A comprehensive view of Kara Sea polynya dynamics, sea-ice compactness and export from model and remote sensing data

S. Kern and I. Harms
Center for Marine and Atmospheric Research, Institute of Oceanography, University of Hamburg, Hamburg, Germany

S. Bakan
Max-Planck Institute for Meteorology, Hamburg, Germany

Y. Chen
Max-Planck Institute for Biogeochemistry, Jena, Germany

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[1] The Shelf Seas of the Arctic are known for their large sea-ice production. This paper presents a comprehensive view of the Kara Sea sea-ice cover from high-resolution numerical modeling and space-borne microwave radiometry. As given by the latter the average polynya area in the Kara Sea takes a value of 21.2×10^3 km^2 ± 9.1×10^3 km^2 for winters (Jan.–Apr.) 1996/97 to 2000/01, being as high as 32.0×10^3 km^2 in 1999/2000 and below 12×10^3 km^2 in 1998/99. Day-to-day variations of the Kara Sea polynya area can be as high as 50×10^3 km^2. For the seasons 1996/97 to 2000/01 the modeled cumulative winter ice-volume flux out of the Kara Sea varied between 100 km^{3}a^{-1} and 350 km^{3}a^{-1}. Modeled high (low) ice export coincides with a high (low) average and cumulative polynya area, and with a low (high) sea-ice compactness in the Kara Sea from remote sensing data, and with a high (low) sea-ice drift speed across its northern boundary derived from independent model data for the winters 1996/97 to 2000/01. **Citation:** Kern, S., I. Harms, S. Bakan, and Y. Chen (2005), A comprehensive view of Kara Sea polynya dynamics, sea-ice compactness and export from model and remote sensing data, *Geophys. Res. Lett.*, *32*, L15501, doi:10.1029/2005GL023532.

1. Introduction

[2] The Arctic sea-ice cover is decreasing in extent [*Johannessen et al.*, 2004] and thickness [*Rothrock et al.*, 2003] and is predicted to decrease even more during summer while remaining fairly stable, at least its extent, during winter [*Johannessen et al.*, 2004]. The Arctic Shelf Seas are of particular importance because of their role in the production of sea ice to be exported into the Arctic Ocean. In the Eurasian Shelf (Kara, Laptev, and East-Siberian Seas) shore leads and flaw polynyas along the fast-ice border are abundant, and primary locations for winter sea-ice production and Arctic cold halocline water formation. Polynyas in the Kara Sea are typically solely wind-driven [*Smith et al.*, 1990; *Winsor and Björk*, 2000; *Morales-Maqueda et al.*, 2004].

[3] Because of their small width (1–10 km) it is difficult to resolve polynyas in large-scale ice-ocean models with grid resolutions in the order of 10–100 km. A solution to that problem is the application of high-resolution regional-scale models in order to investigate in more detail whether those models are able to reproduce small-scale features of sea ice formation and drift. A modified version of the HAMburg Shelf Ocean Model (HAMSOM) [*Harms et al.*, 2003] permits a horizontal grid-resolution of 9.4 km in the Kara Sea. In this paper a time-series (1996–2001) of sea-ice cover, volume and export as obtained with this Kara-Sea Model (KSM) is compared with the polynya extent obtained from Special Sensor Microwave/Imager (SSM/I) data with the Polynya Signature Simulation Method (PSSM) [*Markus and Burns*, 1995] at similar spatial resolution and the sea-ice compactness derived from standard algorithm sea-ice concentrations [*Cavalieri et al.*, 1997]. The goal is to answer the following questions: 1) Does the KSM reproduce the Kara-Sea polynya dynamics? 2) Is there a link between polynya activity and ice volume and/or export in the Kara Sea? 3) Is there a link between polynya activity and sea-ice compactness in the Kara Sea?

2. Description of Methods

[4] Numerical Modeling: A hydrodynamic 3-d coupled ice-ocean model is applied to the Kara Sea (horizontal grid resolution: 9.4 km). The model is based on the coding of the HAMburg Shelf Ocean Model (HAMSOM), previously applied to the Kara Sea by *Harms et al.* [2003]. HAMSOM is a level-type model based on the non-linear primitive equations of motion, invoking the hydrostatic approximation. The circulation model is coupled to a dynamic-thermodynamic sea-ice model, which calculates space and time dependent variations of ice thickness and compactness. The Kara Sea studies are forced with daily atmospheric winds and heat-fluxes (National Center for Environmental Prediction, NCEP data base for 1996–2001 [*Kalnay et al.*, 1996]), daily mean river runoff from Ob (including tributaries Taz and Pur), Yenisei and Pyasina (*Regional Hydrometeorological Data Network for the pan-Arctic Region*, http://www.r- arcticnet.sr.unh.edu/abstract.html) and M_2-tides. For the open boundaries, data (ice cover, sea surface height) from the large-scale AWI/NAOSIM coupled ice-ocean general circulation model for the Arctic and sub-Arctic domain is used [*Karcher et al.*, 2003]. Figure 1 shows the model domain. Remote Sensing: The Polynya Signature Simulation Method (PSSM), which was developed by

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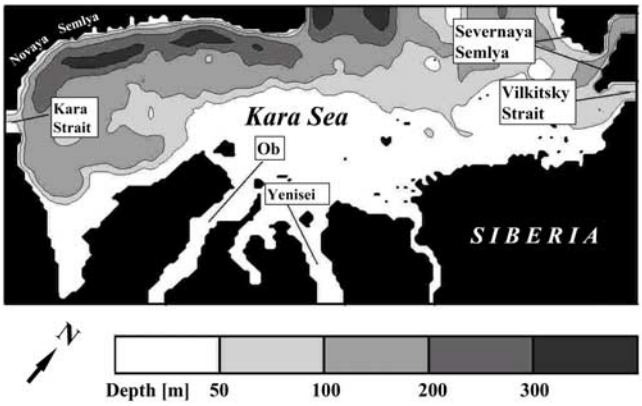

Figure 1. Kara-Sea Model domain (1598 km × 790 km).

Markus and Burns [1995] and refined by *Hunewinkel et al.* [1998], is used to estimate open water and thin-ice extent of a polynya. This method is based on SSM/I brightness temperature polarization ratios (= vertically minus horizontally polarized brightness temperature divided by their sum) at frequencies of 37 and 85 GHz. It combines the finer spatial resolution at 85 GHz with the lower weather influence at 37 GHz in an iterative approach to obtain maps of the polynya extent, and the associated open water and thin-ice fractions at a spatial resolution of about 5 km. A detailed description of the PSSM, including its sensitivity to weather effects, is found in the works by *Markus and Burns* [1995] and *Hunewinkel et al.* [1998]. They report a mean error of 80 km^2, and a minimum observable change in the polynya area in the order of 50 km^2. It was applied in a number of studies [e.g., *Markus et al.*, 1998; *Dokken et al.*, 2002; *Martin et al.*, 2004].

3. Results

[5] The Kara-Sea Model (KSM) was used to obtain the daily ice volume distribution. Figure 2 shows the daily (black line) and the average seasonal (Sep.–Aug., grey bars) sea-ice volume in the Kara Sea for 1996–2001. The peak ice volume occurred in the season 1998/99 (daily: 1420 km^3, average seasonal: 790 km^3) followed by the minimum ice volume in 1999/2000 (daily: 1220 km^3, average seasonal: 620 km^3). This is confirmed by maps of ice-cover duration, giving maximum durations in 1998 and 1999 [*Kern and Harms*, 2004]. Figure 3 shows a comparison between areas occupied by surface classes: open water (<10% ice concentration), thin/loose ice (10–45%) and thick/compact ice (>45%) as derived from KSM sea-ice concentrations, and PSSM polynya extent (same classes) in the Kara Sea for a selected period in Feb. 2001. KSM and PSSM agree concerning location and maximum extent of the polynyas developing along the east coast of Novaja Zemlja. Figure 4 shows the total PSSM polynya area (thin ice and open water) for the Kara Sea for 1995–2004. Sampling is twice daily in about 90% of all days and once daily otherwise. In each season the PSSM analysis starts once the entire Kara Sea is ice covered or an ice bridge has formed in the Kara Strait so that the remaining open water area inside the Kara Sea can be regarded as a polynya. The such defined starting date varies from mid-November to the end of December. The stop date is set to the last May decade. At this time ice melt has started, and thin-ice growth is negligible. Figure 4 permits to distinguish between seasons with high (1999/2000) and low (1998/99) polynya activity, indicated by large and small average polynya areas, respectively.

[6] The KSM is able to simulate the polynya dynamics in the Kara Sea - provided that the polynya area is larger than at least 100 km^2. This is evident from the example given in Figure 3 (and from examples not shown here). A large polynya developed in the lee of Novaya Zemlya during northwesterly air flow from Feb. 3 to 5. This polynya gradually closed and moved toward Kara Strait, where it became fully developed on Feb. 11 during southwesterly airflow. Sea-ice concentration maps (*Cavalieri et al.* [1997], not shown) confirm this development; however, such maps are inadequate to infer the polynya extent as given by the PSSM. The disagreement between KSM and PSSM northeast of Novaya Zemlya is caused by problems with the sea-ice dynamics at the model boundaries. Note also, that the model forcing is based on NCEP data which gives a spatial resolution of approximately two degrees. Therefore, the orographic influence on wind direction and speed close to land boundaries might be underestimated. This might result in an unrealistic distribution of the polynya area compared to remote sensing data. As a shortcoming of the PSSM, the first one to two grid cells adjacent to the land boundaries might be influenced by the microwave signature of the land, biasing the brightness temperatures used in the PSSM. This might result in an unrealistic classification close to land – particularly concerning open water, which is misinterpreted as thin ice; however, the influence on the total polynya area was found to be negligible.

4. Synergy of Results

[7] Figure 5 shows the daily (black line) and cumulative seasonal (Jul.–Jun., grey bars) ice volume flux out of the Kara Sea. The peak ice export occurred during seasons 1996/97 and 1999/2000 (about 560 km^{3}a^{-1}), while it was almost zero during seasons 1997/98 and 1998/99. Superposed are winter (Jan.–Apr.) values of the average total polynya area (compare Figure 4) and the percentage contribution of sea ice of the ice concentration ranges: 65–85% and >95%, to the total Kara Sea sea-ice area (called sea-ice

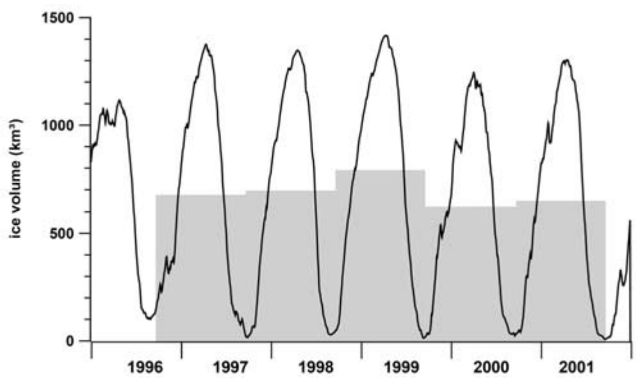

Figure 2. Daily (black line) and average seasonal (Sep.–Aug., grey bars) Kara Sea ice volume obtained with the KSM for 1996–2001.

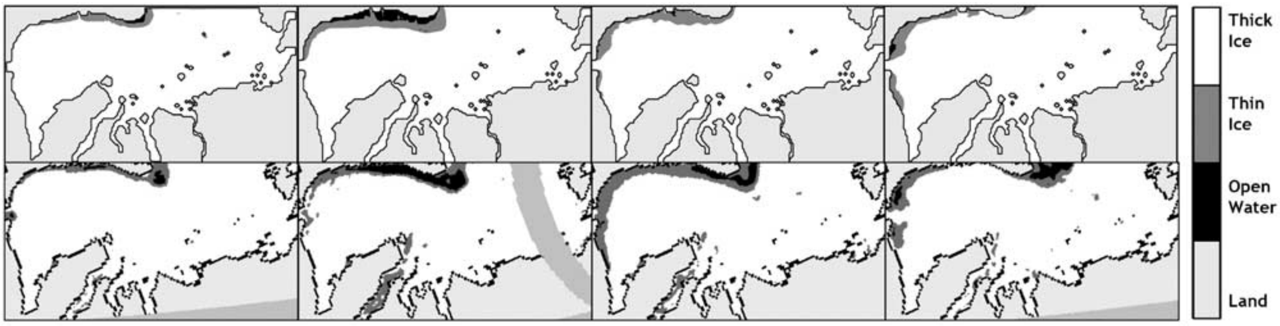

Figure 3. KSM (top) and PSSM (bottom) distributions of open water (<10% ice concentration), thin/loose ice, and thick/compact ice (>45%) for (from left to right) Feb. 3, 5, 8, and 11, 2001. Medium grey areas in bottom row denote missing data. Thin ice areas in rivers (bottom row) are artefacts caused by river ice, which has a higher emissivity than sea ice and therefore can be misinterpreted by the PSSM as thin ice.

compactness, henceforth) derived from the NASA-Team algorithm sea-ice concentration [*Cavalieri et al.*, 1997]. The goal in including the sea-ice compactness is to add an independent measure of the sea-ice conditions of the entire Kara Sea. A large (winter) ice volume as observed in 1997/98 and, in particular, in 1998/99 (Figure 2) is not indicative of a large ice export, being rather zero in these two seasons (Figure 5). This seems to be quite reasonable, because if only a small amount of ice is exported, the sea ice is re-distributed in the Kara Sea and the ice volume remains constant or even increases, whereas if a large amount of ice is exported as observed for 1999/2000 (Figure 5), the ice volume decreases (Figure 2). However, ice export out of a certain region is associated with a divergent sea-ice motion in that region, at least at its boundary, which favors the formation of leads and polynyas. During freezing conditions especially the latter might act as ice-production sites if kept open by persistent cold winds. This might cause some compensation of the sea-ice loss due to the export. Table 1 shows the average winter (Jan.–Apr.) ice volume in and the total winter ice-volume export out of the Kara Sea for 1997–2001, in comparison with the average and the cumulative polynya area for the same period. There is a striking agreement between high (low) ice export and large (small) polynya areas: 1997 and 2000 (1998 and 1999); moderate values occurred in 2001 – also in agreement with each other. So there is a clear link between Kara Sea ice export and polynya area, whereas no link is apparent between Kara Sea ice volume and polynya area.

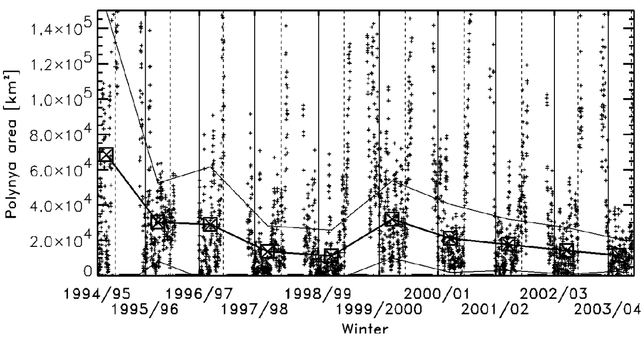

Figure 4. Total polynya area (thin ice and open water) of all Kara Sea polynyas obtained with the PSSM for 1995–2004; sampling is approximately twice daily. The thick solid line connects values of the average winter (Jan.–Apr.) total polynya area; thin solid lines mark one standard deviation.

[8] Kara Sea polynyas are wind-driven. Since the Kara Sea is a semi-enclosed basin, it is very likely that compact sea-ice conditions inhibit polynya formation. Table 1 shows that in winters with a small polynya area (1998, 1999) an above-normal fraction of the total Kara Sea sea-ice area comprises ice of the range >95%, and a below-normal fraction is of the range 65–85%. Sea-ice drift speeds, which are estimated from independent model data (European Center for Medium-range Weather Forecast, ECMWF, instead of NCEP) for the northwestern KSM boundary (see Figure 1) using the surface wind speed, a 30% deviation of the direction to the right and 2% of the wind speed, agree with these findings: above-average drift speeds coincide with a higher ice export, larger polynya area, and a smaller sea-ice compactness. So, there is a link between sea-ice compactness and polynya area in the sense that in years with low polynya area a highly compact sea-ice cover occurred.

5. Summary and Conclusion

[9] In the present paper, space-borne microwave radiometry and high-resolution numerical ice-ocean modeling is

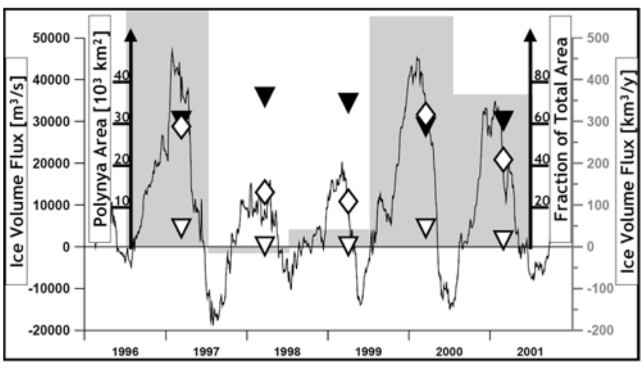

Figure 5. Daily (black line) and cumulative seasonal (Jul.–Jun., grey bars) ice volume flux out of the Kara Sea obtained with the KSM for 1996–2001. Open diamonds denote the average winter total polynya area (see Figure 4). Closed (open) triangles denote the percentage contribution of sea ice within the range >95% (65–85%) to the total Kara Sea sea-ice area for the same periods (see text).

Table 1. Comparison Between the Average Ice Volume in and the Total Ice-Volume Flux Out of the Kara Sea (KSM), the Average and Cumulative Kara Sea Polynya Areas (Thin Ice and Open Water) (PSSM), the Percentage Contribution of Sea Ice of Ranges 65–85% and >95% to the Total Kara Sea Sea-Ice Area, and the Sea-Ice Drift Speed Perpendicular to the Northwestern Model Boundary (See Figure 1) Estimated From Monthly Averaged Daily ECMWF Surface Wind Speed Data, for Jan.–Apr., 1997–2001[a]

	1997	1998	1999	2000	2001
Average ice volume, km^3	1180	1150	1270	1090	1130
Total ice-volume flux, km^3	350	100	100	350	200
Average area, 10^3 km^2	29.2	13.9	11.4	32.0	21.2
Cumulative area, 10^6 km^2	6.3	3.3	2.6	7.5	5.0
Fraction 65–85%, %	8	2	2	8	5
Fraction >95%, %	65	75	70	62	65
Sea-ice drift speed, cm/s	4.7	3.6	2.6	6.2	3.3

[a]The number of PSSM-maps per year is 228.

combined to investigate the interrelation (if any) between polynya area in and the ice export out of the Kara Sea. Sea-ice data output by the HAMburg Shelf-Ocean-Model, HAMSOM, which is able to model the Kara Sea oceanography at a spatial resolution of 9.4 km, is compared to sea-ice data from remote sensing at similar spatial resolution using the Polynya Signature Simulation Method (PSSM). The location and dynamics of polynyas in the Kara Sea obtained with this Kara-Sea Model (KSM) and PSSM agree within the capabilities of these methods. A very consistent view is found concerning the interplay between sea-ice compactness, polynya area, and ice export out of the Kara Sea. In particular, high ice export (KSM) coincides with a large polynya area, a low sea-ice compactness (both from remote sensing), and high ice-drift speeds (ECMWF data). The average polynya area in the Kara Sea takes a value of 21.5×10^3 $km^2 \pm 9.1 \times 10^3$ km^2 for winters 1996/97 to 2000/01, being as high as 32.0×10^3 km^2 in 1999/2000 and below 12×10^3 km^2 in 1998/99. Day-to-day variations of the Kara Sea polynya area can be as high as 50×10^3 km^2. For seasons 1996/97 to 2000/01 the modeled cumulative winter (Jan.–Apr.) ice-volume flux out of the Kara Sea varied between 100 km^3a^{-1} and 350 km^3a^{-1}. The time-series of the average total Kara Sea polynya area (Figure 4) obtained with the PSSM suggests a decreasing polynya activity in the Kara Sea for the recent decade. Further investigations are needed to a) confirm this with model data, to b) extend this time-series further back (which is limited to 1992 due to a failure of the relevant channels of the SSM/I sensor), and to c) relate the observed polynya areas to the period before 1992. With regard to the latter, a first attempt is made relating the average polynya area to the sea-ice compactness. This revealed an almost linear relationship (which is not unexpected because the sea-ice compactness can be influenced by polynyas via a reduction of the ice concentration where the latter occur) which could be used to extend the time-series of the average total Kara Sea polynya area back until 1979. This would be of high importance in the context of the predicted changes in the Arctic environment with respect to air and sea surface temperature, sea surface salinity, freshwater supply by rivers and the Arctic cold halocline layer. We need to understand the variability first before we can predict climate-warming induced changes in ice and deep-water formation linked to polynya activity.

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S. Bakan, Max-Planck Institute for Meteorology, D-20146 Hamburg, Germany.

Y. Chen, Max-Planck Institute for Biogeochemistry, D-07745 Jena, Germany.

I. Harms and S. Kern, Center for Marine and Atmospheric Research, Institute of Oceanography, University of Hamburg, Bundesstr. 53, D-20146 Hamburg, Germany. (kern@ifm.zmaw.de)