Comparison of Variations in Sea-Ice Formation in the Weddell Sea with Seasonal Bottom-Water Outflow Data

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Abstract - Seasonal and interannual variability of Antarctic sea-ice formation is observed using ERS-1 satellite microwave radar in the Weddell Sea. Time-series from six Antarctic regions with recurring ice-shelf polynya systems indicate relationships between the timing of seasonal peaks in measured bottom water outflow and ice formation rates. Results provide evidence about the critical periods of high surface heat fluxes and clues to primary brine production locations.

INTRODUCTION

The Weddell Sea, Antarctica is recognised of primary importance for the production of this water mass, observed to reside in the bottom of the worlds' abyssal oceans. Recent results from analyses of long-term oceanographic measurements in the Weddell Sea, Antarctica [1, 2], reveal outflow of Antarctic Bottom Water (AABW: $T < -0.8°$ C; $S > 34.642$ psu) along the shelf-break of the western Weddell Sea [3] is highly seasonally and interannually variable.. AABW is formed in this part of the Southern Ocean by combination of atmosphere-ice-ocean interaction processes and governed to a large extent by the supplies cold, high salinity water over the continental shelf region. Preconditioning is thought to be closely linked to brine production by sea-ice formation off the major ice-shelves in the southern and western Weddell Sea.

Mixing and vertical thermohaline convection, allows dense, saline, cold water, formed at the surface during ice formation, to be emplaced at depth on the shelf in a thin, cold, oxygenated benthic layer. As this water sinks and moves northwards along the continental shelf margin it mixes with other distinct water masses such as warm Weddell Deep Water (WDW: $T = 0$-$1°C$; $S = 34.58$-34.7 psu) which forms the core of the northward-moving western boundary current beneath the pycnocline at 500-600m depth [1,3]. WDW incursions onto the continental shelf at these depths also allows isopycnal mixing with colder and fresher Surface Water (SW) residing above the pycnocline, originating from summer sea-ice melt, shelf or iceberg melt, and precipitation. Mixtures of these three key water masses during the transit of the dense water from its origin towards the tip of the Antarctic peninsula result in outflow of typical AABW [1,2].

OCEANOGRAPHIC AND SATELLITE DATA

Of particular interest in this study are the 1992-1993 seasonal and interannual variations of Antarctic sea ice in the following six regions; (1) Filchner, (2) Ronne, (3) South Larsen, and (4) North Larsen Ice Shelf fronts; and (5) Wilkes Land, and (6) Marie Byrd Land (Fig. 1). The objective is to relate timing of pulses in brine production in these regions to a recent seasonal bottom-water outflow record acquired near Joinville Island (63°25'S; 52° 32'W), at the tip of the Antarctic peninsula.
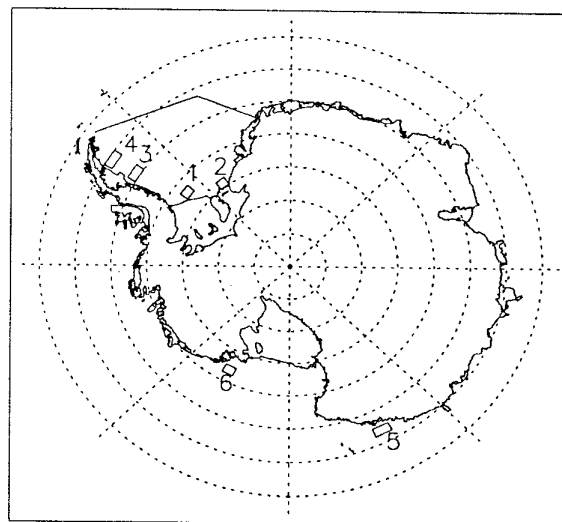

Figure 1. Map indicating W.O.C.E. measurement transect and Weddell Sea sample regions; 1-4 in Weddell Sea; and 5-6 in the Ross Sea and East Antarctica.

Oceanographic Measurements

Recent work [1] summarises 1989-1992 monthly mean AABW outflow, from moorings and repeat hydrographic measurements taken along a W.O.C.E. transect line (Fig. 1) ending off Joinville Island. This interannual record is unique, and indicates considerable variability in outflow between individual years of the study. Seasonally, the record displays a main peak in outflow during early winter (Jun.-Aug.), and a clear summer minima. In this paper we focus on 1992, due to coordinated satellite and field data acquisition campaigns [5,6]. Important characteristics of the 1992 seasonal cycle are a rapid rise from 1.25 Sv (1Sv $= 1 \times 10^6$ m^3 s^{-1}) at the end of January, 1992, to a plateau of ~ 2.75 Sv between March and July, before a final pulse in AABW outflow peaking at a maximum outflow of ~ 4.0 Sv during August 1992. This winter peak in outflow and sudden decrease in September to below 1.0 Sv are indicative of localised centers of seasonally dependent dense-water production.

ERS-1 AMI Data

Radar data acquired in the Weddell Sea by the ERS-1 SAR and Scatterometer (EScat) allowed year-round 1992 and 1993 archiving of ice conditions for the key bottom water production regions shown in Fig.1. Scatterometer backscatter image data [5] illustrate and signal regional distributions of different ice

thicknesses and occurrences of distinct seasonal and interannual fluctuations in ice characteristics.

Meteorological Data

Meteorological analysis fields from the European Center for Medium-Range Weather Forecasting (ECMWF) were used in this study to enable regional calculations of turbulent and conductive heat fluxes at the surface. Required inputs to standard bulk aerodynamic formulae, as used in [7], are air temperature, windspeed and relative humidity, air pressure, and are extracted from gridded ECMWF data. Surface temperatures of ice or water are parameterised based on typical field-measurements of snow depth and ice thickness, and open water amount.

RESULTS

Surface Fluxes

Turbulent surface fluxes of sensible and latent heat are the main mechanism for cooling the mixed layer and are responsible for rapid ice formation and inducing vertical overturning. Running, weighted 7-day means of net surface flux are plotted in Fig.2 for regions 1-4 in the Weddell Sea. Values represent computations using daily means of 4 six-hourly ECMWF fields of the input variables (at 00, 06, 12, and 18 hrs). Net fluxes include conduction (D_i), and components of turbulent sensible (H_i) and latent heat (L_i) from the ice to the atmosphere, combined with components of turbulent sensible (H_w) and latent heat (L_w) from the ocean to atmosphere in leads and polynyas. Timeseries in Fig.2 indicate net heat fluxes weighted by concentration of thick ice (C_{thick}), from;

$$F_{net} = (C_{thick}* (D_i + H_i + L_i) + ..$$
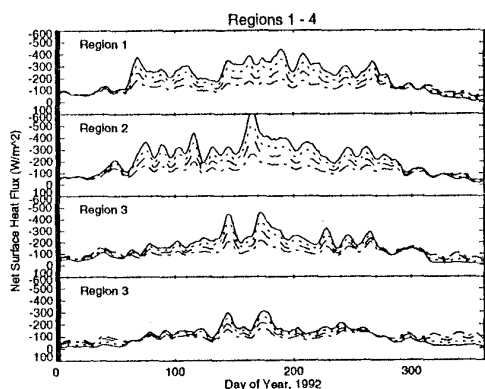$$((1-C_{thick}) * (H_w+ L_w)) \qquad (1)$$

Figure 2. Net ocean-atmosphere heat fluxes in Regions 1-4 weighted by ice concentrations of 0.8, 0.6, 0.4, and 0.2.

Fluxes shown for Regions 1-4, with isolines for weighting by thick-ice concentrations of 0.2, 0.4, 0.6 and 0.8 (remaining fraction is assumed thin ice or open water). Net fluxes remain negative (upward) throughout the year, peaking with ~ 600 W m^{-2} off the Filchner ice shelf (region 2) in winter. Summer air temperatures remain below zero in all regions, confirming that heat fluxes remain significant during minimum concentrations of old ice. Long-term seasonal variations in air temperatures are reflected in the flux record by a winter and summer rise and fall,

while shorter time-scale varying regional windspeeds produce fluctuations in winter magnitudes. Ice concentrations have a large impact upon seasonal variability, by linearly modulating net heat fluxes and by significantly damping seasonality.

Sea-Ice Variability

Distinct seasonal cycles appear in each region in local formation of ice and the evacuation of thick ice remaining at the end of the austral summer. Backscatter variability in region 1 (i.e. Ronne Ice Shelf front) over 1992-93 is reflected in Fig.3, and an example for region 4 (northern Larsen Ice Shelf front) is shown in Fig.4. Both indicate a 40° incidence backscatter value (A) dropping below -20dB due to large concentration of new-ice formation in polynyas and leads between days 5-20 in 1992 [5]. Corresponding gradients of backscatter in the incidence range 20-40° (B) indicate values exceeding 0.3 dB deg^{-1}. Similar features occur within the first 20 days of 1992 in each of regions 1, 2 and 5. This is likely due to the low concentrations of old ice remaining in these regions, with heat fluxes ~ 100 W m^{-2} in Fig.2.
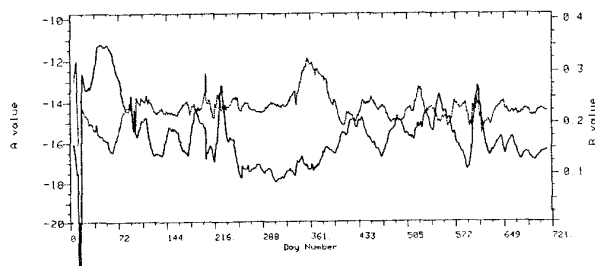

Figure 3. Region 1 time-series of (A) 40° incidence EScat backscatter values, and (B) fitted linear backscatter gradient in the 20° - 30° incidence angle range. Day numbers begin 1 Jan, 1992 and last until 31 December, 1993.
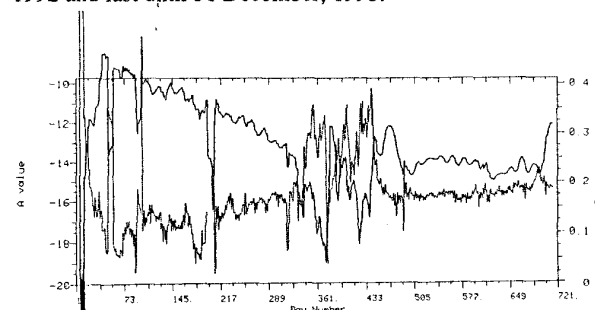

Figure 4. Region 4 time-series of (A) 40° incidence EScat backscatter values, and (B) fitted linear backscatter gradient in the 20° - 30° incidence angle range.

After short periods of potentially high summer heat fluxes, old ice is advected into these regions, abruptly increasing values of A and reducing B. Fig.4 values indicate abrupt closure of the polynya system, with A values peaking above -10 dB on day 36. Thereafter, northwards advection of old ice and icebergs out of these regions appears as a steady decline in the values throughout the year until around day 300 when concentrations of old ice are at a minimum.

Comparison of all six regions shows considerable

403

inter-regional and interannual variability despite similar seasonal trends. Mean backscatter values indicate generally lower values in 1993, which could result from either calibration changes not corrected for during image-data processing, or from real geophysical differences. Region 6 data acquired off Marie-Byrd Land, however, show no interannual variability in A values, thereby refuting the possibility of changes in radar gain with time. Indeed this ice in the Eastern Ross Sea appears land-locked snow-covered fast ice surviving 1992/3 summer months.

CONCLUSIONS

Seasonal heat flux estimates are used to assess the importance of variations in ice formation/brine production rates in the Weddell Sea. Fig.2 fluxes display stable summer values of around 100 W m^{-2} at the Ronne-Filchner Ice Shelf fronts (regions 1 and 2), with a sharp rise in heat flux around day 60, with fall freeze-up. A large seasonal peak in region 1 March-April, 1992 ice production is aided by low starting fractions of old ice [5], continual northwards evacuation of ice, and tidal action which periodically opens and closes the pack in the vicinity of the ice shelf. In contrast, the Larsen Ice Shelf examples show a gradual rise in heat fluxes to a distinct peak at day 145. At this time concentrations of old ice are still high, as indicated by Fig.4, thereby reducing the net capacity for brine production relative to the Ronne-Filchner ice-shelf region.

To achieve an early precursor to the main peak in AABW outflow, beginning around day 60 (early March), requires a source region close to Joinville Island. Dense water produced in the North Larsen ice shelf region has the shortest travel distance to the oceanographic transect in Fig.1. In addition, Fig. 4 results indicate a recurrent ice-shelf polynya system with the potential to produce dense water during the period day 5 - 20, in the austral summer. The lag of 40 d, and the travel distance requires a mean bottom current speed of around 0.15 cm s^{-1}, which is typical of moored current meter measurements made on the shelf in the plume of bottom water exiting at 950 m depth [1]. Winter peaks in Region 2 heat flux are thought to be unimportant, due to the high concentrations of old ice and the significant damping of net fluxes in Fig.2.

It is unlikely that dense water production in Region 4 alone, can account for the main peak in AABW outflow around day 200. The transition from summer to winter heat flux values is gradual and the ice-shelf polynya or shore lead system rapidly closes. If the region 1 brine production peak is assumed to coincide with the early peak in net turbulent and latent heat fluxes, then the lag between the day 60 peak in region 1 and the measured 1992 AABW peak is 140 days. For this water mass to exit the Weddell Sea at a time coinciding with a July peak, the bottom current would be required to have a mean velocity of around 0.10 cm s^{-1} over the transit along the continental shelf. This closely corresponds with measured 1992 values from [1,4]. Hydrographic measurements from a drifting ice station [2] also indicate mean northwards transport rates of saline shelf waters which could account for the time-lag between peak brine production in region 1 and the pronounced July 1992 peak in AABW outflow.

If the source of dense, cold saline water is assumed to be periods of rapid ice production then superimposition of the seasonal timing of peaks in new ice formation and high ocean-atmosphere heat

fluxes upon the annual bottom water outflow (accounting for water mass transit times) can be used to infer potential source locations. The 1992 seasonal records of ice characteristics from these key regions and the Joinville Island interannual record of Antarctic bottom water outflow appear to overlap such that the early plateau in AABW outflow appears to originate from Larsen (region 4) due to the shorter exit time, and such that the main pulse comes from Ronne-Filchner polynya system (region 1 and 2). Other potential sources include dense saline water from the Filchner shelf region and bottom water recirculated in the Weddell Gyre, although the water masses become homogenized over the course of recirculation, thereby reducing the potential for a distinct seasonal peak of outflow of water with the measured characteristics.

These preliminary results show that the supply of cold, brine-enriched water from Ronne-Filchner and Larsen ice front regions by sea-ice production could play an important role in influencing the timing of seasonal peaks in bottom-water outflow. Compilation of longer overlapping oceanographic and satellite archives will allow observed interannual variability in ice production rates to be convincingly linked to the measured variability in outflow.

It remains inconclusive from the limited processing of 1993 oceanographic measurements, whether reduced 1993 old ice concentrations had an impact on AABW outflow. Evidently the lack of old ice in this region allows rapid ice formation in an expansive polynya system located off the Ronne Ice Shelf. Generally lower backscatter values in 1993 appear to indicate lower concentrations of second-year ice at the outset of 1993, than at the outset of 1992. This is particularly true of this region, indicating that the concentration of old ice is perhaps important for controlling the fall heat flux values. Summer preconditioning of the mixed layer due to basal ice melting, and the observation of rapid, brief ice-shelf polynya events appears to be of importance in the production of dense, salt-laden shelf water masses likely due to the stabilising effect which it has upon the mixed layer.

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