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Coastal polynyas in the southern Weddell Sea: Variability of the surface energy budget

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1. Introduction

The surface energy budget of coastal polynyas in the southern Weddell Sea has been evaluated for the period 1992 to 1998, using a combination of satellite observations, meteorological data and simple physical models . In this paper, we present a climatology of the surface energy budget within coastal polynyas off Ronne Ice Shelf between 1992 and 1998 (Fig. 1).

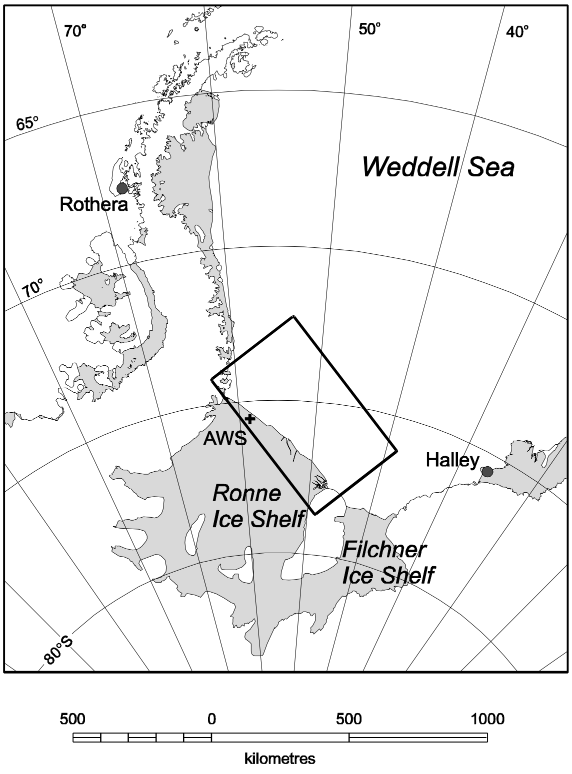

Figure 1 A map of the southern Weddell Sea region. The study region is marked by the inner rectangle.

The surface energy budget can be written as

$$Q_s + Q_l + Q_r + Q_p + Q_o = Q_{tot} = \rho_i L_f F$$

where Q_s is the sensible heat flux, Q_l is the latent heat flux, Q_r is the net radiative heat flux, Q_p is the heat flux from precipitation, Q_o is the upward heat flux from the ocean and Q_{tot} is the total heat flux (e.g. Curry and Webster 1999). We take the sign convention that fluxes from the ocean to the atmosphere are positive. If the ocean is at freezing point the total heat flux can be equated with an ice production rate, F, where ρ_i is the density of ice and L_f is the latent heat of fusion. The Q_p flux can be significant if the precipitation falls as snow, and so draws heat from the ocean as it melts (e.g. Moore et al. 2000). However the amount of precipitation thought to fall within Antarctic polynyas is not large and so we neglect this term. The upward oceanic heat flux, Q_o, is of the order 10 W m^{-2} for the Antarctic sea ice zone (McPhee and Martinson 1994), which is small compared to the other terms, hence we also neglect this component of the surface energy budget.

To develop this climatology a number of data sets and models have been blended to provide a comprehensive treatment of the atmosphere-ocean-ice system. Our philosophy has been to use observational data wherever possible. Hence to determine polynya areas over the period we use passive microwave satellite observations and an advanced multi-channel polynya detection algorithm first presented in Markus and Burns (1995). This data set dictates our choice of the 1992 to 1998 time period of the climatology.

Direct observations of components of the surface energy budget within polynyas are rare, and if they do exist only cover short experimental periods such as scientific cruises. Hence other data sources must be used, for example, observations from Automatic Weather Stations (AWS) positioned on the edge of the ice shelf - generally just upwind of the coastal polynya. Unfortunately the AWS data for the Ronne Ice Shelf do not cover the full 7-year period of our climatology, and so we have chosen to use boundary-layer data extracted from Numerical Weather Prediction (NWP) model analyses, and check this data set against the AWS data to obtain an estimate of its accuracy. Both a 1-year 'AWS' climatology and a 7-year ‘model’ climatology are calculated. The atmospheric boundary layer immediately over an ice shelf and that over an adjacent polynya are very different (e.g. Heinemann 1988). The advection of cold continental air over relatively warm water leads to the development of a convective-thermal internal boundary layer (CIBL), The paper which encompasses a rapid growth of the boundary-layer height, a warming of the boundary layer and a reduction of the surface sensible heat flux with fetch. Observations show the reduction in surface turbulent heat fluxes is systematic and significant; order 20% over tens of kilometres, and up to 50% over hundreds of kilometres. For simplicity, previous studies have either neglected these polynya-induced boundary-layer modifications, or made an unphysical uniform adjustment of the surface turbulent heat fluxes. Here we improve on that approach by employing a CIBL model, devised by Renfrew and King (2000), to estimate the surface turbulent heat fluxes across the coastal polynya (Fig. 2).

The state variables extracted from the NWP analyses, or from the AWS, are also used to estimate the surface radiative fluxes via empirical formulae. Such formulae are frequently used in the polar regions, and appear to work rather well, with the only significant uncertainty due to cloud cover (e.g. Makshtas et al. 1999, Van Woert 1999). Unfortunately satellite retrieved cloud data, and for that matter satellite-based climatologies, are rather inaccurate in the polar regions. Hence previous studies have used these with reservations (e.g. Markus et al. 1998, Van Woert 1999, Winsor and Björk 2000). A more sophisticated approach is taken here as we employ an innovative statistical model, recently developed by Makshtas et al. (1999), which predicts cloud amount from temperature given climatological information about their distributions.

In compiling this climatology every effort has been made to use observational data where possible, or to model in a simple way known meteorological effects. However a note of caution must be made given the paucity of in situ data from sites within polynyas. The surface energy budget estimates are as good as appears possible with the current generation of observing systems, but the uncertainties are still significant.

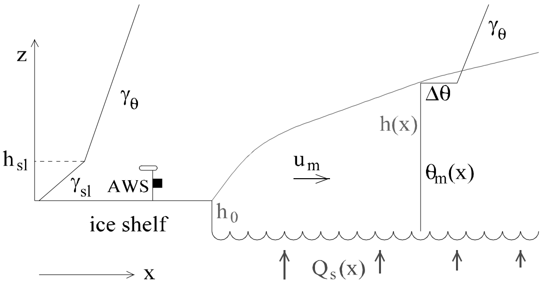

Figure 2 A sketch of a convective-thermal internal boundary layer development for a cold air outbreak over a polynya. The Renfrew and King (2000) model predicts CIBL height h(x), mixed-layer potential temperature θ_m, and surface sensible heat flux $Q_s(x)$ from upstream surface data, given an inital CIBL height h_0, a surface-layer height h_{sl}, and stabilities γ_θ and γ_{sl}.

2. An illustrative case study

We now examine a coastal polynya opening/closing episode for the southern Weddell Sea using data sets described in the previous section. Figure 3 shows one from a sequence of four infra-red satellite images from the AVHRR (Advanced Very High Resolution Radiometer) system, flown on board the NOAA polar orbiting satellites, and received at the British Antarctic Survey’s Rothera station. Examining the image, an opening of a belt of open water / thin ice along the ice shelf front is clear. Note in the panel the decrease in brightness temperature with distance off shore, is indicative of an increase in frazil ice density, or ice thickness, across the polynya.

The polynya opening episode is clear in Figure 4, which shows one of a sequence of four passive microwave images processed via the PSSM algorithm. Each image should be regarded as a daily average, as each is processed from several satellite passes. Comparing Figs. 3 and 4, the correspondence is extremely good, both in terms of location and polynya area.

The polynya opening is coincident with the dramatic deepening of a low pressure system located in the central Weddell Sea. The cyclonic circulation induced by the low system forces offshore winds over the whole Ronne Ice Shelf. The timing of the low pressure system’s rapid development and the ensuing strong offshore winds, suggests that this event leads directly to the opening of the coastal polynya.

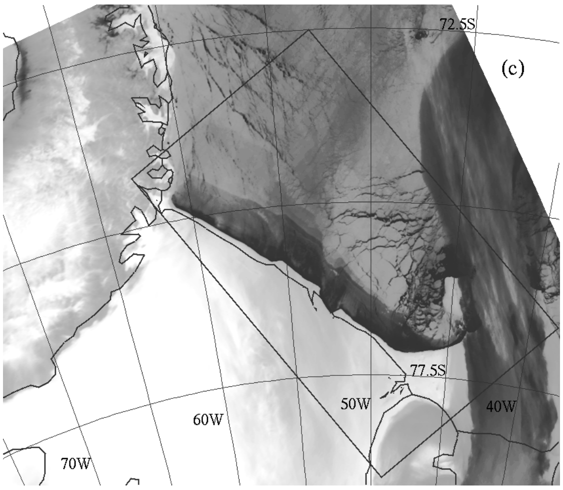

Figure 3 An infra-red AVHRR satellite image of the southern Weddell Sea and the Ronne Ice Shelf, processed so that white is cold, black is warm. The image shows a coastal polynya, with sea ice being blown off the ice shelf, exposing a belt of warmer open water underneath.

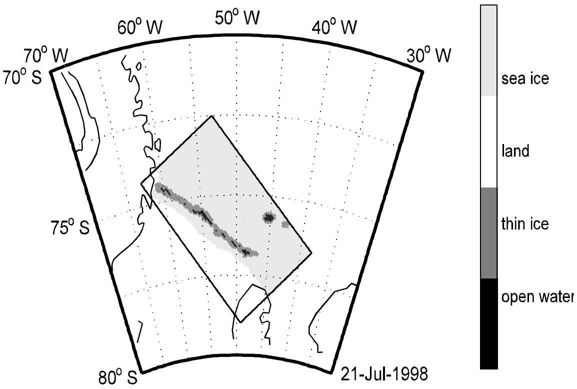

Figure 4 A map of sea ice cover as determined by the PSSM algorithm from SSMI passive microwave brightness temperatures. The inner rectangle shows the region processed. The algorithm differentiates regions of open water and thin ice from those of thicker sea ice.

3. Variability of the surface energy budget

In this section we investigate the 7-year surface energy budget time series. For more details of the calculation method please see the unabridged paper. Figure 5 plots the total surface heat flux (Q_{tot}) integrated over the coastal polynya area. Each year alternates between a summer period of negative values, i.e. atmospheric cooling / oceanic warming; and a winter period of positive values, i.e. atmospheric warming / oceanic cooling. The winters are characterised by periods of positive fluxes, interspersed with quiescent periods. The summer period also has considerable short-term variability, primarily from resolving the diurnal solar radiation signal. There are few summertime periods of zero flux, as there is usually some open water present at this time. There is clearly some interannual variability in the time series, for example, some winters appear more active than others (i.e. more opening episodes); and there are tremendous differences between the summers: compare 1993-94 to 1997-98.

The interannual variability is illustrated more clearly in Fig. 6, which shows the cumulative area-integrated Q_{tot} (in Joules). This time series is initialised at zero on 1 January 1992. Since then there has been an overall oceanic warming due to the presence of coastal polynyas. On average, the summertime oceanic energy gain outweighs the wintertime oceanic energy loss. To our knowledge, this has not been established prior to this study. Previous work has concentrated on the wintertime role of coastal polynyas as an oceanic heat sink and not investigated their summertime role as an oceanic heat source (e.g. Cavalieri and Martin 1994, Markus et al. 1998, Comiso and Gordon 1998, Winsor and Björk 2000). The 7-year period of study is heavily influenced by the 1997-98 summer season, which saw an anomalously large sea-ice melt in the southern Weddell Sea (e.g. Nicholls et al. 1998, Ackley et al. 2000) leading to anomalous SWD absorption over a large area. If one considered (for example) the years 1992 to 1997, the summer oceanic warming and winter oceanic cooling appear

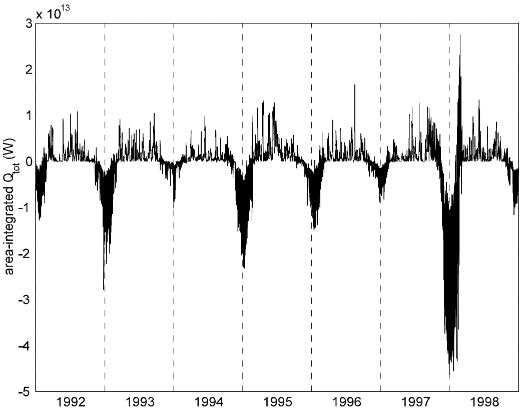

Figure 5 Seven year time series of area-integrated total surface heat flux. Positive values correspond to atmospheric warming (oceanic cooling), negative values correspond to atmospheric cooling (oceanic warming).

closer to being in balance.

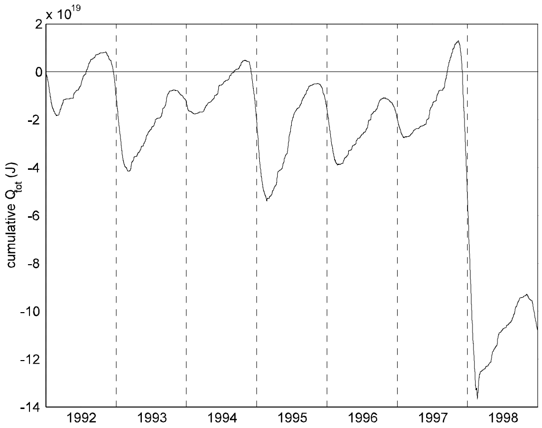

Figure 6 Seven year time series of cumulative area-integrated total surface heat flux, for the coastal polynyas. A positive slope corresponds to the atmosphere gaining energy (the ocean losing energy). The freezing season is defined as the local minimum to the local maximum for each year.

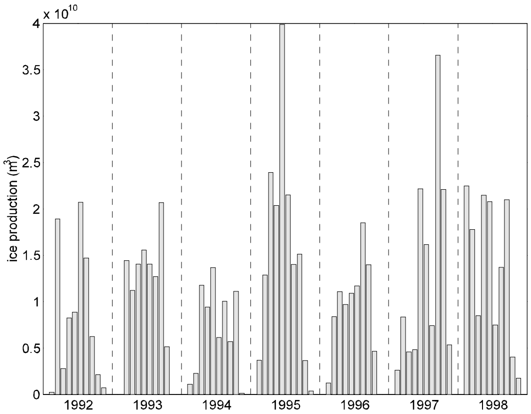

Figure 7 A bar chart of ice production (m^3) for each month of the 7-year climatology. Note there is zero ice production in January, occasionally November, and December of each year.

Figure 7 shows a bar chart of coastal polynya ice production per month. The results echo the freezing season Q_{tot} time series with 1995, 1998 and 1997 being the years of greatest ice production, and 1994 the year of least ice production. Within each year there is a roughly normal distribution, modified by a great deal of month to month variability. The months of January, occasionally November, and December have zero ice production. The highest ice production of any one month is around $4x10^{10}$ m^3 in June 1995. The mean of all (March to October) months is $1.32x10^{10}$ m^3.

4. Conclusions

The surface energy budget of coastal polynyas in the southern Weddell Sea has been investigated through the combination of satellite observations, meteorological data and simple physical models. For coastal polynyas in the freezing season, positive sensible heat fluxes dominate the surface energy budget, with latent and radiative heat fluxes generally augmenting the oceanic cooling. The turbulent heat fluxes are characterised by episodes of high heat fluxes, interspersed with more quiescent periods. Coastal polynya dynamics set the timescales for these changes: strong offshore winds blow open the polynyas, which then re-freeze at rates determined by the atmospheric and oceanic conditions. The total wintertime energy exchange is related to the cumulative coastal polynya area (indeed the latent fluxes are strongly related); however the varying atmospheric boundary layer is also important in modifying the sensible and radiative fluxes. On average the total energy exchange is $3.48x10^{19}$ J, with contributions of 63%, 22% and 15% from the sensible, latent and radiative terms respectively. The wintertime energy exchange is not related to the length of the freezing season. For coastal polynyas in the melting season, the area-integrated fluxes are dominated by the absorption of short wave radiation. Over the 7-year period from 1992 to 1998 the ocean warms more than it cools through the presence of coastal polynyas. In particular the anomalous summertime open-water area of 1997-98 allowed an enormous area-integrated warming of the ocean. During the freezing season, positive surface heat fluxes have been equated with ice production rates. The mean annual coastal polynya ice production is $1.11x10^{11}$ m^3 with a range from $0.71x10^{11}$ (in 1994) to $1.55x10^{11}$ m^3 (in 1995). The interannual variability is large, the standard deviation is 28% of the annual mean.

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