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Salinity trends on the Siberian shelves

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[1] We present an analysis of observed long-term (~100 year) salinity trends on the freshwater-dominated Siberian continental shelves. A multiple regression was performed in the White Sea (WS), the Kara Sea (KS), the Laptev Sea (LS), and the East Siberian Sea (ESS). Since 1930, the WS has gained freshwater while the ESS has lost it, consistent with river discharge trends over this period. Over the past 20 years, increases in both river discharge and direct precipitation can explain observed salinity decreases in the WS, but not in the KS. Salinity trends in the LS and ESS indicate that ocean circulation plays a dominate role in these areas, where in recent years freshwater has been diverted eastward along the coast, rather than northward toward the deep ocean. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4215 Oceanography: General: Climate and interannual variability (3309); 1655 Global Change: Water cycles (1836). **Citation:** Steele, M., and W. Ermold (2004), Salinity trends on the Siberian shelves, *Geophys. Res. Lett.*, *31*, L24308, doi:10.1029/2004GL021302.

1. Introduction

[2] Numerical model simulations have predicted acceleration of the hydrologic cycle with a warming climate [e.g., *Wetherald and Manabe*, 2002]. Recent studies confirm this [*Curry et al.*, 2003], showing a surface freshening of the Atlantic Ocean's subpolar gyre. But does this freshening extend into the Arctic Ocean itself? J. H. Swift et al. (Long-term variability of Arctic Ocean waters: Evidence from a reanalysis of the EWG data set, submitted to *Journal of Geophysical Research*, 2004) have analyzed salinity variability in the central Arctic Ocean since 1950, and *Häkkinen and Proshutinsky* [2004] have performed a similar study using a numerical model. Perhaps surprisingly, both studies find a general decrease in freshwater content over the past several decades. In this study, we focus on the freshwater-dominated Siberian continental shelf seas. We examine summertime salinity data, the season of maximum discharge and sea ice melt. We consider changes both at the surface and at depth, and over various subregions and time periods.

2. Data and Methods

[3] We have combined July, August, and September (JAS) salinity data from the National Oceanographic Data Center's World Ocean Database (WOD [*Conkright et al.*, 2002]) into annual summer fields. These months contain 7093 stations, or 63% of the WOD'01 data in our study region (Figure 1). The data are from 1878 to 2000, although less than 5% of all profiles were collected prior to 1920. Figure 1 shows the four relatively fresh shelf seas that we focus on in this study: the East Siberian Sea (ESS), the Laptev Sea (LS), the Kara Sea (KS), and the White Sea (WS).

[4] We perform a multiple linear regression in each region, using regressors time (i.e., year), space (x, y, z) and the summer mean salinity field from the Polar science center Hydrographic Climatology (PHC [*Steele et al.*, 2001]). The space and PHC regressors compensate for potential spatial sampling bias over the temporal record. The PHC regressor allows the spatial fields (not shown) some degree of non-linearity, which is especially important where the salinity distribution is strongly curved, e.g., around river mouths. We also tried adding a monthly regressor to account for mean seasonal variations, but found

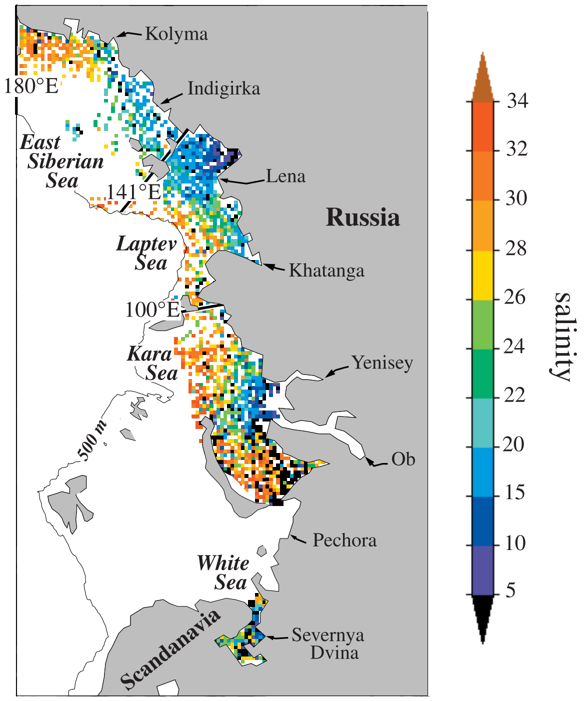

Figure 1. Surface salinity (0–15 m) from WOD'01 for the four Siberian shelf seas studied here, averaged into 25 km bins. The data are from July, August, and September (JAS) over the period 1878–2000. The outer boundaries are defined as the 500 m isobath for the East Siberian Sea and Laptev Sea, and the 30 salinity contour from the PHC data base [*Steele et al.*, 2001] for the Kara Sea and White Sea. Freshest values are generally near the major river mouths. However, exceptionally high variance is evident in many areas.

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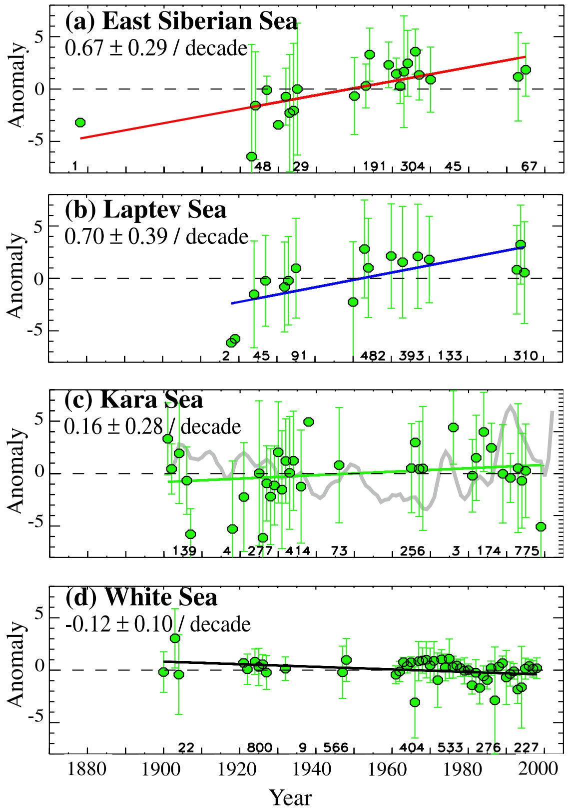

Figure 2. Surface salinity (0–15 m) JAS anomalies, relative to the mean spatial regression for each region. Regional means (green dots) were used to compute the trends (shown in each panel ±95% confidence), after first eliminating years with means greater than 2 standard errors from a first-guess trend line. This eliminates at most 2 years from any of the 4 regions. The vertical lines denote spatial variability within each region (±1 standard deviation). The number of stations for each decade is noted along the bottom axis of each panel. The gray line in panel (c) shows the smoothed (5 year running mean followed by 3 year running mean) January–March standardized Arctic Oscillation index, scaled by the daily standard deviation.

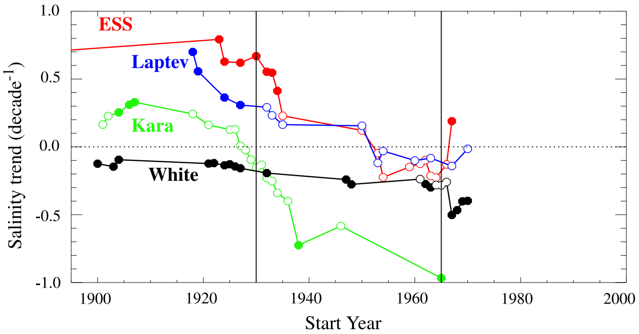

Figure 3. Surface salinity (0–15 m) JAS anomaly trends as a function of start year, where all trends end with the most recent year of observed data. Trends with significance greater than 90% are denoted with filled circles. ESS data start in 1878 (not shown; see Figure 2). Heavy vertical lines denote the years 1930 and 1965, which are referred to in Figures 4–6. Trends with start years after 1970 (not shown) are often off the scale of this plot.

similar results and no reduction in variance (owing to poor data coverage within each month).

3. Results

[5] Figure 2 shows time series of regional-mean sea surface salinity (SSS) anomalies. The linear trends are strongly positive in the ESS and LS, not significant in the KS, and weakly negative in the WS. Rapid changes occur over decadal time scales in several instances, e.g., increasing salinity during 1920–1935 in the KS and perhaps the LS and ESS, decreasing salinity during 1975-present in the KS, and a decadal-scale oscillation during 1960-present in the WS. This variability will obviously impact the slope of our calculated linear trends. Also, older data may be of questionable quality. To address these issues, the dependence of SSS trends versus the regression start date is shown in Figure 3. We see that the sign of the trends plotted in Figure 2 is fairly robust in each sea until about 1930, when ESS, LS, and KS trends begin to drop to negative or nearly zero values. This is not true in the WS, which shows negative trends over all periods that end in the present.

[6] What is happening below the surface? Figure 4 shows that non-zero trends in salinity over 1930–1995 are largely confined to the upper 20–50 m. We see that SSS trends are generally good proxies for trends in total vertically integrated freshwater content, i.e., there are no significant “zero crossings” which might indicate a vertical redistribution of freshwater.

[7] Figure 5a shows the spatial variation of SSS trends over the period 1930–1995. Although not statistically significant, the spatial patterns in all seas suggest weakly increasing or decreasing salinity near and to the east of many river deltas. This suggests a riverine influence, since

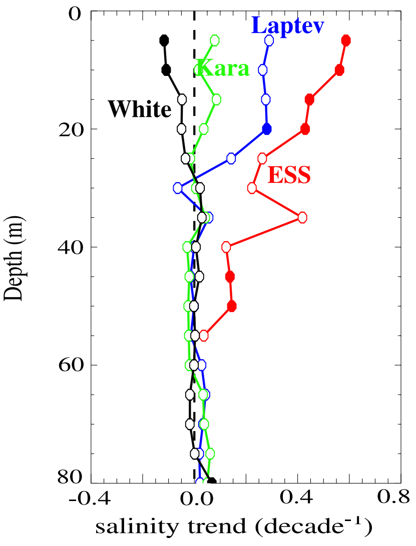

Figure 4. Salinity JAS anomaly trends 1930–1995 as a function of depth. Trends with significance greater than 90% are denoted with filled circles. The uppermost points (at 5 m depth) represent trends over the layer 0–15 m, while deeper values represent trends over a 20 m layer centered on each depth.

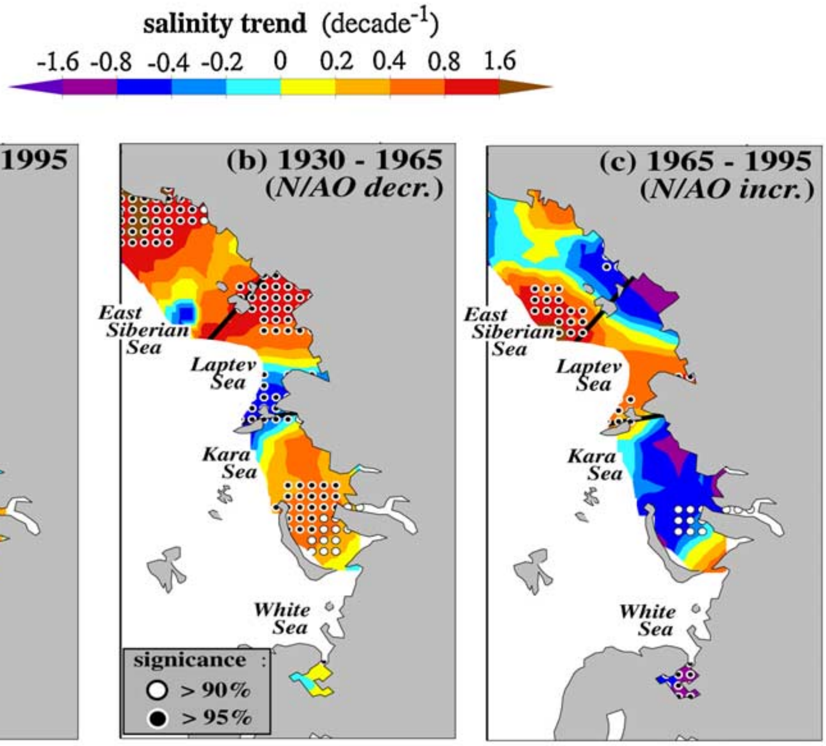

Figure 5. The spatial pattern of surface salinity (0–15 m) JAS anomaly trends for (a) 1930–1995, (b) 1930–1965, and (c) 1965–1995. Average trends over a 300 km radius were calculated at each point on a 200 km grid. The black (white) dots represent areas with 95% (90%) significant trends.

sea ice melt or precipitation presumably would be spread more uniformly along the coast or shelf.

4. Discussion

[8] Recently, two physical mechanisms have been identified that might influence decadal variability of the Siberian shelf seas' salinity. First, *Peterson et al.* [2002] discuss how high North Atlantic Oscillation (NAO) index deflects storm tracks toward northern Eurasia, increasing precipitation and thus river discharge. This should lead to decreasing salinities especially in western Siberian shelf seas, i.e., the WS and KS. Second, *Steele et al.* [2004] and *Johnson and Polyakov* [2001] discuss how high NAO or Arctic Oscillation (AO) winds force eastward ocean currents in the ESS and LS seas. In contrast, low NAO or AO winds tend to push freshwater northward across the LS shelf, and Pacific waters westward along the ESS shelf.

[9] Figure 5b shows a loss of freshwater in the KS and WS over 1930–1965. This might be a result of decreasing NAO and AO indices (collectively, N/AO; Figure 2c), which divert the jet stream to the south and thus decrease river discharge as well as net precipitation less evaporation (P-E) over the ocean [*Groves and Francis*, 2002] (hereinafter GF02). Figure 5c indicates the opposite trend over the following period 1965–1995. Spatial variation in KS and WS trends is small in Figures 5b and 5c, which is consistent with the 3-year freshwater residence time calculated by *Pavlov and Pfirman* [1995] for the KS. However, KS data indicate that correlation of SSS and N/AO trends is weaker prior to 1930 (Figure 2c).

[10] Can we quantify the roles of increasing river discharge and P-E in observed WS and KS freshening trends? Table 1 shows the observed trends in SSS over two periods: 1930-present, and 1980-present. During the former period, *Peterson et al.* [2002, Figure S1] show that annual river discharge increased by $\sim$20 km^3 in the Severnya Dvina and by $\sim$70 km^3 in the combined Pechora, Ob, and Yenisey. These are converted in Table 1 to SSS decreases by assuming the freshwater is distributed over a 25 m depth mixed layer, with an initial salinity of 22 for the WS and 25 for the KS, and a surface area of 90,000 km^2 for the WS and 890,000 km^2 for the KS. Table 1 shows that river discharge supplies only 5–15% of the observed SSS decreases since 1930. (We also calculated changes for the inner 20% of the KS shelf, over which river discharge changes are still not enough to explain SSS decreases.) Next, consider the period 1980–2000, during which satellite P-E data are available (GF02). We use GF02's Table 3 and Figure 10, where an upper bound for the annual increase from the 1980's to the 1990's is $\sim$0.3 cm mo^{-1} over the WS (and nil over the entire KS). The table shows that the observed freshening

Table 1. Negative SSS Trends (decade^{-1}) in the WS and KS, Calculated Using Observed SSS Trends (Figures 2 and 3), River Discharge Trends [*Peterson et al.*, 2002], and Net Precipitation Trends [*Groves and Francis*, 2002][a]

	Observed SSS		Rivers		Net Precip.	
Period	WS	KS	WS	KS	WS	KS
1930-present	0.2	0.2	0.03	0.01	-	-
1980-present	0.4	2.9	0.1	0.1	0.3	0.0

[a] River and precipitation trends are converted to SSS trends by distributing the freshwater over a surface mixed layer (see text).

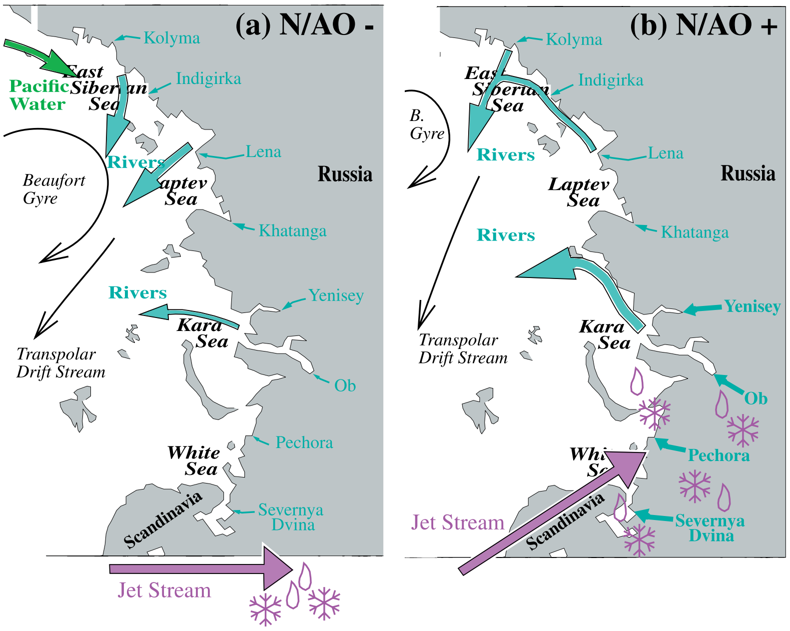

Figure 6. Idealized freshwater schemes in years with (a) a relatively low N/AO index and (b) a relatively higher N/AO index. Low N/AO conditions deflect the jet stream to the south, reducing precipitation to the western Siberian watersheds, which leads to increasing salinity in the WS and KS. Also, stronger anticyclonic winds tend to push Pacific-origin waters into the ESS, and river waters rapidly northward across the continental shelves. High N/AO conditions bring precipitation to the western Siberian watersheds and the WS and KS, freshening these shelves. Also, cyclonic winds tend to force freshwater against the coast and eastward before it enters the deep basins. Further, high N/AO conditions are associated with more sea ice melting in eastern Siberian seas [*Rigor and Wallace*, 2004].

over the past 20 years in the WS is easily explained by a combination of discharge and P-E, while the freshening in the KS is larger than can be explained by these two effects. We suspect that ice melt/growth and circulation changes may also play significant roles in the KS.

[11] Turning to the LS and ESS (Figures 5b and 5c), we see that spatial variations are strong in the LS and ESS, where decreasing N/AO during 1930–1965 (Figure 2c) brings relatively salty Pacific waters into the eastern ESS and the Lena River discharge is pushed more directly northward to the outer shelf. In the following period 1965-present, Pacific waters retreat from the eastern ESS, creating a freshening trend, while Lena River discharge moves eastward along the coast and the LS outer shelf salinifies. During the past few decades, the ESS and LS have recently shown record minimum summer sea ice extent [e.g., *Rigor and Wallace*, 2004]. However, the net freshwater impact on the shelf seas is still unclear.

[12] So are the Siberian seas getting fresher? The long-term trends (>70 years) indicate a freshening of the WS, but a salinification of the eastern Siberian shelves (ESS and LS). Combining the WOD'01 data with recent field observations indicates that as the N/AO index increases, the western Siberian shelf seas (WS and KS) broadly freshen, while the eastern Siberian shelves (ESS and LS) redistribute freshwater laterally. These processes are illustrated schematically in Figure 6. The interplay between these changes on the shelves and the deep basins is yet to be determined.

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