal isotherm corresponding with snow melting. It would appear from the interannual record that expression of surface melt ponding may more widespread in this region than originally thought, judging from the occurrence of this signature in other years

Ongoing work involves development of a capability to use large-scale tracked ice kinematics products from scatterometer and SSM/I images in conjunction with these interannual time series. Dynamical information such as opening/closing will facilitate correction of the time series, such that advective and dynamic influences upon the variability may be removed. On this basis, smart algorithms may be developed to extract thermodynamically-driven features from the corrected regional melt signatures such as the fraction of ponded or flooded area.

ACKNOWLEDGMENTS

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