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# Wind-driven summer surface hydrography of the eastern Siberian shelf

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[1] High interannual variability of summer surface salinity over the Laptev and East Siberian Sea shelves derived from historical records of the 1950s–2000s is attributed to atmospheric vorticity variations. In the cyclonic regime (positive vorticity) the eastward diversion of the Laptev Sea riverine water results in a negative salinity anomaly to the east of the Lena Delta and farther to the East Siberian Sea, and a positive anomaly to the north of the Lena Delta. Anticyclonic (negative) vorticity results in negative salinity anomalies northward from the Lena Delta due to freshwater advection toward the north, and a corresponding salinity increase eastward.

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## 1. Introduction and Motivation

[2] The surface salinity distribution over the Siberian continental shelf is dominated by Siberian river discharge, ice-related processes (ice formation and melting, brine rejection in coastal polynyas), vertical mixing and exchange with the Arctic Ocean and adjoining seas. All these factors result in considerable interannual and interdecadal salinity variations mentioned by *Shpaikher et al.* [1972], and also recently reported by *Johnson and Polyakov* [2001], *Polyakov et al.* [2003], and *Steele and Ermold* [2004]. This study was motivated by high salinity variance in the Laptev Sea reported by *Polyakov et al.* [2003]. Surface salinity standard deviation ($\sigma$) from *Polyakov et al.* [2003] updated with data from 1950s and extended onto the East Siberian Sea demonstrates rather high interannual variability in the southern and central Laptev Sea, and along the coastline in the eastern East Siberian Sea (Figure 1). Here, we examine the main driving mechanisms responsible for interannual surface salinity variations with a focus on wind-driven processes, utilizing available historical hydrographic records from the Laptev and East Siberian Seas.

## 2. Data Set

[3] Winter historical hydrographical data from 2839 stations were obtained mainly during Russian aircraft surveys in the 1960–90s from March to May, i.e. conditions still representative of the winter regime. Summer ship-based observations were made between July and September (6548 stations) in the 1950s–2000s. Nansen bottles were used prior to 1993 while in recent years CTD measurements were obtained. The distribution of stations among 8 sub-regions of the Laptev and East Siberian Seas is shown in Figure 2. Considering the rather uniform data coverage over most of the Laptev Sea and southern East Siberian Sea (sub-regions 6 and 8), we assume that the derived long-term mean spatial distributions of various parameters are representative of the actual conditions. NCEP sea level pressure (SLP) data were employed to describe the atmospheric circulation over the Arctic Ocean. Monthly mean Siberian river discharge data were taken from Arctic-RIMS (Regional Integrated Monitoring System, http://rims.unh.edu). These data show that about 40% of the mean annual Siberian river discharge takes place during river-ice breakup which usually occurs at the end of May and beginning of June. Between November and April steady low-flow discharge is observed.

## 3. Methods

[4] The Laptev and East Siberian Seas are situated on the central and eastern Siberian Arctic shelf within the zero vorticity contour separating two predominant large-scale centers of atmospheric circulation over the Arctic Ocean [*Johnson and Polyakov*, 2001]. During anticyclonic circulation phases the high SLP center in the western Arctic (the Siberian High) is well developed and the Icelandic Low is suppressed, while during cyclonic phases the SLP high in the western Arctic is weaker and the Icelandic Low is stronger, extending farther into the Barents and Kara Seas [*Gudkovich*, 1961; *Johnson and Polyakov*, 2001]. We hypothesize that this unique position of the Laptev and East Siberian Sea shelves and the associated SLP centers renders their hydrography very sensitive to the shifts between predominant cyclonic and anti-cyclonic atmospheric circulation.

[5] We have employed a vorticity index as a descriptor of atmospheric circulation for further comparison with surface salinity fields. The vorticity index shows the direction and intensity of atmospheric vorticity, and was first employed to describe the circulation over the Arctic Ocean by *Walsh et al.* [1996]. It is the finite-differenced numerator of the Laplacian of SLP for the area within 550 km of 80°N and 150°E. The negative vorticity index corresponds to anticyclonic, and positive to cyclonic regimes of atmospheric circulation. Winter (November–May, Figure 3, top) and summer (June–September, Figure 3, bottom) averaged vorticity indexes were derived from monthly SLP NCEP data.

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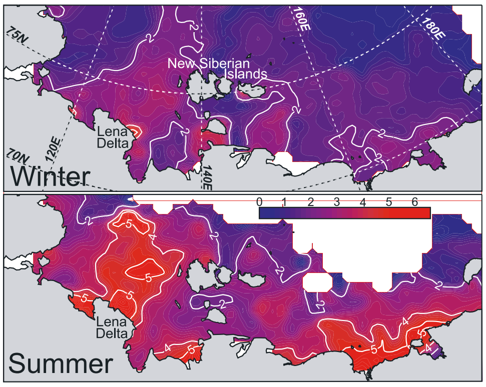

**Figure 1.** Surface salinity standard deviation adopted from *Polyakov et al.* [2003]. Data set was updated with additional data, extended to the 1950s, and into the East Siberian Sea (see part 2 for detailed description).

[6] SLP fields, averaged seasonally through the positive and negative vorticity years reveal the characteristic differences between cyclonic and anticyclonic regimes for both winter and summer long-term seasonal means (Figure 4). For anticyclonic circulation, winds typically exhibit offshore components towards the north over the Laptev Sea and along-shore westward components over the East Siberian shelf. Prevailing cyclonic wind in summer is oriented along-shore towards the east over the entire Laptev Sea and the western East Siberian Sea. In contrast to summer, during winter the difference between cyclonic and anticyclonic predominant wind patterns is substantially less (Figure 4, top).

[7] As an alternative description of atmospheric circulation, the SLP difference between 77.5° and 67.5°N that actually describes the intensity of zonal wind was employed. Seasonally mean SLP was zonally averaged along 77.5° and 67.5°N between the 110° and 180°E meridians. The difference between these two averages is referred to here as the SLP difference. A negative SLP difference corresponds to winds generally oriented towards the east (cyclonic regime), while positive numbers mainly represent conditions typically found for anticyclonic circulation. Obtained SLP difference numbers are well correlated with the annual vorticity index (correlation coefficients of −0.60 for winter and −0.71 for summer seasons, Figure 3, right).

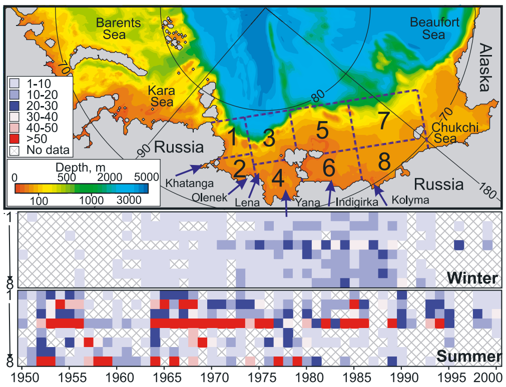

**Figure 2.** Map of the eastern Arctic Ocean. Dashed lines show sub-regions of the Laptev (1–4) and East Siberian (5–8) Seas. The number of stations completed between 1950 and 2000 within sub-regions 1–8 is shown by colors in the lower panels for winter (top) and summer (bottom).

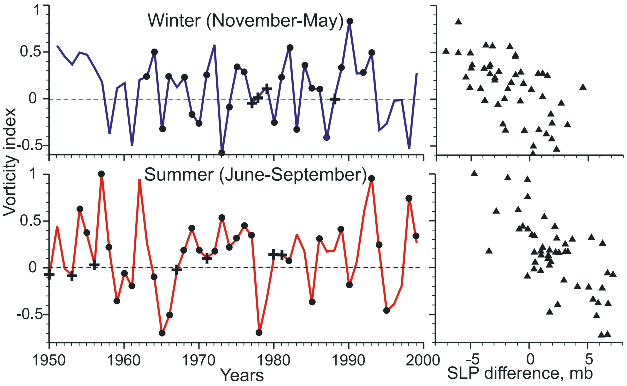

**Figure 3.** Seasonally averaged winter (top left) and summer (bottom left) vorticity index describing atmospheric vorticity northward from the Laptev and East Siberian shelves. Positive numbers correspond to cyclonic and negative to anticyclonic vorticity. Dots indicate years, where salinity data were used for calculations of salinity means. Crosses mark those years, for which no data were derived due to insufficient spatial coverage or identity vorticity numbers. Triangles on the right demonstrate the relationship between vorticity index and SLP difference.

[8] In order to investigate the response of the surface hydrography to atmospheric impacts, salinity data averaged over the upper 5 m mixed water layer were examined separately for years with positive and negative vorticity. Annual salinity measurements, linearly interpolated to a regular 50 km grid over an 80 km radius, were averaged through the positive (cyclonic) and negative (anticyclonic) vorticity years (sign of vorticity index shown in Figure 3). Salinity data were only taken into consideration for cases in which sequential annual observations cover at least four sub-regions (see Figure 3 for additional details).

## 4. Results

[9] The difference in surface salinity between positive (anticyclonic) and negative (cyclonic) vorticity years is shown in Figure 5. We suggest that the zero contour traces the areas where surface salinity is invariant to atmospheric circulation variability. The negative difference corresponds to saltier water in an anticyclonic and fresher in a cyclonic circulation regime. During summer this area is typically found located over most of the East Siberian Sea and in the coastal areas of the central and western Laptev Sea (Figure 5, bottom). In winter it covers the entire East Siberian Sea extending further westward up to the eastern coastal part of the Laptev Sea. In summer the negative difference maximum of 8–10 is found near the Kolyma River mouth in the central-southern East Siberian Sea.

[10] Positive salinity anomalies are mainly located in the central and northern Laptev Sea during both summer and winter, tracing the fresher water in an anticyclonic and saltier water in a cyclonic regime (Figure 5). In contrast to summer, winter positive anomalies extend far south,

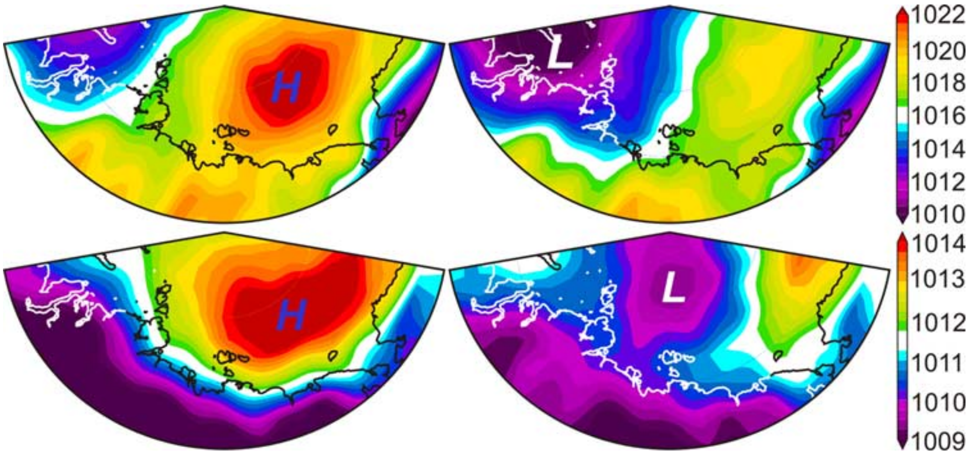

**Figure 4.** Seasonal long-term mean SLP (mb) for negative (left) and positive (right) vorticity years, depicted in Figure 3 by dots, in winter (November–May, top) and summer (June–September, bottom).

covering most of the Laptev Sea. The maximum positive difference of 5–6 is observed in the central Laptev Sea during summer. The response of winter hydrography to the variability of atmospheric circulation is much less pronounced. The winter long-term mean surface salinity difference between cyclonic and anti-cyclonic years does not exceed 2. However, winter exhibits mostly the same patterns as summer, similarly responding to atmospheric variability.

## 5. Discussion

[11] *Shpaikher et al.* [1972] first postulated the wind-driven redistribution of Siberian river runoff. Based on the example of two years (1956 and 1961) they showed that under the cyclonic regime (1956, positive vorticity), the eastward diversion of Lena River water results in a negative salinity anomaly to the east of the Lena Delta. Anticyclonic (negative) vorticity in 1961 results in negative salinity anomalies northward from the Lena Delta due to freshwater advection toward the north, and a corresponding salinity increase eastward. Drifter observations in the anticyclonic summer of 1995 showed distinct water transport from the East Siberian Sea towards the west [*Münchow et al.*, 1999], and the absence of the Siberian Coastal Current [*Weingartner et al.*, 1999]. The distribution of river discharge inferred from tracer data shows cross-shelf off-shore transport of river water from the Laptev Sea for anticyclonic summers of 1995–1996 while during the cyclonic summer of 1993 an along-shore eastward transport was observed [*Guay et al.*, 2001]. These conclusions are in good agreement with earlier findings by *Shpaikher et al.* [1972], and also supported by modeling results of *Weingartner et al.* [1999], *Proshutinsky and Johnson* [1997], and *Johnson and Polyakov* [2001].

[12] The long-term mean difference in surface salinity between positive (anticyclonic) and negative (cyclonic) vorticity years in Figure 5 agrees very well with previously reported results and represents the hydrographic response to atmospheric circulation variability. Along-shore winds towards the west dominated over the East Siberian Sea under the anticyclonic regime and resulted in an influx of more saline waters from the Chukchi Sea into the East Siberian Sea. The Kolyma and Indigirka river runoff plumes are forced to move offshore and westward to the New Siberian Islands and the Laptev Sea. Off-shore wind components that prevail over the Laptev Sea during the anticyclonic phase shift the Lena River plume northward. Dominant along-shore winds toward the east in the cyclonic regime over the entire Laptev Sea and the western East Siberian Sea introduce Lena River runoff influx into the East Siberian Sea. Note, that at the average shelf depth of about 20–25 m (Figure 2, top) the wind-forced flow is essentially controlled by wind stress and bottom friction, and the Coriolis force becomes insignificant; the surface current aligns almost completely with the wind direction.

[13] More precise evidence of the relationship between hydrography and atmospheric circulation comes from the high correlation between annual salinity anomalies and the vorticity index or SLP differences (Figure 6). Correlation coefficients above 0.5 exceed a 95% confidence level. In summer, high correlation exceeding 0.5 was obtained for

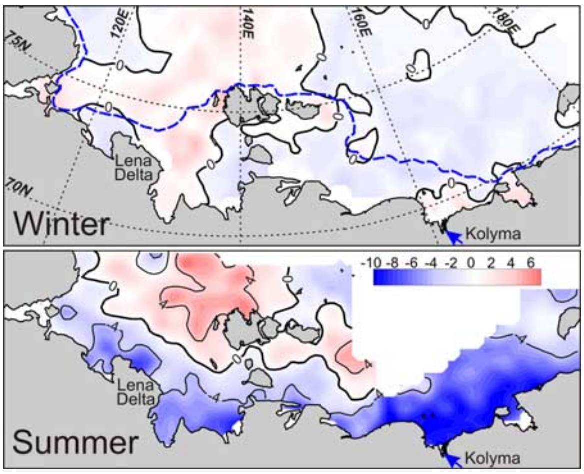

**Figure 5.** Difference between surface salinity averaged for the years with positive and negative vorticity index. Top and bottom panels show winter and summer correspondingly. The blue dashed line in the top panel shows the long-term mean position of the landfast ice edge.

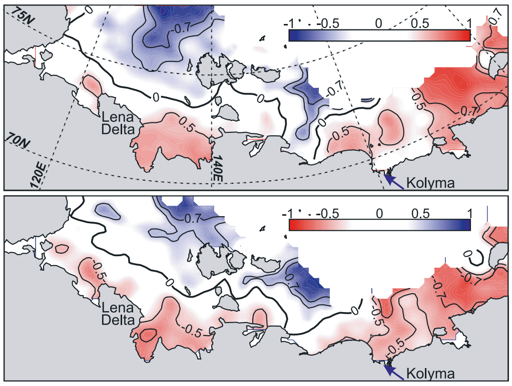

**Figure 6.** Correlation of annual salinity anomalies with SLP zonal difference (top) and vorticity index (bottom) calculated for summer periods of the 1950s–2000s.

most of the East Siberian Sea and the eastern Laptev Sea. Relatively high correlation values (dark red and blue in Figure 6) appear to delineate the areas in which interannual salinity variations are mainly wind-driven. The zero correlation contours in Figure 6 correspond to the zero salinity difference in Figure 5 (bottom) leading us to speculate that its position is mostly governed by shifts in atmospheric circulation. No substantial differences were apparent between the vorticity index and SLP difference correlation fields (Figure 6). During winter, the correlation is considerably less and mostly below the confidence level (not shown), although the patterns are similar. Only small areas in the eastern East Siberian Sea and northern Laptev Sea have shown correlation slightly exceeding 0.5. Apparently, the landfast ice cover (Figure 5, top) eliminates wind impact on surface hydrography. Weak differences between cyclonic and anticyclonic predominant wind patterns during winter (Figure 4, top) may also result in a weak relationship between atmospheric circulation and surface hydrography.

[14] In fact, the results obtained from the correlation analysis (Figure 6) parallel our previous findings that salinity anomalies are linked to shifts in atmospheric vorticity. Summer variability in atmospheric vorticity explains about 50–80% of the surface salinity variability, particularly within the areas with high $\sigma$ values in the northern Laptev Sea and southeastern part of the East Siberian Sea (Figure 1, bottom). However, the region with high $\sigma$ in the central Laptev Sea in Figure 1 may not be driven by atmospheric forcing because it coincides with both zero salinity difference contours in Figure 5 (bottom), and zero correlation contours (Figure 6).

[15] Local wind patterns over the eastern Siberian shelf are governed by shifts of the large-scale atmospheric circulation over the Arctic Ocean. *Polyakov and Johnson* [2000], *Johnson and Polyakov* [2001], and *Steele and Ermold* [2004] reported a relation between decadal surface salinity anomalies on the Siberian shelf with the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) indices, which describe the large-scale atmospheric circulation patterns. Correlation between annual seasonal mean salinity anomalies with annual and seasonal mean AO index is consistent with our results, as shown in Figure 6. However, we did not obtain statistically significant correlation coefficients exceeding 0.3. The NAO index does not demonstrate any similar, regular patterns.

[16] Interannual river discharge variability may be considered as another potential contributor to salinity interannual variations. However, *Steele and Ermold* [2004] did not find freshening of the Kara, Laptev and East Siberian Seas in response to substantial increases of Siberian river discharge during the last decades. *Berezovskaya et al.* [2002] observed surface salinity response to interannual variations of Lena River discharge only under the cyclonic atmospheric circulation phase, when lateral exchange is suppressed by on-shore wind components. We have found no substantial correlation between seasonally averaged river discharge and surface salinity for all Siberian rivers, shown in Figure 2 (top).

[17] Apparently, an as of yet undetermined interplay between atmospheric circulation, river runoff, and ice-related processes (which were not part of our analysis) may explain those components of the salinity variance that are not well described by local wind patterns. Particularly wind-driven coastal Ekman circulation may induce vertical mixing that leads to saltier water influx from below [*Sanders and Garvine*, 2001]. Neglected vertical density stratification may also affect the surface wind-driven dynamics. These considerations might degrade our correlation results accordingly. The differential response of a buoyant river plume to upwelling and downwelling provides an additional complication in our analysis.

## 6. Concluding Remark

[18] The observed high variability of summer surface salinity over the Laptev and East Siberian shelves is mainly attributed to the difference in local wind patterns for positive and negative phases of atmospheric vorticity over the adjacent Arctic Ocean. These results are in good agreement with basic conclusions by *Shpaikher et al.* [1972]. Most likely, we did not obtain a similarly clear signal for winter due to the comparatively high stability of the anticyclonic mode of winter atmospheric circulation. Less known feedbacks may be responsible for salinity variations not explained by wind-driven circulation anomalies.

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## References

Berezovskaya, S. L., I. A. Dmitrenko, V. A. Gribanov, S. A. Kirillov, and H. Kassens (2002), Distribution of river waters over the Laptev Sea shelf under different atmospheric circulation conditions, *Dokl. Earth Sci.*, *386*(7), 804–808.

Guay, C. K., K. K. Falkner, R. D. Muench, M. Mensch, M. Frank, and R. Bayer (2001), Wind-driven transport pathways for Eurasian Arctic river discharge, *J. Geophys. Res.*, *106*, 11,469–11,480.

Gudkovich, Z. M. (1961), Relation of the ice drift in the Arctic Basin to ice conditions in Soviet Arctic seas (in Russian), *Tr. Okeanogr. Kom. Akad. Nauk SSSR*, *11*, 14–21.

Johnson, M. A., and I. Polyakov (2001), The Laptev Sea as a source for recent Arctic Ocean salinity change, *Geophys. Res. Lett.*, *28*(10), 2017–2020.

Münchow, A., T. J. Weingartner, and L. W. Cooper (1999), The summer hydrography and surface circulation of the east Siberian shelf sea, *J. Phys. Oceanogr.*, *29*, 2167–2182.

Polyakov, I., and M. A. Johnson (2000), Arctic decadal and interdecadal variability, *Geophys. Res. Lett.*, *27*(24), 4097–4100.

Polyakov, I., D. Walsh, I. Dmitrenko, R. Colony, and L. Timokhov (2003), Arctic Ocean variability derived from historical observations, *Geophys. Res. Lett.*, *30*(6), 1298, doi:10.1029/2002GL016441.

Proshutinsky, A. Y., and M. A. Johnson (1997), Two circulation regimes of the wind-driven Arctic Ocean, *J. Geophys. Res.*, *102*, 12,493–12,514.

Sanders, T. M., and R. W. Garvine (2001), Fresh water delivery to the continental shelf and subsequent mixing: An observational study, *J. Geophys. Res.*, *106*, 27,087–27,101.

Shpaikher, O., Z. P. Fedorova, and Z. S. Yankina (1972), Interannual variability of hydrological regime of the Siberian shelf seas in response to atmospheric processes (in Russian), *Proc. AARI*, *306*, 5–17.

Steele, M., and W. Ermold (2004), Salinity trends on the Siberian shelves, *Geophys. Res. Lett.*, *31*, L24308, doi:10.1029/2004GL021302.

Walsh, J. E., W. L. Chapman, and T. L. Shy (1996), Recent decrease of sea level pressure in the central Arctic, *J. Clim.*, *9*, 480–486.

Weingartner, T. J., S. Danielson, Y. Sasaki, V. Pavlov, and M. Kulakov (1999), The Siberian coastal current: A wind- and buoyancy-forced Arctic coastal current, *J. Geophys. Res.*, *104*, 29,697–29,714.

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