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The Laptev Sea as a source for recent Arctic Ocean salinity changes

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Abstract.
This study was motivated by observations of significant salinification of the upper Eurasian Basin that began around 1989. Observational data and modeling results provide evidence that increased arctic atmospheric cyclonicity in the 1990s resulted in a dramatic increase of the salinity in the Eurasian Basin. Two mechanisms account for the Laptev Sea salinization: eastward diversion of Russian rivers and increased brine formation due to enhanced ice production in numerous leads in the Laptev Sea ice cover. Both these mechanisms are linked to changes in wind patterns and were essential to the formation of salinity anomalies. The resulting Laptev Sea salinity anomaly was advected to the central Eurasian Basin. The strong salinization over the Eurasian Basin altered the formation of cold halocline waters, weakened vertical stratification, and released heat upward from below the cold halocline layer. Our analysis suggests that local processes in the Laptev Sea may have a basin-wide impact on the thermohaline structure of the Arctic Ocean.

1. Introduction

Recent observations show major changes in the Arctic environment. Since 1988 there has been a decrease in sea level pressure (SLP) and an enhancement of atmospheric cyclonic vorticity over the Arctic Ocean [*Walsh, et al.,* 1996]. The anomalous, cyclonic wind pattern over the Arctic Ocean and Greenland-Iceland-Norwegian Sea in the 1990s dominates previous cyclonic patterns both in magnitude and spatial extent [*Johnson, et al.,* 1999]. *Rigor et al.* [2000] documented an increase in Arctic surface air temperatures (SAT) during the 1979–1990 period. *Rothrock et al.* [1999] found substantial reduction in ice thickness in the central Arctic in the 1990s relative to the 1958–1976 climatology. *Polyakov and Johnson* [2000] showed that the observed recent reduction of arctic ice thickness may be related to the positive, cyclonic, phases of two modes of natural arctic variability: decadal-scale variability and an interdecadal low-frequency oscillation (LFO) with 50–80 year period.

Compared to historical observations, new data indicate that the volume of Atlantic-origin water has increased with a corresponding displacement towards the Canadian Basin of the Pacific–Atlantic water boundary [*Carmack et al.,* 1995, 1997; *Morison,* 1996; *Mclaughlin et al.,* 1996]. *Steele and Boyd* [1998] found a retreat of fresh surface waters and loss of the cold halocline layer from the Eurasian Basin and linked this water mass change to a shift in atmospheric winds. *Steele and Boyd* [1998] and *Dickson* [1999] argued that salinization of the upper Eurasian Basin in the late 1980s and early 1990s stemmed from the eastward diversion of Russian rivers in response to the anomalous atmospheric circulation. *Zhang et al.* [1998] explained the observed salinization as a shoaling of warm, salty Atlantic Water due to increased Atlantic inflow, particularly via the Barents Sea.

This study addresses the major driving mechanisms responsible for this upper Arctic Ocean salinification by investigating observational data and results from a coupled ice-ocean model.

2. Model Description

The coupled model includes ice and ocean dynamics and thermodynamics [*Polyakov, et al.,* 1999]. The ocean is described by a 3-D time-dependent, baroclinic, z-coordinate free-surface model with 29 levels which emphasize the upper layer. Ice dynamics are governed by an elastic–plastic constitutive law and ice thermodynamics apply individually to each of the six ice-thickness categories. Thermodynamical coupling between the ice and ocean depends on oceanic heat flux to the ice which in turn depends on the upper ocean's vertical shear and buoyancy. The upper ocean temperature and salinity are defined as weighted averages of the water column temperature or salinity under ice and in leads for each category. The model domain has a horizontal resolution of 55.56 km (Figure 1). Two regions are enclosed for analysis of the modeling results. Region 1 is the East Siberian Sea and region 2 is the Laptev Sea. Both gain freshwater from Siberian rivers.

The model is initialized with multi-year mean winter ocean temperature and salinity and ice thickness. The transports at oceanic open boundaries are specified as 7 Sv *out* at the Denmark Strait, 8 Sv *in* at the Norwegian Sea, 0.8 Sv *in* at the Bering Strait, and about 0.1 Sv *in* from rivers. The straits of the Cana-

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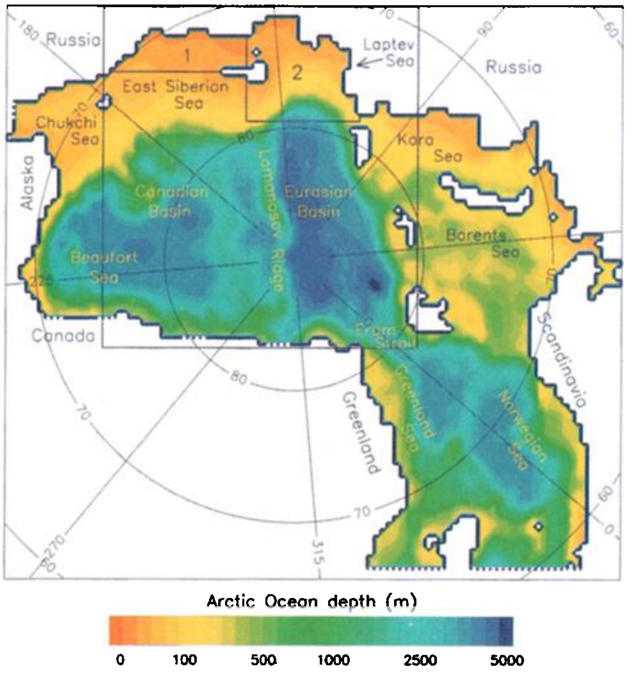

Figure 1. Arctic Ocean model domain. Boxes 1 and 2 denote the East Siberian Sea and Laptev Sea regions. The large square box over the central Arctic Ocean marks the region shown in Figures 4 and 5. Dotted segments of the boundary line show open boundaries.

dian Archipelago are open for free water exchange. The monthly mean climatic river discharges are specified. The daily wind stresses are computed from the NCAR SLP. NCEP/NCAR reanalysis daily SAT were provided by the NOAA-CIRES Climate Diagnostic Center, Boulder, Colorado. The model was integrated from 1946 through 1997, beginning with a 5-year model spin-up with prescribed winds and SAT repeated for 1946, and water temperature and salinity strongly restored to their initial values. No restoring was used during the 1946–1997 model run.

3. SLP and Winds

SLP and geostrophic winds averaged over 1979–1988 and 1989–1997 are shown in Figure 2. Six out of ten years from 1979–1988 were years of prevailing anticyclonic wind vorticity in the eastern Arctic, and the 1989–1997 period was completely within the positive LFO phase having dominant cyclonic wind vorticity (see Figure 3 from *Polyakov and Johnson* [2000]). During the negative, anticyclonic, LFO phase, the center of high SLP in the western Arctic is well developed and the Icelandic Low is depressed. During the positive, cyclonic, LFO phase, the SLP high in the western Arctic is weaker and the Icelandic Low is stronger, extending farther into the Barents and Kara Seas. The same tendencies are found in Figure 2. The prevailing winds over the Laptev Sea in 1979–1988 were towards the Eurasian Basin, while during 1989–1997 the winds had a component towards the East Siberian Sea (Figure 2). These SLP and wind patterns drove substantial changes in the Arctic Ocean hydrography in the 1990s.

4. Laptev Sea Riverine Water Pathways

To examine the role of fresh water in the Laptev Sea region and its contribution to the formation of oceanic salinity, we computed the fresh water flux in the upper 50 m ocean layer following *Häkkinen* [1993]. The monthly means used in the computation of the fluxes represent averages for the period 1946-1996 for each month. Prior to 1989 there was little freshwater advecting from the Laptev Sea toward the East Siberian Sea, and after 1989, winds drove transport of fresh water from the Laptev Sea towards the East Siberian Sea (Figure 3A). Note that the river discharge in the Laptev Sea (Lena and Kotuy rivers only) is about 0.0198 Sv ($Sv=10^6\ m^3s^{-1}$). The model shows that about the same amount of freshwater (i.e. almost all riverine water) was diverted from the Laptev Sea towards the East Siberian Sea in the 1990s. The resulting freshening of the East Siberian Sea, about 1.6 psu in the 1990s, is evident in Figure 4. This result corroborates the *Steele and Boyd* [1998] and *Dickson* [1999] scenario where 1990s salinification of the eastern Arctic Ocean was due to eastward diversion of the Siberian river discharge.

5. Salinity in the Laptev Sea and Eurasian Basin

In addition to freshwater input from rivers, we found one more mechanism responsible for the recently observed Eurasian Basin salinification. Figure 3B shows saltier water advecting poleward after 1990. The saline anomaly was due to the eastward diversion of river waters as mentioned above, as well as an increase in salinity from brine rejected from growing ice. The Laptev

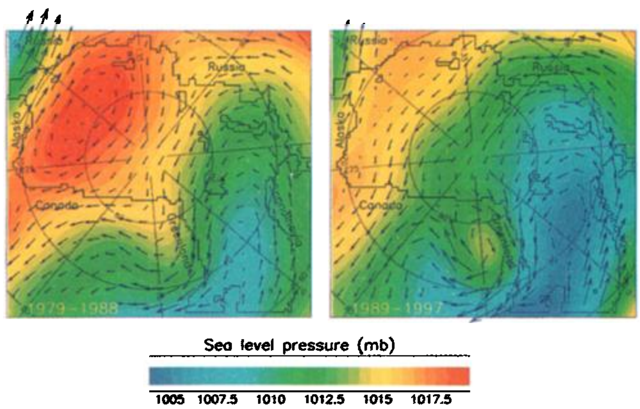

Figure 2. NCEP/NCAR SLP (mb) averaged over 1979–1988 and 1989–1997. Changes from the first to second period include weakening of the SLP high in the western Arctic toward Russia, and extension of the Icelandic Low farther into the Barents and Kara Seas. Winds over the Laptev Sea in 1979–1988 were towards the pole and Eurasian Basin. In 1989–1997, the winds were more eastward, with a component towards the East Siberian Sea.

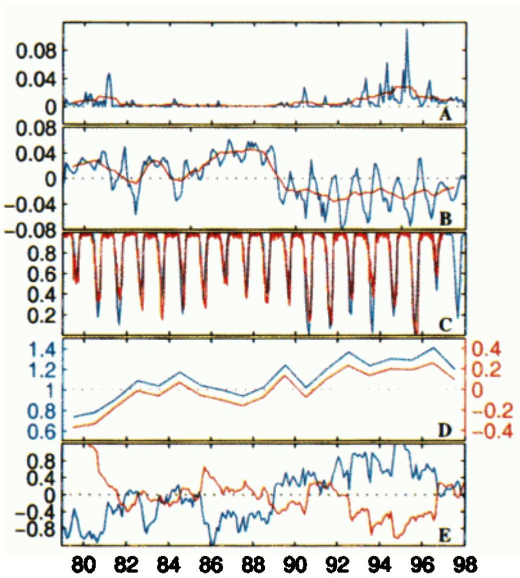

Figure 3. Time series of (A) monthly mean (blue) and annually averaged (red) eastward (positive) freshwater flux from the Laptev Sea toward the East Siberian Sea (Sv); (B) monthly mean (blue) and annually averaged (red) freshwater flux between the Laptev Sea and the central Arctic Ocean (Sv); (C) observed (red) and modeled (blue) ice concentration in the Laptev Sea; (D) Laptev Sea annual ice growth (m, blue) and salinity anomaly in the upper mixed layer due to ice growth only (psu, red); (E) monthly mean salinity anomaly (psu) in the Laptev Sea (blue) and in the East Siberian Sea (red).

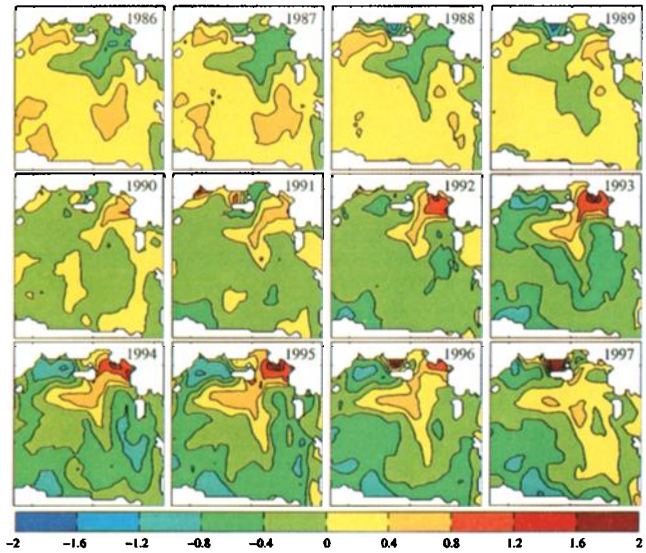

Figure 5. Annual salinity anomalies (psu) for 1986–1997 in the upper 50 m of the Arctic Ocean region. The 1979–1997 mean has been removed.

Sea ice responded to the wind anomalies in the 1990s by increasing the area of open water (Figure 3C, observed ice concentrations over the Laptev Sea are courtesy of Joerg Bareiss, Department of Climatology, University of Trier). The model simulates well the interannual variations in ice concentration, tracking the higher summer ice concentration in the 1980s and the markedly reduced ice concentration in the 1990s. A noticeable difference exists between modeled and observed ice concentration in the anomalous summer of 1993 when multi-year ice recirculated back into the western Laptev Sea from the central Arctic Ocean (personal communication, Hajo Eicken, University of Alaska Geophysical Institute).

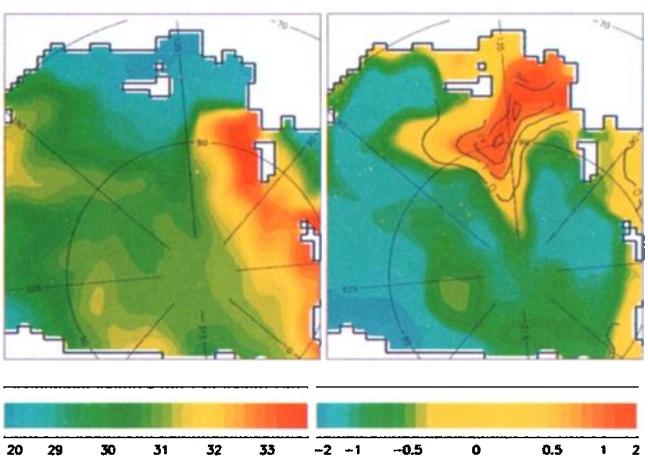

Figure 4. (Left) Surface (0-50m) salinity (psu) averaged over 1979–1988; (Right) surface salinity anomaly (psu) for 1989–1997 showing salinization in the Laptev Sea. Contour lines are the increase in heat flux (Wm^{-2}) associated with the reduced upper layer vertical stratification for 1989–1997.

The increased amount of open water in the 1990s resulted in accumulation of solar radiation and warming of the upper Laptev Sea. This process led to additional ice melt (not shown). The difference between the annual mean ice melt rate in 1979–1988 and 1989–1997 was about 12 cm. However, anomalously strong ice growth in numerous ice-free areas of the Laptev Sea caused additional brine rejection from ice growth in winter (Figure 3D). According to our modeling results, this salt flux provided a substantial salinification of the upper Laptev Sea which was much stronger than summer freshening due to increased ice melt. For example, there was a sharp increase of the salinity, almost 1 psu, in 1989 in the Laptev Sea region (Figure 3E). In the core of the salinity anomaly, higher values, more than 1.6 psu, were reached in the 1990s (Figure 5). As shown in Figure 3B, both summer and winter processes led to the stronger seasonal signal in the 1990s than in the 1980s in this region.

We estimate that the Laptev Sea annual river runoff would cover the sea surface (area shown in Figure 1) with an approximately 1m thick layer. The freshwater lost from the Laptev Sea due to the simulated brine rejection during ice growth would be about half this value. Thus, both eastward diversion of river runoff and enhanced ice production and brine rejection were both essential for Laptev Sea salinification in the 1990s.

The mean surface salinity from 1979 through 1988 is shown in Figure 4A. Surface salinities in the Nansen Basin are up to 34 psu, with fresher surface arctic waters in the Canadian Basin at 29-31 psu, and substantially fresher Siberian shelf waters. The salinity anomaly for 1989–1997 reveals an increase over the Laptev Sea region of more than 1 psu (Figure 4B). The temporal evolution of this salinity anomaly is shown in Figure 5. Consistent with the above discussion is the fresh upper layer in the Laptev Sea region in 1979–1988 (1986–1988 are shown in Figure 5) and the marked change in 1989 when the upper East Siberian Sea freshened and the upper Laptev Sea became more saline. By 1995, the positive salinity anomaly extends along the shelf break to the east and along the Lomonosov Ridge, deep into the Eurasian Basin, consistent with data from SCICEX'95 [*Steele and Boyd,* 1998]. By 1996, the signal begins to decay.

The replacement of fresh surface water with more saline water reduced vertical stratification and increased heat flux, releasing heat from below the cold halocline layer to the upper layer of the Eurasian Basin. The corresponding heat flux increase for the 1989-1997 period is as much as 3 W m^{-2} in this region (Figure 4B), comparable to the change in heat flux over the Lomonosov Ridge and Amundsen Basin computed from SCICEX'95 data and a 1-D mixing model [*Steele and Boyd,* 1998].

6. Concluding Remarks

Wind patterns changed over the Laptev Sea in 1989, diverting Laptev Sea river water eastward, and opening sea ice cover to produce record minimums in ice extent during the 1990s. Both eastward diversion of Siberian rivers and rejected brine from ice growth were essential to forming the positive salinity anomalies that advected poleward from the Laptev Sea into the Eurasian Basin. The resulting strong salinization over the Eurasian Basin altered the formation of cold halocline waters. Freshwater redistribution and brine rejection weakened upward stratification, increasing the vertical heat flux. Thus, the late 1980s – 1990s processes which originated in the Laptev Sea had a dramatic impact on the thermohaline structure of the Eurasian Basin of the Arctic Ocean.

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