The Storfjorden polynya: ERS-2 SAR observations and overview

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Persistent polynyas have been observed over several winters in Storfjorden, situated between Spitsbergen and Barentsøya/Edgeøya in the south of the Svalbard archipelago. Polynyas are in general active regions with respect to ocean-atmosphere heat exchange, presenting strong convection phenomena and as such being involved in important water mass formation and having an impact on the marine ecosystem. Hydrographic observations have revealed very dense (cold and saline) brine-enriched bottom waters leaving the continental shelf as gravity driven plumes into the deep sea west of Spitsbergen. Satellite observations, using ERS-2 SAR imagery, reveal the evolution of the Storfjorden polynya during winter 1997/98. After forming a complete ice cover until mid-January, Storfjorden responds dynamically to northerly winds by opening a large latent heat polynya. It occupies at its largest extent a region of up to 6000 km^2 of open water, thin ice and brash ice. Comparable in size to other large Arctic polynyas, the Storfjorden polynya might have the same or even greater importance in the thermohaline circulation and bottom water mass formation. Ice production is estimated at 30 km^3 in Storfjorden, rejecting around 700 Mt (Megatons) of salt that can raise the salinity in Storfjorden by 0.9–1.0 PSU. First studies and the winter 1997/98 evolution of this polynya are presented in this paper.

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Introduction

First ERS-2 SAR (synthetic aperture radar) observations from Storfjorden on 6 March 1996 revealed the presence of a half-moon shaped polynya between Agardhbukta and Freemansundet (Fig. 1a). Polynyas and leads contribute intensively to the ocean-atmosphere heat exchange and important convection phenomena take place in these regions because of densification of the water by strong cooling and brine rejection during freezing (Smith et al. 1990; Gawarkiewicz & Chapman 1994). A Storfjorden polynya is the most likely source for brine-enriched shelf water, which has been observed by Midttun (1985), Quadfasel et al. (1988) and Schauer (1995) in Storfjorden and Storfjordrenna. Characteristics of this water mass are temperatures near freezing point and salinities greater than 34.75 PSU. Quadfasel et al. (1988) even measured 35.4 PSU in 1986. Flowing out from Storfjorden as a gravity driven plume over the continental shelf into the deep sea west of Spitsbergen (Jungclaus et al. 1995), the brine-enriched shelf water has an important role in the global thermohaline circulation (Rudels 1995). It is therefore of great interest to observe by satellite the evolution of the Storfjorden polynya over the entire winter to estimate the brine production. In the first section, Storfjorden and the regional ice conditions are presented. The evolution of the ice conditions during winter 1997/98 is described next, with an estimate of the ice production, and thus the salinity increase due to salt rejection. An attempt at automatic classification is made in the third section, before concluding this paper.

Storfjorden and regional ice conditions

Storfjorden (Big Fiord), situated between Spitsbergen and Edgeøya/Barentsøya in the south-east of the Svalbard archipelago, is not actually a true fiord. The northern part of Storfjorden is breached by two shallow straits about 20 m deep (Fig. 1a): in the north, Heleysundet, between Spitsbergen and Barentsøya; and in the east, Freemansundet,

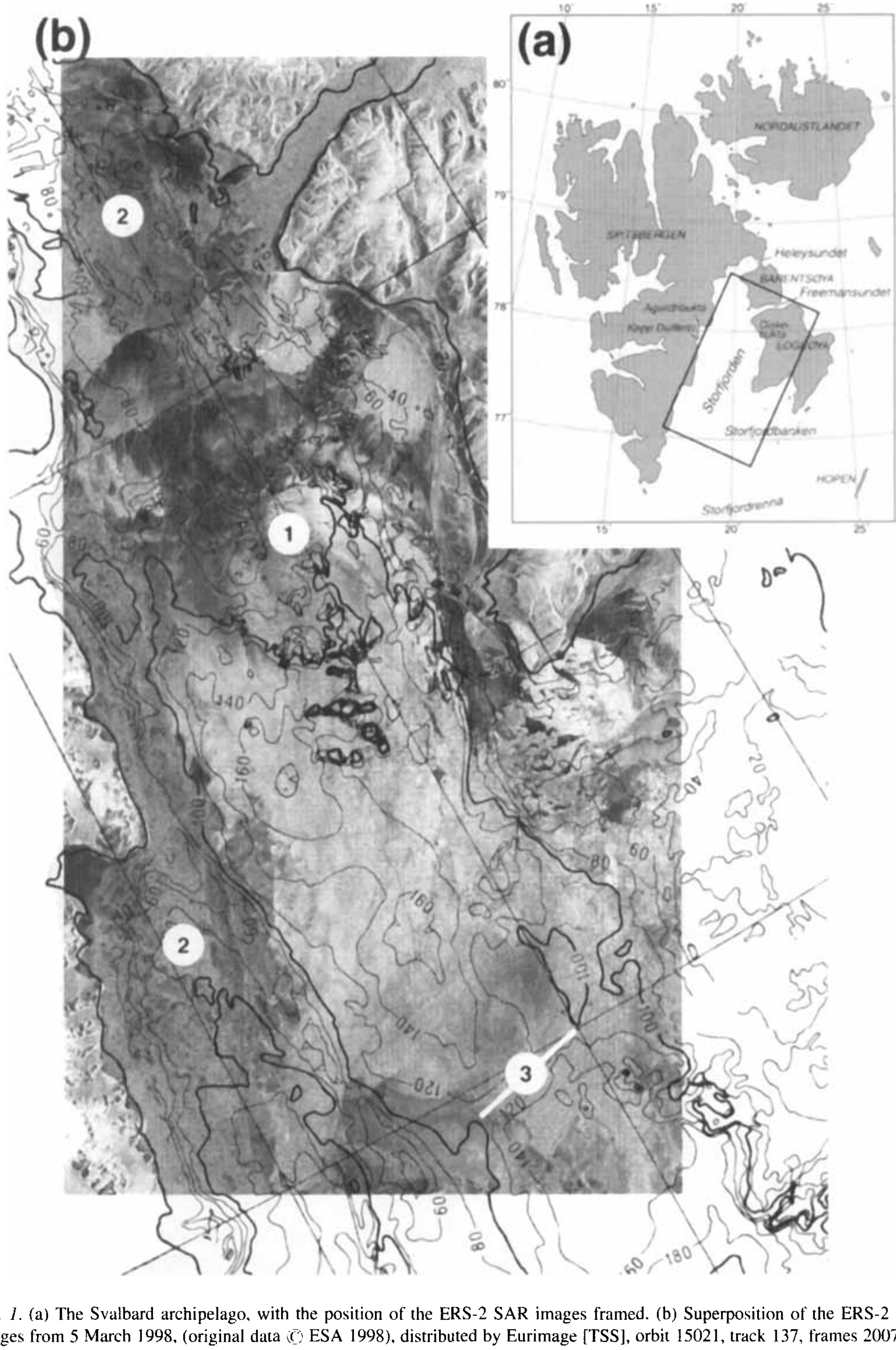

Fig. 1. (a) The Svalbard archipelago, with the position of the ERS-2 SAR images framed. (b) Superposition of the ERS-2 SAR images from 5 March 1998, (original data © ESA 1998), distributed by Eurimage [TSS], orbit 15021, track 137, frames 2007 and 2025) with the Storfjorden bathymetry. It shows the horseshoe-shaped Storfjorden polynya ①, extending southward from a semicircle approximately bounded by Agardhbukta and Diskobukta to the sill ③ at 77°N. ② indicates fast ice regions in the north and in the west of Storfjorden.

dividing Barentsøya and Edgeøya. Strong currents of 4–5 m/s and 2 m/s in Heleysundet and Freemansundet, respectively, have been observed (Norges Sjøkartverk 1988). Tidal models have shown that these currents might result from a half phase shift of the tides between inner Storfjorden and the northern Barents Sea around Kong Karls Land (Gjevik et al. 1994). The northern part of Storfjorden is shallower than 80 m with the exception of two ca. 120 m depressions at the north-west; these can trap some dense waters. A depression is located in the centre of Storfjorden, at about 77°30′N 19°E, with a maximum depth of 190 m. It is separated from Storfjordrenna by a sill (Fig. 1b) of about 120 m depth at 77°N. This opening is bounded by Storfjordbanken (shelf about 20 m deep) to the east, the Spitsbergen coast and a 40 m deep ridge to the west. Storfjordrenna is the extension of this connection from Storfjorden to the deep sea west of Spitsbergen.

Figure 1b shows a typical view of the Storfjorden polynya and ice conditions in late winter (5 March 1998) after two weeks of north-easterly winds. The satellite image is superposed on a bathymetry map of the Barents Sea. The fast ice boundary at the Spitsbergen coast closely follows the 100 m depth contour. North of an imaginary line between Freemansundet and Agardhbukta, a solid fast ice cover about 120 cm thick was measured during field work in April 1998. At its largest extent, the polynya spreads out as far as the sill at 77°N, extending southward from a semicircle roughly bounded by Agardhbukta, Freemansundet and Diskobukta. We assume katabatic winds are responsible for the bright areas visible in Diskobukta inside the polynya; these winds roughen the sea surface with capillary waves. The Storfjorden polynya is a wind-driven latent heat polynya opening under northerly winds. The strong tidal current through Freemansundet probably helps by weakening the ice cover and leading to the break-off of ice floes from the northern fast ice. These ice floes and fields are carried southwards by stress from northerly winds. During winter, the pack ice limit in the Barents Sea is mostly between 75°N and 76°N, i.e. south of Storfjorden and blocking the ice drift out of it. Thus, an accumulation of ice floes must take place, creating an ice reservoir that can refill Storfjorden under southerly wind conditions. Large quantities of ice floes drift northwards around Spitsbergen's Sørkapp (South Cape) with the West Spitsbergen Current, which might partly have their origin in Storfjorden, signifying a net freshwater export.

1997/98 winter survey of the Storfjorden polynya

The satellite survey by ERS-2 SAR imagery over the winter 1997/98 gives a first rough estimate of the evolution of the extent of the Storfjorden polynya (Fig. 2). In total, 27 ERS-2 SAR images have been acquired from the end of November 1997 until the end of April 1998, comprising the basis for this study. Two images form each view over Storfjorden, giving the ice condition on 13 dates. One single image from 27 March 1999 is not presented. Three ERS-2 satellite flight paths have

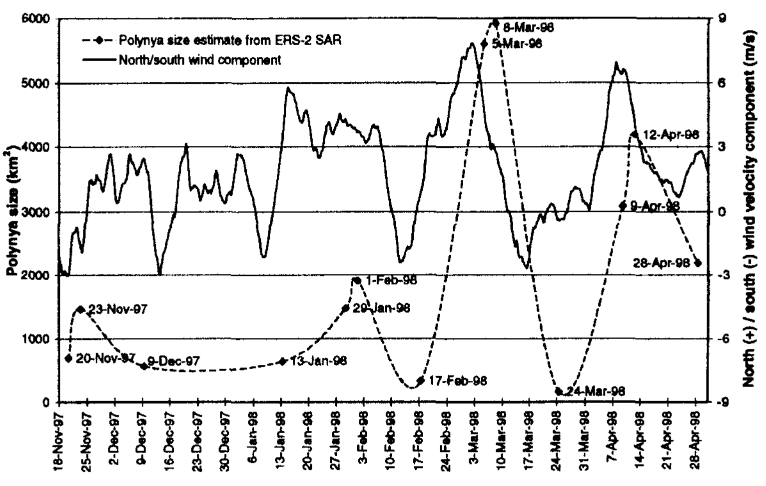

Fig. 2. The approximate size evolution of the Storfjorden polynya during winter 1997/98 estimated from 13 ERS-2 SAR images (dashed line) and the north/south wind velocity component (solid line) from the Norwegian weather station situated on Hopen Island.

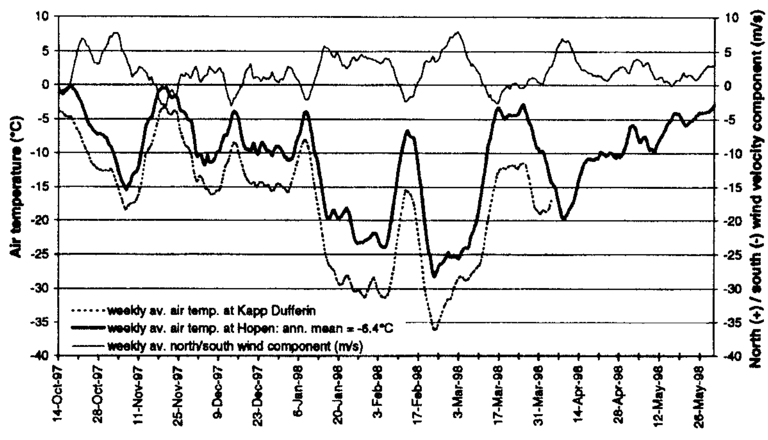

Fig. 3. Weekly averaged north/south wind component and air temperature data from the Norwegian meteorological station at Hopen and, until 4 April 1998, from an automatic weather station at Kapp Dufferin on the west coast of Storfjorden. Initially 3 m high, the automatic weather station was damaged soon after it was established. Therefore, no wind data have been acquired and the air temperature has been measured at ground level. The temperature is on average 6°C higher on Hopen than at Kapp Dufferin.

been used to acquire these images. For the polynya size estimate, we only considered the region that is covered by all tracks, covering about 10 000 km^2 of Storfjorden. The area of interest is indicated in Fig. 1 and in detail in Fig. 4. The north-south wind velocity component is also presented in Fig. 2 and correlates well with the opening and closing of the polynya. Wind and air temperature (Fig. 3) have been acquired from Hopen, a station of the Norwegian Meteorological Institute (DNMI). An automatic weather station at Kapp Dufferin indicates temperatures in Storfjorden on average 6°C colder than on Hopen over the whole winter. However, this weather station was badly damaged shortly after its set-up, and thereafter measured the air temperature close to the ground. Therefore, for our ice calculation we assume an air temperature in Storfjorden only 2°C colder than on Hopen. Northerly winds are always correlated to colder temperatures.

Every ERS-2 SAR view has been interpreted visually using four time series that are part of our image set and relying on the knowledge of the region acquired during field work. Two views separated by three days constitute one time series. It is relatively straightforward to divide Storfjorden into three regions: fast ice, polynya and pack ice. Figure 4 shows how the ice cover on 5 March 1998 has been segmented into these three classes (see Fig. 1b for comparison). The fast ice region, identified by the fact that it does not show any dynamics in time series, can be distinguished very easily from a polynya region, which presents a wide range of backscatter coefficients and no obvious structures of ice floes. Pack ice, by contrast, has a structure of big ice floes and a quite homogeneous backscatter coefficient. A distinction between fast and pack ice is only possible when the dynamics of the pack ice are obvious in the time series. The wide range of backscatter coefficients inside the polynya is due to several causes. Under calm conditions, thin nilas and open water have a very low backscatter coefficient. Higher backscatter coefficients may be due to the effect of wind on open water, and frost flowers, which can form at the surface of thin ice by condensation and freezing of water vapour (Ulander et al. 1995). In addition, young new ice is very sensitive to movement induced by wind and currents and piles up in pressure ridges and/or breaks into flows, which can slide partly over each other – so-called rafting. Thus, the polynya region includes open water, frazil ice, nilas and ridged and rafted young ice. The separation of young ice and water inside the polynya is difficult with SAR alone, but is possible by modelling the frazil ice production and assuming its accumulation at the lee side of the polynya.

SAR images from early winter (mid-November until mid-January) show that until the end of November only unstructured ice (pancake and frazil ice) is present in Storfjorden. In December, some ice floes are initially transported into Storfjorden through Freemansundet and Heleysundet. Until mid-January Storfjorden is almost totally ice-covered with large areas of fast ice in the north and at the Spitsbergen coast, leaving open a coastal polynya in Diskobukta, west of Edgeøya. A first break-off of the ice cover happens at the end of January 1998 north-east of Agardhbukta after three weeks of northerly winds of about 4–6 m/s, opening a polynya of about 2000 km^2. It closes again with freezing and southerly winds until mid-February. An image from 17 February 1998 shows

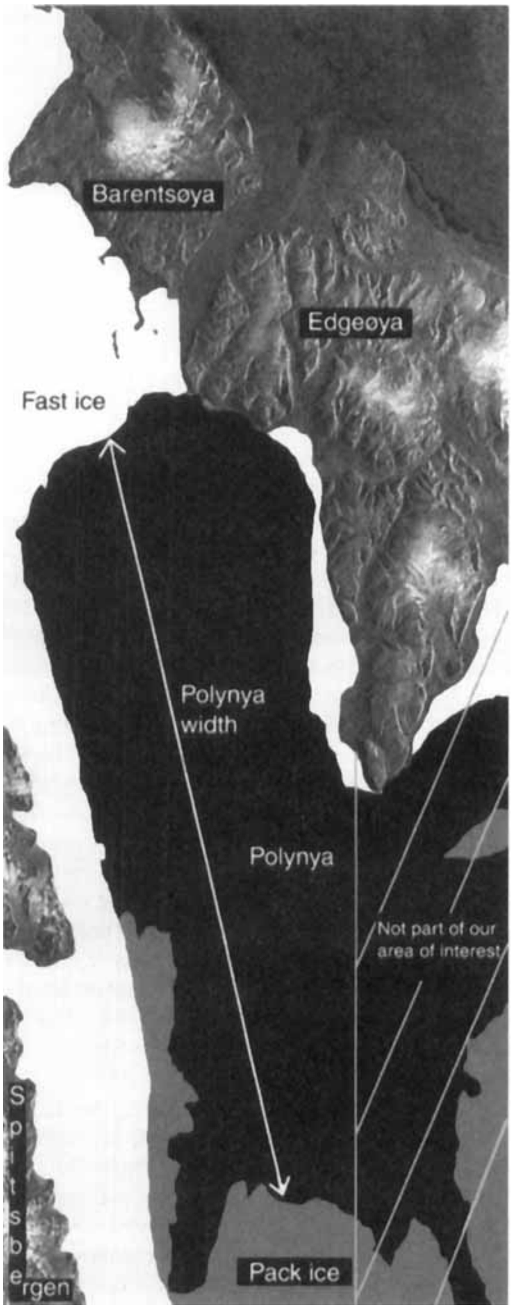

Fig. 4. Manual segmentation of the Storfjorden ice cover on the ERS-2 SAR image from 5 March 1998 (Fig. 1) into three classes: fast ice, polynya and pack ice. The striped area is not covered by all used satellite tracks and is therefore not considered for the polynya size estimate.

leads along the typical break-off line "Agardh-Freeman-Diskobukta" of the polynya, but the ice has not yet been driven away. From this time on, this break-off line is visible and remains stationary during the rest of the winter. The size of the polynya is then probably only dependent on wind direction and wind speed, and of course ice formation (Willmott et al. 1997). The peak of the polynya size in the beginning of March was preceded by two weeks of north-easterly winds of about 4–8 m/s. It seems that at the end of March, southerly winds filled Storfjorden with first year ice in addition to newly formed ice. Northerly winds opened the polynya again at the beginning of April. The automatic weather station at Kapp Dufferin gives us air temperature data between October 1997 and April 1998 (Fig. 3) and shows that even very low temperatures (−30°C) cannot prevent the polynya from developing. At its largest extent, the polynya exposes an area of 6000 km^2 of open water and thin new ice to very rough atmospheric conditions, resulting in large ocean-atmosphere heat exchanges and ice formation (Leppäranta 1993).

Hydrographic measurements (CTD) from April 1998 showed that the whole water column of Storfjorden is near its freezing point (< -1.85°C), and that there is no heat available from below which could prevent new freezing. During frazil ice formation around two-thirds of the salt is rejected instantly as brine (Martin & Kauffman 1981) and sinks down to the bottom where it forms brine-enriched shelf water. This fills the deep depression in Storfjorden and later flows over the sill into Storfjordrenna and the deep sea west of Spitsbergen (Jungclaus et al. 1995). Haarpaintner et al. (unpubl. ms.) coupled these observations with polynya size and ice production models. They interpolated the polynya size estimates from SAR using wind data and distinguished, inside the polynya, between thin ice and open water using Pease's approach (Pease 1987) to frazil ice accumulation at the lee side of the polynya. These calculations suggest that an ice volume of about 30 km^3 is produced in Storfjorden between November 1997 and the end of May 1998, rejecting 700 Mt (Megatons) of salt. Without advection, this could increase the salinity of the entire Storfjorden water volume (7.5×10^{11} m^3) by 0.9–1.0 PSU. About two-thirds of the entire ice volume form inside the polynya, which covers on average only 13% of Storfjorden. Maximum salinity measured in April 1998 in the centre of the depression was 35.05 PSU at the bottom (160 m depth) at freezing temperature (−1.9°C), giving a sigma-t, σ_t, of 28.22 kg·m^{-3}. If we suppose an average salinity increase of 0.3 PSU in the water column, the rejected salt from the six winter months could enrich three times the volume of Storfjorden, confirming the renewal time of two months for the entire Storfjorden waters suggested by Schauer (1995).

SAR imagery of sea ice and ice classification

The SAR (synthetic aperture radar) of the European satellite ERS-2 is an active microwave sensor that emits a signal at 5.3 GHz (C-band) at 782 km altitude. It is independent of solar radiation, penetrates clouds and has a resolution of 30 m. Thus, it is a suitable instrument for remote sensing in the polar regions. The reflected (backscattered) signal from the ground, here mostly ocean and ice, is then received and by signal processing gives a grey level image of an area covering 100×100 km^2. The images were delivered by the Tromsø Satellite Station in full and low resolution format (FRI and LRI format). The resolution was reduced by averaging to 1000×1260 pixels per scene to eliminate the SAR-specific speckle noise and for easier visualization and handling. Radar backscatter depends mostly on the surface roughness of the sea ice (Carsey 1992). Before freezing to a smooth ice cover, the backscatter coefficient may vary enormously from very dark grey level (low backscatter coefficient) for open water in absence of wind, to very bright (high backscatter coefficient) for wind roughened sea or ice crystals and frost flowers growing on thin ice (nilas). Thin smooth ice has a very low backscatter coefficient, which will increase with ageing and deformation of the ice. With time the ice becomes thicker by continuous growth and often rougher due to compression, shear movements, rafting and ridging. These signatures can be very clear on the SAR image, but can also be very ambiguous, especially for very young ice and open water as explained above. From the tentative classification on the image from 6 March 1996, we sketched a possible evolution of the backscatter coefficient with ageing and freezing for first year ice (Fig. 5). In calm wind conditions and calm sea, the large variation in the backscatter coefficient might be less than sketched or even absent during ice

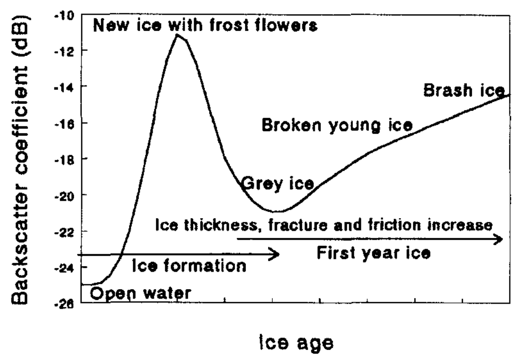

Fig. 5. Sketch of a possible SAR backscatter coefficient variation versus ongoing ice formation and ageing. Under rough wind conditions, the variation between open water and grey ice might be very strong, passing by a maximum backscatter coefficient. Under calm conditions (no wind and waves), the variation could be minimal.

formation. However, this evolution of the backscatter coefficient during ageing is dependent on ocean dynamics and weather and can therefore differ with region and time (Steffen & Heinrichs 1994). Classification of sea ice by satellite and ice tracking is important in order to define the origin, age and type of ice (Askne 1996; Carsey 1992; Kergomard et al. 1994; Steffen & Heinrichs 1994; Sun 1996). The evolution of the backscatter coefficient is complex and highly variable, especially during ice formation (Fig. 5). This explains the different appearance in brightness of the Storfjorden polynya between 1996 (Fig. 6a) and 1998 (Fig. 1).

The first attempts to classify the Storfjorden ice cover have been made on the SAR image from 6 March 1996, when the polynya appeared as a bright region. This area of more than 1000 km^2 has a very high backscatter coefficient. This strong signal might be either due to frost flowers growing at the surface by condensation and freezing of water vapour through very thin ice or due to wind-roughened open water. We reduced the high resolution image to two images by taking for one the mean value and for the other one the variance of a 5×5 pixel window. Then, using a two-dimensional supervised classification, we arrived at a classified image presented in Fig. 6b. Multi-year ice is not very common in Storfjorden, but early winter images show that some might be transported through the straits or around Edgeøya. The ice classification is an attempt to sub-classify first year ice by SAR imagery. The polynya is well defined, but a reliable ice type classification has

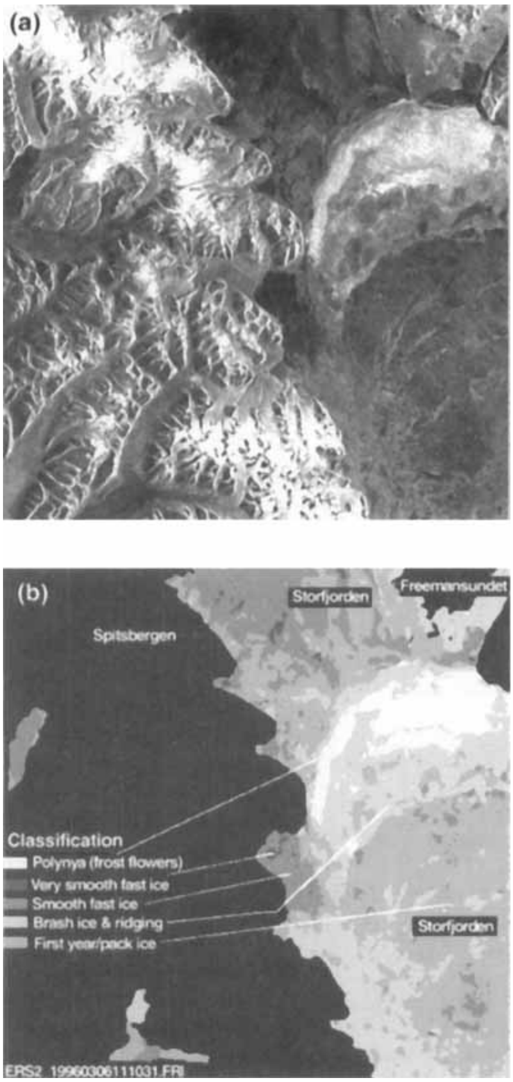

Fig. 6. (a) ERS-2 SAR observation of the Storfjorden polynya on 6 March 1996 (original data © ESA [1996], distributed by Eurimage [TSS]). The polynya has a very strong backscatter coefficient. (b) First attempt at first year ice sub-classification using a two-dimensional supervised classification.

not been achieved yet, even though it is possible to recognize different structures in the ice cover and especially to differentiate the northern fast ice from big ice floes south of the polynya. Figure 1 shows that the situation in Storfjorden can be very variable and that it is nearly impossible to differentiate individual ice floes in the southern part of the polynya, where brash ice, accumulation, rafting and ridging of thin ice strongly reflects the SAR signal. Thus, different ice type signatures need further investigation to improve ice classification by SAR imagery.

Discussion and conclusion

The Storfjorden polynya is probably the cause of the abundance of brine-enriched shelf water found in this area. Satellite remote sensing techniques, such as synthetic aperture radar (SAR) from the European earth remote sensing satellite ERS-2, seem to be adequate tools for studying the extent and evolution of the polynya. First analyses of a data set comprising a large quantity of images give a good and precise overview of the winter evolution of the polynya, the ice conditions and the dynamics of the fiord. The polynya comprises, at its largest extent, a region of up to 6000 km^2, which is comparable to other large polynyas already investigated in the Arctic (Smith et al. 1990). Wind direction data from the Norwegian meteorological station on Hopen show that the opening of the Storfjorden polynya is correlated with northerly winds, and closing with southerly winds. On account of this dynamic response to wind, it can be classified as a latent heat polynya, as defined in Smith et al. (1990), in contrast to sensible heat polynyas that form due to heat fluxes from the ocean like up-welling of warmer water. The Storfjorden polynya is responsible for the production of two-thirds of the total Storfjorden ice volume of about 30 km^3. The 700 Mt of rejected salt could raise the salinity of Storfjorden by 0.9–1.0 PSU. Comparison between the Hopen station and the automatic weather station at Kapp Dufferin shows that the temperature in Storfjorden is some degrees colder than on Hopen.

Further investigation of different ice type signatures on SAR images is necessary to provide a reliable classification, which is important to calculate the heat exchange between the atmosphere and the ocean. Nevertheless, classification by hand and eye is possible to some degree, depending on the kind of classes chosen. Using a relatively large number of ERS-2 SAR images, including time series, we could with comparative accuracy distinguish three classes: fast ice, pack ice and polynya, as explained earlier. This rough classification should be reproducible, though regional knowledge and ground truthing make the task much easier. However, the problem is how informative is this classification regarding the calculation of heat exchange between the ocean and the atmosphere and thus, for ice formation, i.e. what do we actually define as a polynya? In our case, the class of polynya is not only open water as some would define a polynya, but a region, showing high dynamics in time series, where no big ice floe structure is visible and presenting a wide range of backscatter levels. Field work by helicopter showed that this region includes open water, brash ice and accumulation, ridging and rafting of thin ice. It is therefore important to verify remote sensing observations by modelling to accurately estimate the ice production. Modelling the polynya size and the open water fraction shows that on average only 17% of the polynya is ice-free. Winter hydrographic measurements are important to study water mass evolution over the year and to make the estimation of brine production using SAR possible in the future. An interesting approach in sea ice remote sensing is the superposition of bathymetry and SAR satellite data to observe depth dependent ice and oceanographic features.

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