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Sea-ice production over the Laptev Sea shelf inferred from historical summer-to-winter hydrographic observations of 1960s–1990s

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[1] The winter net sea-ice production (NSIP) over the Laptev Sea shelf is inferred from continuous summer-to-winter historical salinity records of 1960s–1990s. While the NSIP strongly depends on the assumed salinity of newly formed ice, the NSIP quasi-decadal variability can be linked to the wind-driven circulation anomalies in the Laptev Sea region. The increased wind-driven advection of ice away from the Laptev Sea coast when the Arctic Oscillation (AO) is positive implies enhanced coastal polynya sea-ice production and brine release in the shelf water. When the AO is negative, the NSIP and seasonal salinity amplitude tends to weaken. These results are in reasonable agreement with sea-ice observations and modeling. **Citation:** Dmitrenko, I. A., S. A. Kirillov, L. B. Tremblay, D. Bauch, and S. Willmes (2009), Sea-ice production over the Laptev Sea shelf inferred from historical summer-to-winter hydrographic observations of 1960s–1990s, *Geophys. Res. Lett.*, *36*, L13605, doi:10.1029/2009GL038775.

1. Introduction

[2] The Laptev Sea shelf situated within the seasonal sea-ice zone is believed to be the main source of the Arctic sea-ice Transpolar drift, transporting ice across the Eurasian Basin from the Siberian shelf toward Fram Strait [*Eicken et al.*, 1997; *Rigor and Colony*, 1997; *Mysak*, 2001] Over the northeastern Laptev Sea the annual mean winds exhibit an off-shore component feeding the Transpolar ice drift from October to April, while summer mean winds are weaker, turning along-shore towards the east in May–September [*Dmitrenko et al.*, 2006]. The Arctic Oscillation (AO) explains most of seasonal variance in wind and sea-ice motion: winter wind anomalies associated with high-index AO conditions increases the advection of ice away from the Eurasian and Alaskan coast [*Rigor et al.*, 2002; *Armstrong et al.*, 2003]. The offshore components of winter surface wind forcing over the Eurasian coast create persistent areas of open water and young ice downwind of the land-fast ice in the absence of sensible ocean heat input from below [*Martin and Cavalieri*, 1989; *Bareiss and Görgen*, 2005]. During winter the extensive stretches of open water (up to 200 km wide), known as the Great Siberian Polynya, combined with extremely low air temperatures, induce intensive thermodynamic ice formation. This provides a strong salt input to the underlying shelf water due to brine release and gives rise to the seasonal salinity changes.

[3] Based on the regular summer-to-winter historical hydrographic records from the 1960s–1990s, *Dmitrenko et al.* [2008a] demonstrated that quasi-decadal variations in the seasonal salinity difference (SSD) over the Laptev and East Siberian sea shelves is partly controlled by quasi-decadal oscillations of summer atmospheric vorticity between cyclonic and anticyclonic modes. In this context, the interannual variations in winter atmospheric patterns, and seasonal salinity adjustment associated with wind-driven winter sea-ice production, were omitted given the relative stability in the anticyclonic mode of the winter atmospheric circulation. In contrast to the report by *Dmitrenko et al.* [2008a], the present study mainly focuses on ice-related shelf water modification in winter, a period of steady low-flow river discharge, for the first time linking the seasonal salinity adjustment to winter ice formation in the Laptev Sea using continuous summer-to-winter Soviet hydrographic observations from the 1960s–1990s. More specifically, this study focuses on evaluating the sea-ice production and its interannual variability based on hydrological rather than sea-ice observations. A new perspective on this issue appears from the role of winter off-shore meridional wind in terms of its influence on winter sea-ice production through polynya formation as inferred from the SSD.

2. Data

[4] The summer-to-winter hydrographic surveys cover the entire thirty-year period from 1963–1993. Winter hydrographic data from 1321 stations were obtained during Soviet aircraft surveys from March to May. Summer ship-based observations (3870 stations) were collected in the ice-free regions of the Laptev Sea in August–September (see Figure 1 for spatial and temporal data coverage). Salinity was measured with a Russian GM-65 salinometer with an accuracy of 0.05 psu. National Center for Environmental Prediction (NCEP) sea-level wind data [*Kalnay et al.*, 1996] are used to describe the atmospheric circulation. Daily gridded sea-ice concentrations [*Cavalieri et al.*, 1996] provided by the U.S. National Snow and Ice Data Center are used to calculate daily open water areas in pre-defined sub-masks over the Laptev Sea coastal polynya. Sub-masks were chosen to cover the prevailing positions of the Taymir (T), Anabar Lena (AL), and West New Siberian (WNS) polynyas (Figure 1) following the sub-masks nomenclure suggested by *Bareiss and Görgen* [2005]. The occurrence of polynya event within a sub-mask was recognized once the

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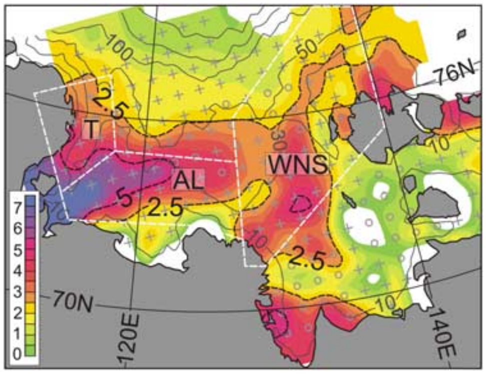

Figure 1. Long-term mean (1960s–1990s) vertically-integrated summer-to-winter seasonal salinity difference (SSD, psu) from *Dmitrenko et al.* [2008a]. The white dashed boxes show sub-masks for the prevailing positions of the Taymir (T), Anabar Lena (AL), and West New Siberian (WNS) coastal polynyas following *Bareiss and Görgen* [2005]. Dots mark those grid nodes where the salinity data from 15–30 years of continuous summer-to-winter observations were used. Crosses correspond to 5–15 years of continuous summer-to-winter observations. Grid nodes with fewer than 5 summer-to-winter observations are not depicted. Over the shallows and coastline in the southern Laptev Sea, the blanked areas mark artificially negative SSD values (see *Dmitrenko et al.* [2008a] for more details). Bathymetry is shown by gray solid lines.

area of open water exceeds 1.5% of the total sub-mask area. The winter mean (November 1–May 15) of daily integrated open water areas in these three sub-masks, hereafter referred to as *Laptev Sea polynya open water area*, was calculated for the winter seasons from 1978/1979 to 1991/1992.

3. Methods

[5] The SSD is considered to be a measure of the salinity field adjustment to winter sea-ice formation assuming there is no salt influx through the Laptev Sea domain boundaries. At the moment there are no available data to justify this assumption and/or estimate the error associated with this assumption. From this consideration, the sea-ice production (I, km^3) was computed from continuous 1960s–1990s summer-to-winter salinity observations in the upper 50 m by

$$I = \frac{dS}{S_c} V_0 \frac{S_c}{S_c - S_{ice}} = dFWC \frac{S_c}{S_c - S_{ice}},$$

where $dFWC$ is seasonal summer-to-winter fresh water content difference, $dS = (\overline{S_W} - \overline{S_S})$ is the SSD integrated over the entire Laptev Sea domain (the long-term mean SSD vertically integrated at each node of a regular 50 km grid shown in Figure 1, following *Dmitrenko et al.*, 2008a), S_c is the long-term mean (1960s–1990s) salinity of the Laptev Sea in the upper 50 m layer (28 psu), S_{ice} is the sea-ice salinity, and V_0 is the Laptev Sea domain volume. The method used to calculate $\overline{S_S}$ and $\overline{S_W}$ over a regular grid (x, y and z) as well as smoothing procedure follow those of *Dmitrenko et al.* [2008a, 2008b].

[6] While the salinity of newly formed sea ice can range between 4 and 12 psu, salinity decreases rapidly with age [*Nakawo and Sinha*, 1981; *Melling and Moore*, 1995]. For the sea-ice production calculations, we use two categories of sea-ice with different salinities. First we assume that 1.5 m of sea-ice at 4 psu salinity grows each year everywhere in the Laptev Sea. The 1.5 meter thick sea-ice fraction at S_{ice} = 4 psu represents the average values for the first-year sea-ice in the Laptev Sea [*Appel and Nazintsev*, 1981]. Additional sea ice formation (required to balance the winter to summer salt excess) is then assumed to have a salinity S_{ice} = 8 psu. This accumulated fraction of sea-ice (above 1.5 meter growth) is associated with young sea-ice that has been continuously exported from the domain during one winter season and hereafter is referred (by definition) to as the net winter sea-ice production (NSIP). The long-term mean NSIP calculated using the two ice-category salinities along with standard deviations are shown in Figure 2. The NSIP time series integrated over the Laptev Sea domain for a range of sea-ice salinities between 0 and 12 psu show the sensitivity of the NSIP calculation to the particular assumption regarding sea-ice salinity fractionation (Figure 3). Statistical error of annual values reflects both the scaling error which is due to the limited data coverage and the standard error calculated from the salinity measurements (for more details see *Dmitrenko et al.* [2008b]). A 7-year running mean was applied to the NSIP time series to filter the noise associated with the limited data coverage and the errors attributed to the scaling procedure (Figure 3).

4. Results

[7] While the NSIP spatial distributions exhibit no clearly attributable patterns, elevated NSIP values exceeding 2 m mostly occupy the mid-shelf area that is roughly limited by the depth contour of ∼15–25 m usually associated with land fast ice edge position and the southernmost polynya extension (Figures 1 and 2, left). This mid-shelf area also has elevated NSIP standard deviations exceeding 2 m (Figure 2, right), implying large interannual variability in NSIP. Based on the 7-year running mean, the periods of 1963–1970 and 1978–1985 have negative NSIP anomalies of 200–300 km^3 depending on the sea-ice salinity assumption. In contrast, the 1970–1978 and 1985–1991 periods have positive anomaly values of about the same order of magnitude (Figure 3).

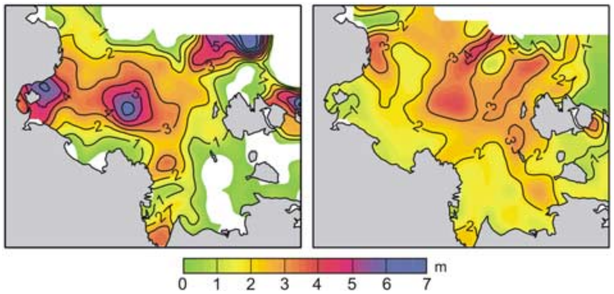

Figure 2. (left) Long-term mean net sea-ice production (NSIP, m) and (right) NSIP standard deviation (m). Blanked areas on the outer shelf are regions of insufficient data coverage.

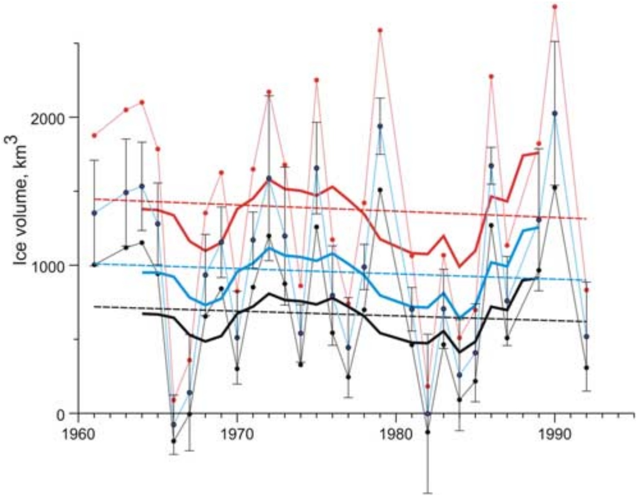

Figure 3. The Laptev Sea integrated NSIP (km^3). Black, blue, and red lines show the sea-ice volume calculated at 0, 4, and 8 psu salinity for the sea-ice fraction thinner than 150 cm, respectively. The NSIP fraction thicker than 150 cm take as 4 psu saltier. Error bars show the NSIP estimation error (see *Dmitrenko et al.* [2008b] for more details). Bold lines indicate 7-year running mean. Dashed lines show linear trends.

[8] Our calculations also show that the NSIP estimates are within the range of realistic sea-ice growth values, although they are rather sensitive to the particular assumption regarding sea-ice salinity of newly formed ice (Figure 3). For a Laptev Sea domain area of 495,000 km^2 the mean winter net sea-ice growth are 1.37, 1.95, and 2.81 m (not including an additional 1.5 m sea-ice growth over the Laptev Sea domain, at a salinity of 0, 4, and 8 psu, respectively). In this calculation, the mean NSIP fraction of 679, 964, and 1390 km^3 was assumed to be 4 psu saltier than the 1.5 m sea-ice fraction. As shown in Figure 3, the NSIP estimates strongly depend on the sea-ice salinity assumption, and therefore may not be used for quantitative purposes. In the discussion, therefore, we will mainly focus on the robust patterns of NSIP quasi-decadal variability which demonstrates similar features regardless of the sea-ice salinity assumption (Figure 3) and the exact number of years used in the running average (not shown).

5. Discussion

[9] The sea-ice formation in the Laptev Sea coastal polynya is important in determining the winter salinity of surface waters [*Zakharov*, 1966; *Dmitrenko et al.*, 2005b]. However, based only on historical winter salinity data, *Dmitrenko et al.* [2005a] report a weak relationship between winter wind and salinity fields. Following this approach, *Dmitrenko et al.* [2008a] explain the SSD interannual variability mainly by quasi-decadal changes in summer wind-driven circulation which in turn affect the spatial distribution of river runoff in the Laptev Sea. In doing so, they omit the variable salt influx from changing winter sea-ice formation. Based on our new results we argue that interannual variability in winter atmospheric forcing controls the salt flux in the surface waters through the sea-ice formation and in this way affects the SSD.

[10] Our results on quasi-decadal variations in the Laptev Sea NSIP are in agreement with the source pattern of Transpolar drift. *Rigor and Colony* [1997] reported that on average as much as 20% of the ice area transported through Fram Strait is produced in the Laptev Sea shelf. Based on the Arctic buoy trajectories, *Pfirman et al.* [2004] demonstrated that the source area of multiyear sea-ice in Fram Strait exhibits substantial interannual variability. In 1983–1986 the Fram Strait sea-ice was dominated by the 3-year old fraction mostly originating from the north-western Laptev and the Kara seas. Afterwards, since 1987, the main source of the Transpolar drift has been substantially shifted eastward, and the older (4–5 year) fractions from the East Siberian and Chukchi seas prevailed until 1989–1990 after which the Laptev Sea contribution became predominant. A shift in the source region conditioned by more intense winter off-shore winds implies higher sea-ice production in the new source region through polynya formation. For our domain of interest (Figure 1), assuming a mean sea-ice travel time of 3–4 years [*Pfirman et al.*, 2004], the interannual variability in the main source area of sea-ice for the Transpolar drift implies higher ice production period from 1985–1986 to 1992–1993 and a lower ice production period from 1982–1983 to 1985–1986 (note that the north-western Laptev Sea is not included in the domain due to insufficient data coverage). This is in qualitative agreement with NSIP shown in Figure 4. Figure 4 is also qualitatively consistent with numerical modeling by *Rothrock and Zhang* [2005] which shows a sea-ice volume decrease over the Laptev Sea of ~0.5–1 × 10^3 km^3 in 1966–1970 and 1981–1984. Note, however, that the 1988–1992 sea-ice volume decrease [*Rothrock and Zhang*, 2005] is not matched to our data shown in Figure 4. Numerical modeling by *Alexandrov et al.* [2000] on average also supports our results showing relatively lower sea-ice areal flux from the Laptev Sea at the end of 1970s and in mid-1980s, while later in the same decade this link seems to break down (Figure 4). In this context, it is very likely that the breakdown in the comparison with output from *Rothrock and Zhang* [2005] and with *Alexandrov et al.* [2000] in the late 1980s is due to the

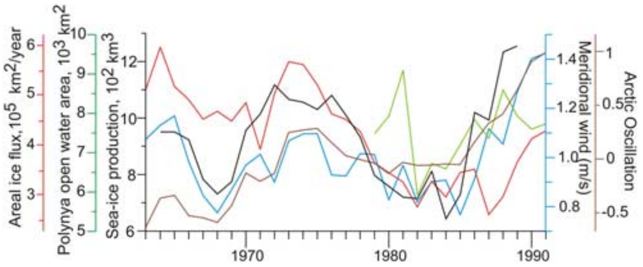

Figure 4. The NSIP for the first-year sea-ice salinity of 4 psu (black), winter mean (October–May) NCEP meridional wind averaged over the Laptev Sea (blue), winter mean AO index (brown), the Laptev Sea polynya open water area (green), and the Laptev Sea ice export according to a modeling study by *Alexandrov et al.* [2000] (red). All data except polynya area were smoothed by 7-year running mean.

relatively high NSIP errors (Figure 3) attributed to the insufficient data coverage.

[11] We link the fraction of quasi-decadal variability in NSIP (and SSD) to the patterns of atmospheric circulation over the northern hemisphere. *Rigor et al.* [2002] reported the sea-ice response to the AO. In contrast with the beginning of 1980s, the beginning of 1990s is associated with high-index AO conditions (Figure 4) that results in increase of the wind-driven sea-ice export from the Laptev and East Siberian seas [*Rigor et al.*, 2002] and in rapid decrease in the area of old ice in the Arctic Ocean from 1988 to 1990 [*Rigor and Wallace*, 2004]. The increased wind-driven advection of ice away from the Laptev Sea coast during winter at high-index AO conditions implies enhanced coastal polynya sea-ice production as demonstrated by our NSIP, polynya, and local wind records (Figure 4). More precise evidence of the relationship between NSIP and atmospheric circulation comes from the high correlation with both local and large scale atmospheric circulation patterns. A statistically significant correlation of 0.56 and 0.67 between the 7-year running mean NSIP with AO index and meridional wind, respectively, provides a qualitative assessment of the NSIP amplification by atmospheric forcing.

[12] While the coastal polynyas seem to be the main source for NSIP during winter (Figure 2), the Laptev Sea NSIP is not entirely associated with sea-ice formation within the polynya. The mean NSIP of 964 km^3 (at a first-year sea-ice salinity of 4 psu), assuming that all sea-ice is formed within a polynya area of 7500 km^2, requires about 128 m net sea-ice growth. This is unrealistic and suggests the importance of sea-ice export during the initial stage of ice growth and also the summer hydrographic preconditioning.

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