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# Change in the Arctic Influence on Bering Sea Climate during the Twentieth Century

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To be submitted to *International Journal of Climatology*

February 11, 2005

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## Abstract

Surface air temperatures (SAT) from three Alaskan weather stations in a north-south section (Barrow, Nome, and St. Paul) show that on a decadal scale, the correlation relationship among the stations changed during the past century. From 1916–1966 Barrow and Nome were dominated by arctic air masses and St. Paul was dominated by North Pacific maritime air masses. After 1966 the SAT correlation in winter between Barrow and St. Paul increased from 0.2 to 0.7 and between Nome and St. Paul from 0.4 to 0.8, implying greater north-south penetration of both air masses. The correlation change in the winter Barrow/St. Paul pair is significant at a 95% confidence level. The Nome/St. Paul pair in spring also shows some of this characteristic change in correlation. Relatively-stable, high correlations are found among the stations in the fall; correlations are low in the summer. Our study shows a change in the climatological structure of the Bering Sea in the late 20th century, at present of unknown origin, and occurring earlier than the well-known 1976/1977 shift. These climatological results further support the concept that the southeast Bering Sea ecosystem may have been dominated by arctic species for most of the century, with a gradual replacement by sub-arctic species in the last 30 years.

## Introduction

The Bering Sea, with its commercially valuable fish and shellfish, marine mammals, and major seabird habitat, is one of the most important large marine ecosystems in the world. Information on the historical context of the physical environment and its relation to the biota, is critical for understanding the climate/ecosystem connection and therefore of importance to fishery management. The Bering Sea is a semi-enclosed sea that connects the North Pacific and Arctic Oceans (Figure 1). Its climate is influenced both by the cold dry air from the north and by warm moist flows from the south. Bering Strait acts as an oceanic and storm track pathway between the Pacific and Arctic Ocean, and as such is important for south/north heat flux. The surface air temperatures (SAT) at representative stations in the Bering Sea (Nome, and St. Paul) and Barrow, Alaska, have been observed for more than 100 years by the National Oceanic and Atmospheric Administration (NOAA) and its predecessors. We investigate the temporal variations of Bering Sea SAT, beginning when these records became nearly continuous in the 1910s, with emphasis on the relationship among the stations during the last century.

There is evidence that the Bering Sea ecosystem is changing in response to a northward retreat of cold atmospheric and ocean temperatures in recent decades, with a shift in the 1970s and again in the late 1990s (Overland and Stabeno, 2004). How representative is this recent period compared to earlier in the 20th century? With 89 years of observed SAT, we are able to address this issue. The paper is organized as follows: data sources are described in the next section, followed by presentation of seasonal variability at each station. Changes in the correlation structure among the stations are investigated using a statistical test, followed by a summary and discussion.

## Data collection

### *Surface Air Temperature*

The Bering Sea stations are Nome (WMO code 70200) and St. Paul (70308). Nome, located near Bering Strait (Figure 1), represents the conditions of the northern Bering Sea, while St. Paul in the Pribilof Islands is representative of the primarily maritime southeastern Bering Sea. The influence from arctic cold air is represented by Barrow (70026) on the Arctic coast. Monthly mean SAT are from GHCN dataset version-2 (<http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=ghcn.html>). Although the monthly data at St. Paul started as early as 1840, there are large gaps between 1844 and 1916. The records for Nome and Barrow begin in the late 1890s and have good temporal coverage. We analyze the same length of the data records for the three stations from 1916 to 2004.

### *Sea Level Pressure*

Gridded monthly Sea Level Pressure (SLP) analyses are obtained from National Center for Atmospheric Research (NCAR) following the link <http://dss.ucar.edu/datasets/ds010.1>. These SLP fields are for the Northern Hemisphere on a 5-degree latitude/longitude grid starting in January 1899, as updated from Trenberth and Paolino (1980).

## Variations of the Seasonal Surface Air Temperatures

Although the distance between Barrow and St. Paul is more than 2000 km (Figure 1), they share some common features in seasonal variability. From November to December, there is a decrease in temperature of about 5 degrees at Barrow and Nome and 2 degrees at St. Paul. Strong interannual variability is observed in the months from December through March with temperature fluctuations in similar ranges during the four-month period. We therefore defined

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2  
3 the winter season to be the averages of these four months (Dec. to Mar.). June and September are  
4 transition months, characterized by large interannual variability and relatively distinct  
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6 temperature records from their neighbor months; for clarity, we choose not to include them in  
7  
8 seasonal averages. Thus, our spring includes April and May, summer is the average of July and  
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10 August, and fall is the average of October and November.  
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15 Figure 2 shows the time series of seasonally averaged SAT at these three stations with a 5-  
16 year running mean applied to filter interannual variations. In winter (Figure 2a–c) these stations  
17 are distinguished by their north/south geographic location, in the sense that the climatology of  
18 each station is offset by about 10 degrees. Since the late 1970s all three stations switched from a  
19 cold period, with nearly 20 years of negative anomalies, to warm anomalies. The warming at  
20 Barrow lasts longer than at the other two stations, and it became stronger since late 1990s  
21 (Figure 2a); Nome and St. Paul returned to more neutral levels after the early 1990s (Figures 2b  
22 and c). In the early part of the century, from the late 1920s to early 1940s, a decade of warm  
23 anomalies is shown at each station, although the anomalies did not occur in the same years. In  
24 the spring season (Figure 2d–f) two warm periods are shown in the time series: the first is from  
25 1930 to the early 1940s and the second is around 1980 for St. Paul, from about 1980 and on for  
26 Nome, and after 1990 for Barrow. In the late 1930s, a short period of warming is seen at Barrow  
27 and Nome, while the warming at St. Paul happened a few years earlier. The cold anomalies at  
28 Barrow in the 1960s are weaker than in the winter season and last until the early 1980s. During  
29 this cold period, there is large interannual variability (even with a 5-year running mean) at  
30 Barrow and Nome, but less at St. Paul.  
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53 The summer season (Figure 2g–i) shows weak anomalies and covariability among the  
54 stations. St. Paul displays a typical marine climate with a colder summer mean temperature than  
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3 at Nome. In fall (Figure 2j–l), there is covariability between Nome and Barrow: both show  
4 positive anomalies during the 1920s and again from the late 1930s to early 1950s. Warm  
5 anomalies are observed at St. Paul for a decade until the late 1930s. The cold period from the late  
6 1950s to late 1970s is obvious at all stations; however, the timing and magnitude are different  
7 among the stations. Overall, cold anomalies prevail in the region from the late 1950s to late  
8 1970s for all seasons, while during the last two decades warm anomalies are seen in most  
9 seasons in the three records. The changing relationships among the stations are of interest, based  
10 on inspection of the seasonal averaged time series. A discussion of these relationships is further  
11 developed in the next paragraph and in the next section using running correlations.  
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25 The covariability among the stations in winter is easily seen in Figure 3, a scatter plot of  
26 seasonal mean temperatures between pairs of stations. With climatologies indicated by a thin  
27 line in each panel, the four quadrants are composed of the years with warm/warm, cold/warm,  
28 cold/cold, and warm/cold combinations of anomalies. To emphasize the early and late periods,  
29 years before and after 1970 are shown in the upper and lower panels. The color coding of the  
30 values is associated with each decade. For the Barrow/Nome pair, among 89 winters, 69 are  
31 located in quadrants I and III and 19 are located in quadrants II and IV (left panels), which  
32 suggests considerable covariability between these stations. Before 1970 more years are located in  
33 quadrant III, while after 1970 more are in quadrant I and even less are in quadrants II and IV.  
34 This suggests that a cold-cold regime is replaced by a warm-warm regime in recent decades. For  
35 the Barrow/St. Paul pair (middle panels) distribution patterns are different before and after 1970.  
36 Many years are located in quadrants II and III near the origin before 1970; but most years are in  
37 quadrant I afterwards, with a few years in the early 1970s in quadrant III. The portion of years in  
38 quadrant I and III before 1970 is 57%; for the last 35 years this value is 77%, showing a major  
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3 increase in covariability. For the St. Paul/Nome pair, there is also a change in distribution of  
4 points (right panels). Here the distribution of the years moved from quadrants II and III to  
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6 quadrants I and III. There are 55% of the years before 1970 located in quadrants I and III, while  
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8 this number increased to 71% over the last 35 years.  
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12 The covariability between north and south is weaker in spring than in winter. Although  
13 there are about 60 cases when both stations show the same sign of anomalies, more than 20% of  
14 those are actually close to their climatologies (figures are not shown). Again, most of the recent  
15 years are in quadrant I.  
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## 22 **Decadal changes in relationship among north/south stations**

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24 Table I shows the correlation coefficients between the stations over the period of record for  
25 the four seasons. All but two (indicated by \*) are statistically significant at the 95% confidence  
26 level. The low correlation in summer is not surprising as the variability in that season is low.  
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28 The correlations between Barrow and Nome are relatively high for the other three seasons, as is  
29 the correlation between Nome and St. Paul. The correlation between Barrow and St. Paul is  
30 lower than the other two pairs, with highest correlation occurring during the winter.  
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40 Except for the Barrow/Nome pair, the interpretation of these time-independent correlations  
41 is misleading because of suggested time-dependent relationships in the north/south correlations.  
42 Based on inspection of Figure 3, we investigate this time-dependent hypothesis objectively by  
43 computing running correlation coefficients over blocks spanning 25 years; deviations within a  
44 given block were recentered with the sample mean for the block rather than using the sample  
45 mean of the entire data record. The 25 years size was chosen to ensure a degree of statistical  
46 stability in the estimated correlations, while providing some localization in time. In winter  
47 (Figure 4, top panels), the running correlation coefficient is fairly constant for Barrow and  
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Nome, but not, however, between Nome and St. Paul and between Barrow and St. Paul. The maximum difference of the running correlation between Barrow and Nome is 0.3, which is between the two 25-year periods centered in 1975 and 1989. The running correlation between Barrow and St. Paul shifts from about 0.2 to 0.7 between the 1940s and 1980s, with a prominent drop to slightly negative correlations in the early 1950s; between Nome and St. Paul the shift in correlation is from about 0.4 to 0.8.

To determine the extent to which the observed fluctuations in the running correlations might be attributable to statistical variations, we performed the following study. Let  $\{X_t\}$  and  $\{Y_t\}$  represent two first order autoregressive processes that will serve as models for any two particular SAT time series; i.e.,

$$X_t = \mu_X + \phi_X (X_{t-1} - \mu_X) + \varepsilon_t,$$

and

$$Y_t = \mu_Y + \phi_Y (Y_{t-1} - \mu_Y) + \eta_t,$$

where  $(\varepsilon_t, \eta_t)$  is a bivariate Gaussian white noise process such that the correlation between  $\varepsilon_t$  and  $\eta_t$  is  $\rho$  for any given  $t$ ; this implies that the cross correlation between the  $\{X_t\}$  and  $\{Y_t\}$  is  $\rho$  at zero lag and is zero at all other lags. After fitting the above models to a pair of time series, with  $\rho$  estimated via the observed instantaneous cross correlation, we generated simulations of  $\{X_t\}$  and  $\{Y_t\}$  of the same length as the observed SAT time series. We then consider a test statistic given by the difference between the maximum and minimum values of 25-year running correlations. This statistic should be “small” when the null hypothesis of no change in correlation is true and “large” under the alternative hypothesis that the cross correlation between the series has been subject to a change. By generating a large number (10,000) of simulated pairs of  $\{X_t\}$  and  $\{Y_t\}$  and computing the test statistic for each pair, we determined the distribution of the test statistic

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3 under the null hypothesis of no change. We can then use this distribution to assess the value of  
4 the statistic from the observed pair of SAT time series. If the observed value is in the upper tail  
5 of the distribution, we have evidence that the null hypothesis is untenable and that we should  
6 entertain the alternate hypothesis that the correlation between the two series has changed.  
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12 The lower panels of Figure 4 show the results of this study for the three time series. In each  
13 figure we show the distribution of the test statistic (as a histogram) under the null hypothesis,  
14 with the distribution being determined by the simulation procedure described above. The vertical  
15 line in each figure shows the value of the actual test statistic from the observed series. The  
16 observed level of significance,  $\alpha$ , for each test is given by the area under the histogram to the  
17 right of the vertical line. We can interpret  $\alpha$  as being the probability of obtaining a result at least  
18 as extreme as the observed value when in fact the null hypothesis is true. When  $\alpha$  is small  
19 (corresponding to large values of the test statistic), we can regard the null hypothesis as  
20 untenable. The values of  $\alpha$  for Barrow/Nome, Barrow/St. Paul, and Nome/St. Paul are 0.58, 0.03,  
21 and 0.23, respectively. There is no serious reason to doubt the null hypothesis for the winter  
22 Barrow/Nome pairing, and there is strong evidence to reject the null hypothesis for the  
23 Barrow/St. Paul pairing. Because the level of significance is 0.03, under the null hypothesis of no  
24 change, we would only observe a value at least as extreme as what was actually observed 3% of  
25 the time. The value of  $\alpha$  between Nome and St. Paul (0.23) does not allow us to reject the null  
26 hypothesis at a reasonable level of significance, but still suggests only a 1 in 4 chance that there  
27 was no shift in correlation.  
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51 The same technique was applied to the other season series. Figure 5 shows the running  
52 correlations for the three pairs of stations with 25-year window length. In spring, visually we see  
53 that the correlation between Barrow and Nome is high during 1940 to the 1960s, and slightly  
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3 lower at both ends. The correlation has increased since the late 1960s between Nome and St.  
4 Paul, similar to the winter analysis. However, none of these changes are accepted as significant  
5 based on our rather rigorous test; the values of  $\alpha$  are above 0.6 for all three pairs. The running  
6 correlation for the summer season is not only small, but is also negative for some periods. We do  
7 detect significant changes in the relationship between Barrow and Nome from the 1930s to late  
8 1990s (top middle panel of Figure 5), even though the average value of these correlations is  
9 small. The relatively high correlation between Barrow and Nome and between Nome and St.  
10 Paul for the fall season may indicate alternating Pacific and Arctic air masses at Nome in  
11 different years. No significant changes in correlations are found for the fall.  
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## 26 **Atmospheric circulation patterns associated with decadal change** 27 **over the Bering Sea** 28 29

30 Regional atmospheric circulation changes are observed before and after the winter shift in  
31 correlation structure in the late 1960s, as shown in Figure 4. Because the covariability plot for  
32 the Barrow/ St. Paul pair (Figure 3) for the early period shows little structure, we plot the  
33 composite of winter SLP for the years before 1966 when the absolute value of the anomalies at  
34 both Barrow and St. Paul are less than one-half of their standard deviation (Figure 6a). The  
35 strong zonal nature of the isobars is evident. In contrast, we plot the SLP anomaly composite  
36 fields after 1966 for the periods when the absolute values of anomalies are both larger than one-  
37 half of the standard deviation (Figure 6b and c). After 1966 a common feature of the composites  
38 for both warm/warm and cold/cold cases is that anomalous atmospheric flows are meridionally  
39 orientated although opposite in sign. When both Barrow and St. Paul experience warm SAT  
40 anomalies, inferred anomalous wind flow is from the North Pacific to the Chukchi and Beaufort  
41 Seas (Figure 6b). Overland *et al.* (2002) and Stone *et al.* (2002) note warm air temperatures and  
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3 early snow melt in northeast Alaska in the last two decades. On the contrary, in the early 1970s,  
4 when both Barrow and St. Paul experienced cold SAT anomalies, there was a weaker Aleutian  
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6 low over the central Bering Sea, which allowed the cold Arctic air to penetrate as far south as the  
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8 Aleutian Islands (Figure 6c).  
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## 12 13 14 **Summary and Discussion**

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17 There was a shift in the climatic relationship between the northern and southern Bering Sea  
18 during the last century. Significant increased covariability is observed since the late 1960s.  
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20 Statistical tests confirm the changing relationship between Barrow and St. Paul. There is also a  
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22 suggestion, though at a weak level, of a change in correlation between Nome and St. Paul in  
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24 winter and spring. This supports the concept that arctic air and Pacific air had fewer meridional  
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26 excursions before the late 1960s, as shown by the low and even negative correlation coefficients  
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28 between Barrow and St. Paul during this period. After the mid-1970s, the warming in the Bering  
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30 Sea is due in part to the deepening of Aleutian low (Overland *et al.*, 1998) and the reduced SLP  
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32 in the Arctic (Savelieva *et al.*, 2000), which allows warm Pacific flows to penetrate into the  
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34 Arctic Basin.  
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41 However, more may be going on than simply a change in the Pacific North America  
42 (PNA)/Pacific Decadal Oscillation (PDO) patterns (Trenberth and Hurrell, 1994) associated with  
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44 a deepening of the Aleutian low. The increase in the north/south correlation structure does not  
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46 begin near the well-known shift of 1976/7, but earlier in the late 1960s with a series of cold years  
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48 at St. Paul. Thus the increase in the north/south correlation in the Bering Sea may be more  
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50 related to changes in the larger general circulation. Overland and Stabeno (2004) hypothesize  
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52 that the southeastern Bering Sea shelf shifted from a more arctic ecosystem to a more sub-arctic  
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54 ecosystem after the mid-1970s based on fisheries abundance, benthic biomass and species  
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3 composition, and marine mammal populations. The implications of the change in climatology  
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5 documented in our paper support the hypothesis that the southeast Bering Sea was most likely an  
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7 arctic ecosystem from at least the mid-1970s back to the early 20th century.  
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12 **Acknowledgements.** We appreciate the support of the NOAA Arctic Research Office  
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14 through the Northern Bering Sea Project, and the FOCI program at PMEL. The PMEL  
15  
16 contribution number is 2793. This publication is also partially funded by the Joint Institute for  
17  
18 the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No.  
19  
20 NA17RJ1232, contribution #1116.  
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Table I. Correlation coefficients between meteorological stations for each season. All but two (indicated by \*) are statistically significant at the 95% confidence level.

Station Pair	Winter	Spring	Summer	Fall
Barrow/Nome	0.67	0.59	0.23*	0.69
Barrow/St. Paul	0.43	0.37	0.14*	0.37
Nome/St. Paul	0.61	0.58	0.29	0.65

## Figure Captions

Figure 1. The location of Barrow, Nome, and St. Paul stations in the Bering Sea region.

Figure 2. Seasonal Surface Air Temperatures (SAT) at Barrow, Nome, and St. Paul for 1916–2004; a 5-year running mean has been applied to suppress interannual variability. From top down: winter (a–c), spring (d–f), summer (g–i) and fall (j–l).

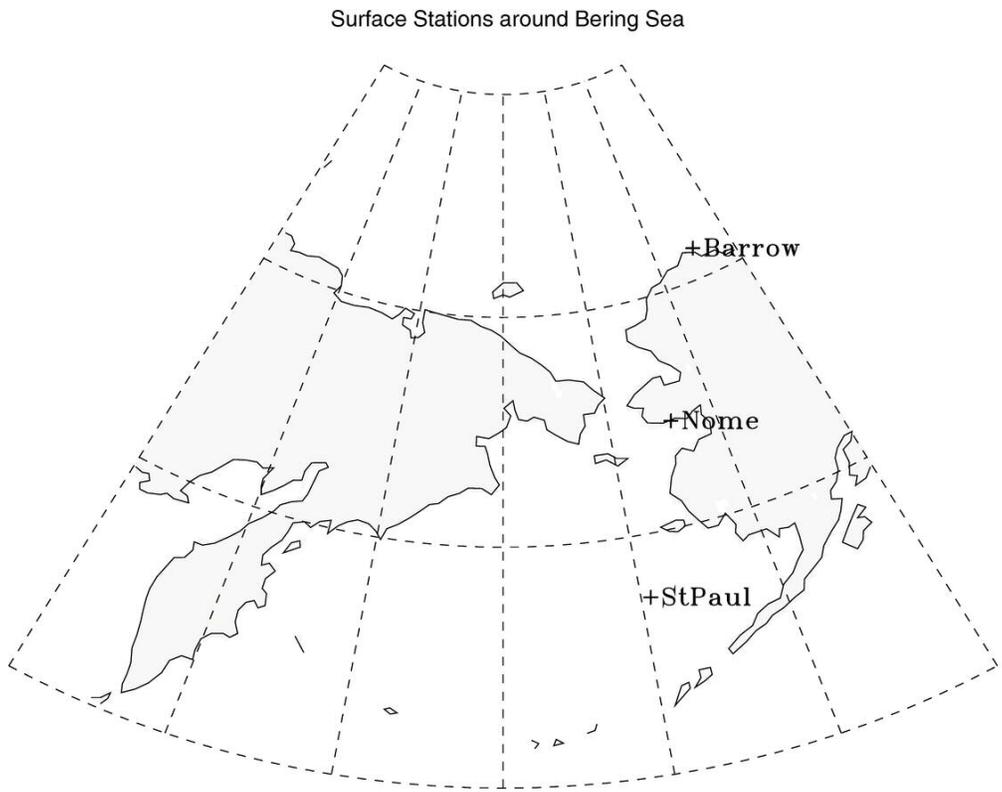
Figure 3. Scatter plot of the winter season covariability in SAT at Barrow–Nome (left), Barrow–St. Paul (middle) and Nome–St. Paul (right) stations. The thin line in each plot indicates the climatology based on entire record, and the color denotes the decade as shown in the legend. The 2-digit numbers in the plot indicate the year. The top (bottom) panels are for the decades before (after) 1970.

Figure 4 (Top) Running correlations with 25-year window for winter between Barrow/Nome (left), Barrow/St. Paul (middle), and Nome/St. Paul (right). (Bottom) The histogram for 10,000 realizations of maximum difference in correlation. Alpha ( $\alpha$ ) represents the level of significance and is the area under the curve to the right of the observed value (vertical line).

Figure 5 Same as in the top panels of Figure 4, but for the three remaining seasons: (from left to right) spring, summer, and fall. Values of  $\alpha$  are also given; none of the maximum differences in correlation (except Barrow/Nome summer) are accepted as significant.

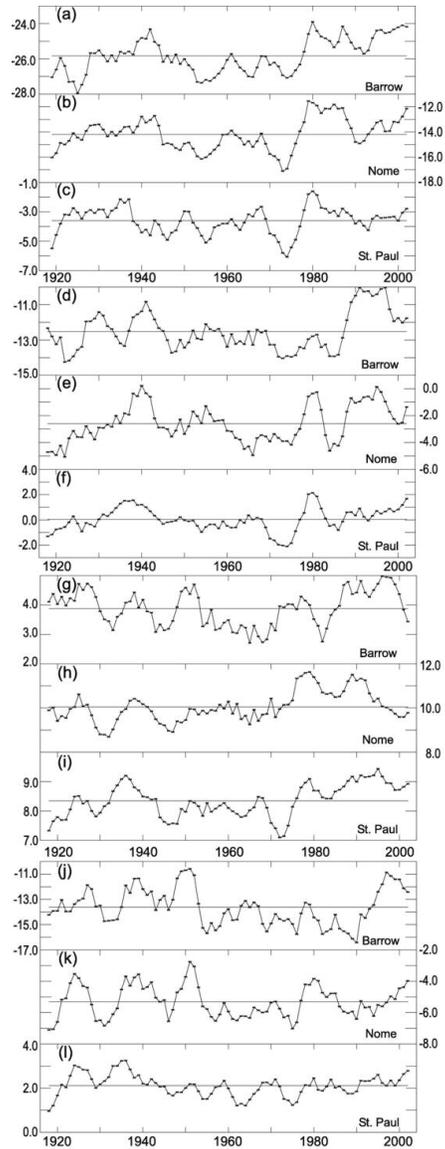
Figure 6 (a) Composite of the winter Sea Level Pressure (SLP) field for the years before 1966 when absolute SAT anomalies are less than one-half of their standard deviation (see Figure 3). (b and c) Composites of SLP anomaly fields after 1966 when the absolute SAT anomalies are larger than one-half standard deviation. The warm-warm (b) and cold-cold (c) cases are separated to distinguish anomalies in the positive and negative SLP fields.

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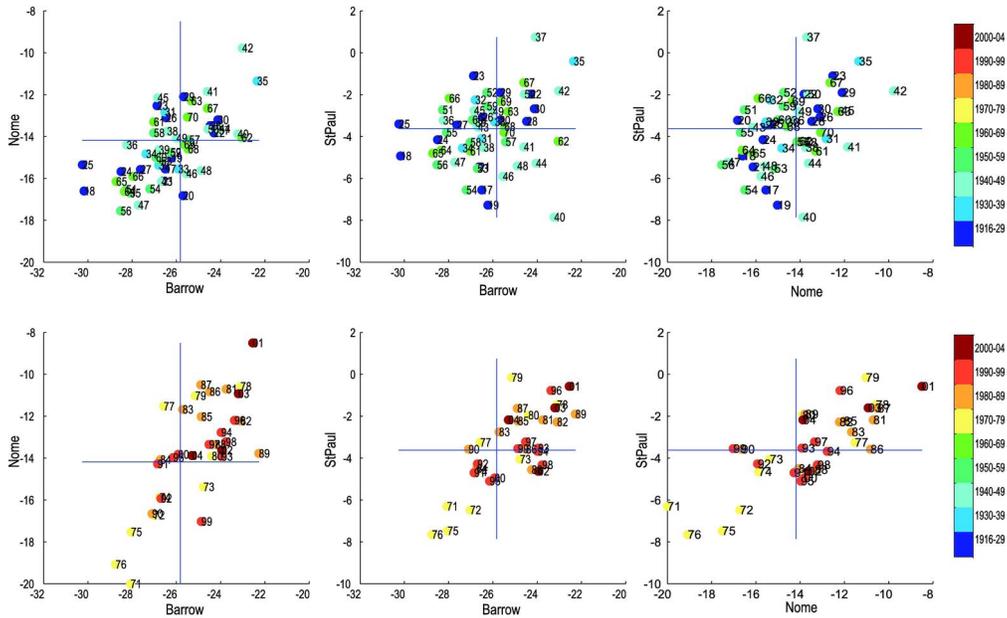
Wang et al., Figure 1

**The location of Barrow, Nome, and St. Paul stations in the Bering Sea region.**  
190x201mm (150 x 150 DPI)



Wang et al., Figure 2

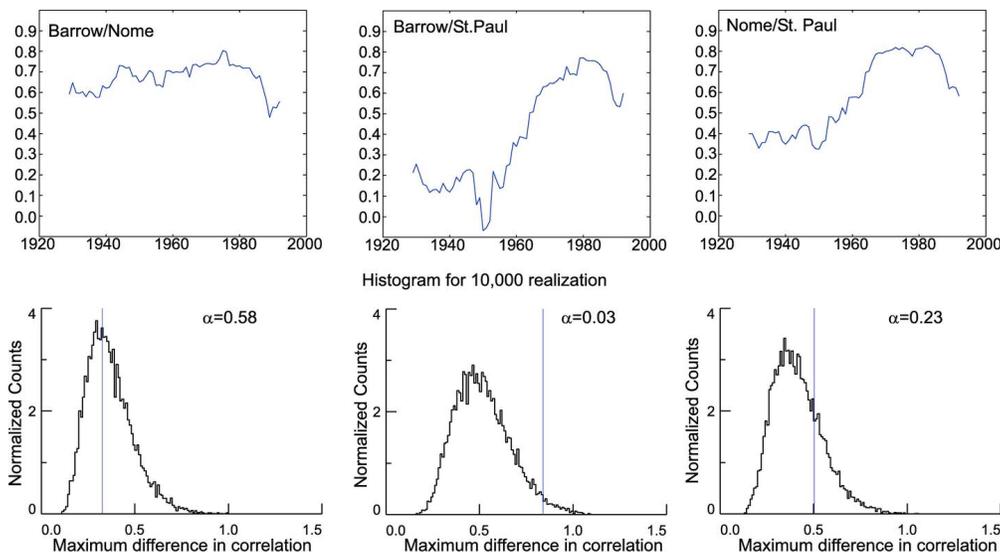
**Seasonal Surface Air Temperatures (SAT) at Barrow, Nome, and St. Paul for 1916–2004; a 5-year running mean has been applied to suppress interannual variability. From top down: winter (a–c), spring (d–f), summer (g–i) and fall (j–l).  
140x257mm (150 x 150 DPI)**



Wang et al., Figure 3

**Scatter plot of the winter season covariability in SAT at Barrow Nome (left), Barrow St. Paul (middle) and Nome St. Paul (right) stations. The thin line in each plot indicates the climatology based on entire record, and the color denotes the decade as shown in the legend. The 2-digit numbers in the plot indicate the year. The top (bottom) panels are for the decades before (after) 1970.**

263x180mm (150 x 150 DPI)

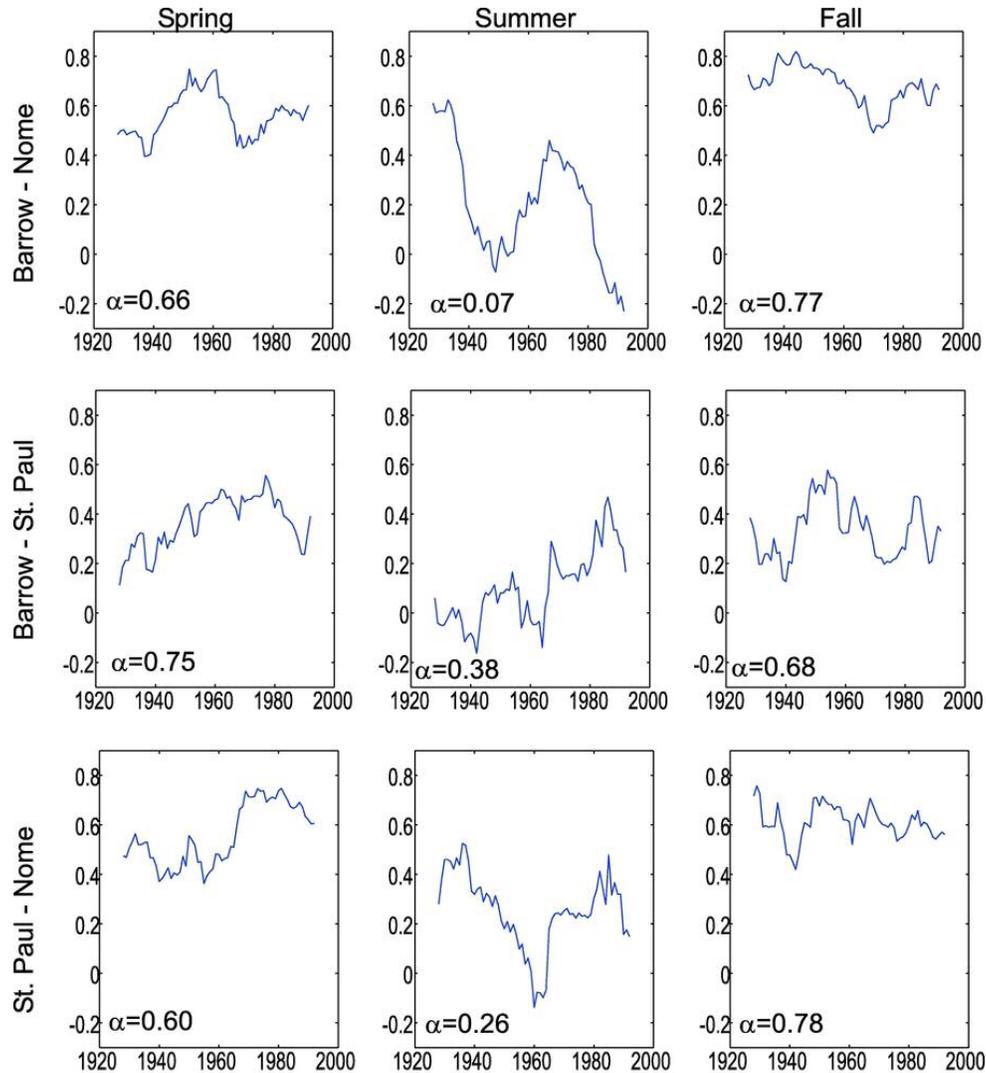


Wang et al., Figure 4

**(Top) Running correlations with 25-year window for winter between Barrow/Nome (left), Barrow/St. Paul (middle), and Nome/St. Paul (right). (Bottom) The histogram for 10,000 realizations of maximum difference in correlation. Alpha ( $\alpha$ ) represents the level of significance and is the area under the curve to the right of the observed value (vertical line).**

243x151mm (150 x 150 DPI)

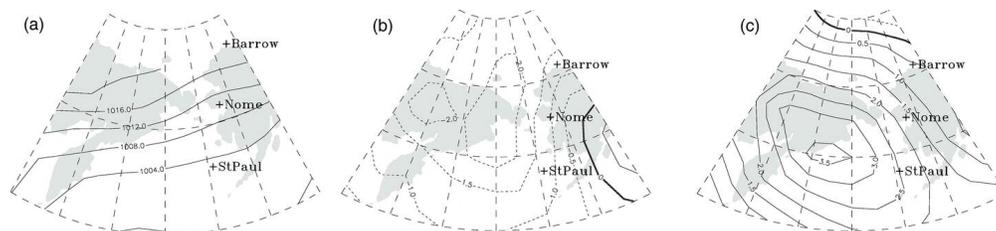
Only



Wang et al., Figure 5

Same as in the top panels of Figure 4, but for the three remaining seasons: (from left to right) spring, summer, and fall. Values of  $\alpha$  are also given; none of the maximum differences in correlation (except Barrow/Nome summer) are accepted as significant.

153x188mm (150 x 150 DPI)



Wang et al., Figure 6

**(a) Composite of the winter Sea Level Pressure (SLP) field for the years before 1966 when absolute SAT anomalies are less than one-half of their standard deviation (see Figure 3). (b and c) Composites of SLP anomaly fields after 1966 when the absolute SAT anomalies are larger than one-half standard deviation. The warm-warm (b) and cold-cold (c) cases are separated to distinguish anomalies in the positive and negative SLP fields.**

244x86mm (150 x 150 DPI)