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SHORT COMMUNICATION

CHANGE IN THE ARCTIC INFLUENCE ON BERING SEA CLIMATE DURING THE TWENTIETH CENTURY

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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 among the stations changed during the past century. Before the 1960s, Barrow and Nome were dominated by Arctic air masses and St. Paul was dominated by North Pacific maritime air masses. After the 1960s, 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 of the 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 twentieth 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. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: Bering Sea; Arctic; climate change; fisheries; air temperatures

1. INTRODUCTION

The Bering Sea is one of the most important large marine ecosystems in the world. Information on its historical physical environment and its relation to the biota is critical for understanding the climate/ecosystem connection and therefore is of importance to fishery management. The Bering Sea is a semienclosed sea that connects the North Pacific and Arctic Oceans (Figure 1). Its climate is influenced by both the cold dry air from the north and warm moist flows from the south. Bering Strait acts as an oceanic and storm track pathway between the Pacific and Arctic Oceans and is important for north/south 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 investigated the temporal variations of Bering Sea SAT, beginning with the 1910s when these records became nearly continuous, with emphasis on the relationship among the stations during the last century.

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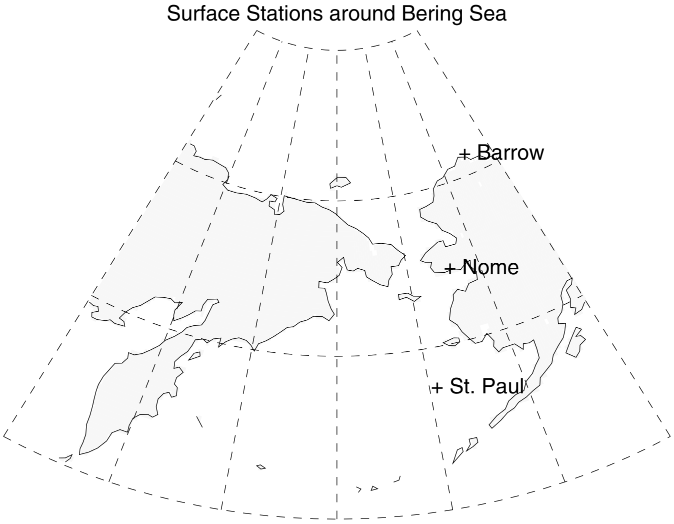


Figure 1. The location of Barrow, Nome, and St. Paul stations in the Bering Sea region

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. On the basis of the depth-averaged temperature measured from a biophysical oceanographic mooring (M2), it was found to be warmer by 2 °C in the 2002–2004 winter compared with 1995–1997 on the southeastern Bering Sea continental shelf. Fish, invertebrates, and marine mammal populations have responded to these shifts. On the basis of the surveys conducted by National Marine Fisheries Service, cold-climate-favored species show a decrease in biomass, while other typical southern Bering Sea species are now reported from further north (Overland and Stabeno, 2004). We would like to know how representative the climatology of this recent period is, compared to earlier in the twentieth century. Although there are no major, long ecological records to directly investigate the changes before the 1960s, with 89 years of observed SAT, we were able to address the stability of the climate system in the Bering Sea and by implication draw conclusions about the climate/ecosystem state in the early and mid-twentieth century.

2. DATA COLLECTION

2.1. Surface air temperature

Two Bering Sea weather stations were selected for analysis: Nome (WMO code 70200), located near Bering Strait (Figure 1) representing the northern Bering Sea, and St. Paul (70308) in the Pribilof Islands representing the maritime southeastern Bering Sea. The influence of Arctic cold air is represented by Barrow (70 026) on the Arctic coast. Monthly mean SAT are from GHCN data set version-2 (http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=ghcn.html). Although the monthly data collection at St. Paul started as early as 1840, there are gaps between 1844 and 1916. The records for Nome and Barrow begin in the late 1890s and have good temporal coverage. We have analyzed the same-length data records for the three stations from 1916 to 2004.

2.2. Sea level pressure

Gridded monthly sea level pressure (SLP) analyses were 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).

3. 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° at Barrow and Nome and 2° at St. Paul. Strong interannual variability is observed in the months from December through March with temperature fluctuating in similar ranges during the four-month period. We therefore defined the winter season to be the averages of these four months (December to March). June and September are transition months, characterized by large interannual variability and relatively distinct temperature records from their neighbor months; for the sake of clarity, we have not included them in seasonal averages. Thus, our spring includes April and May, summer is the average of July and August, and fall is the average of October and November.

Figure 2 shows the time series of seasonally averaged SAT at these three stations with a 5-year running mean applied to filter interannual variation. In winter (Figure 2(a–c)) these stations are distinguished by their north/south geographic location, in the sense that the climatology of each station is offset by about 10 °C. Since the late 1970s, all three stations switched from a cold period, with nearly 20 years of negative anomalies, to warm anomalies. The warm anomalies at Barrow last longer than at the other two stations, and are stronger since the late 1990s (Figure 2(a)); Nome and St. Paul returned to more neutral levels after the early 1990s (Figure 2(b) and (c)). From the late 1920s to the early 1940s, a decade of warm anomalies is shown at all three stations, although the anomalies did not occur in the same years. In the spring season (Figure 2(d–f)), two warm periods are shown in the time series: one is from 1930 to the early 1940s and the other is around the 1980s. In both periods, the warm anomalies at St. Paul happened a few years earlier. The cold anomalies at Barrow in the 1960s are weaker than in the winter season and last until the early 1980s.

The magnitude of the anomalies in summer at all the three stations (Figure 2(g–i)) is small compared to other seasons and there is weak covariability among the stations. St. Paul displays a typical marine climate with a colder summer mean temperature compared to Nome. In fall (Figure 2(j–l)), covariability between Nome and Barrow is strongest in the early part of the century: both show positive anomalies during the 1920s and again from the late 1930s to the early 1950s. Warm anomalies are observed at St. Paul for a decade until the late 1930s. The cold period from the late 1950s to the late 1970s is obvious at all stations; however, the timing and magnitude are different among the stations. Overall, cold anomalies prevail in the region from the late 1950s to the late 1970s for all seasons, while during the last two decades warm anomalies are seen in most seasons in the three records.

The covariability among the stations in winter is easily seen in Figure 3, a scatter plot of seasonal mean temperatures between pairs of stations. With climatological means indicated by thin lines in each panel, the four quadrants are composed of the years with warm/warm, cold/warm, cold/cold, and warm/cold combinations of anomalies. To distinguish the periods, years before/after 1970 are shown in the upper/lower panels. For the Barrow–Nome pair, among 88 winters, 69 are located in quadrants I and III and 19 are located in quadrants II and IV (Figure 3(a)), which suggests considerable covariability between these stations. Before 1970 more years are located in quadrant III, while after 1970 more are in quadrant I and even less in quadrants II and IV. This suggests that a cold/cold regime has been replaced by a warm/warm regime in recent decades. For the Barrow–St. Paul pair (Figure 3(b)), many years are located in quadrants II and III near the origin before 1970 (Figure 3(b), top); but afterwards most years are in quadrant I, with a few years in the 1970s in quadrant III (Figure 3(b), bottom). The portion of years in quadrants I and III before 1970 is 57%; for the last 35 years this value is 77%, showing a increase in covariability. For the St. Paul–Nome pair, there is also a change in distribution of points (Figure 3(c)). The rather evenly distributed cluster of dots changes to a more linearly, covariant shape along the diagonal. Fifty-five percent of the years before 1970 are located in quadrants I and III, while this number increases to 71% over the last 35 years.

The covariability between north and south is weaker in spring than in winter. Although there are about 60 cases when both stations show the same sign of anomalies, more than 20% of them are actually close to their climatologies (figures not shown). Again, most of the recent years are in quadrant I.

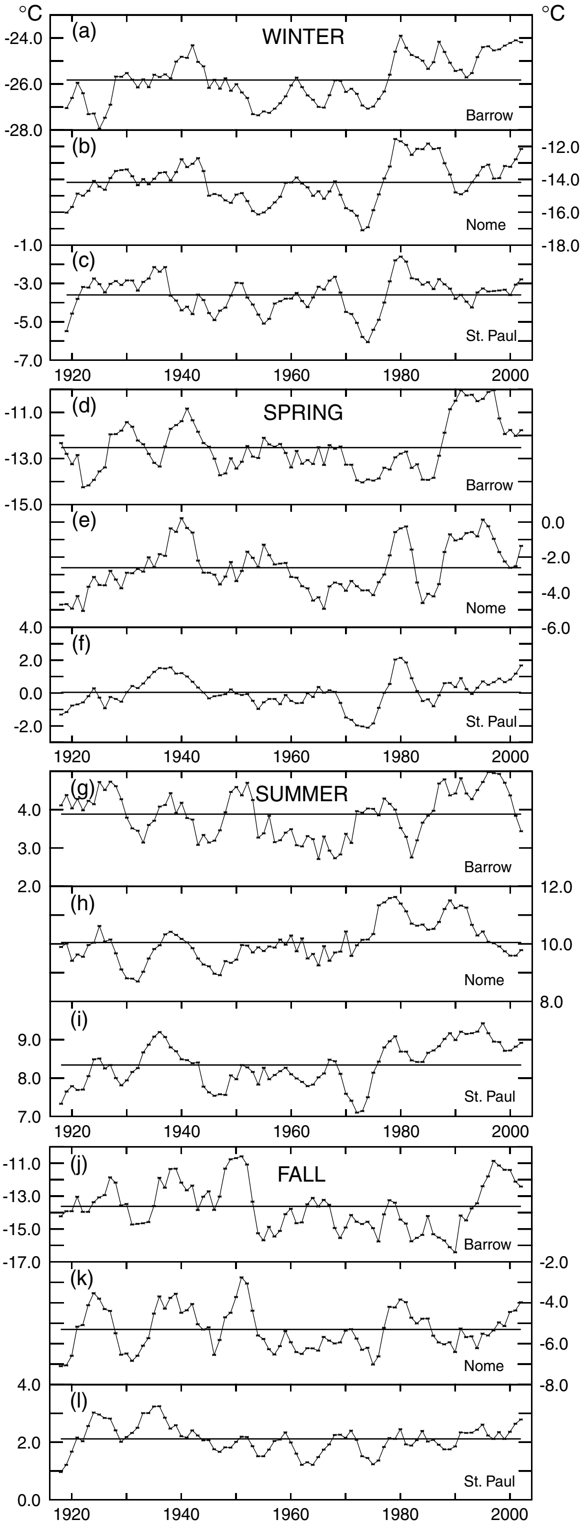


Figure 2. Seasonal surface air temperatures (SAT) at Barrow, Nome, and St. Paul for 1916–2004; A 5-year running mean has been applied to suppress interannual variability. Winter (a–c) spring; (d–f) summer (g–i); and fall (j–l)

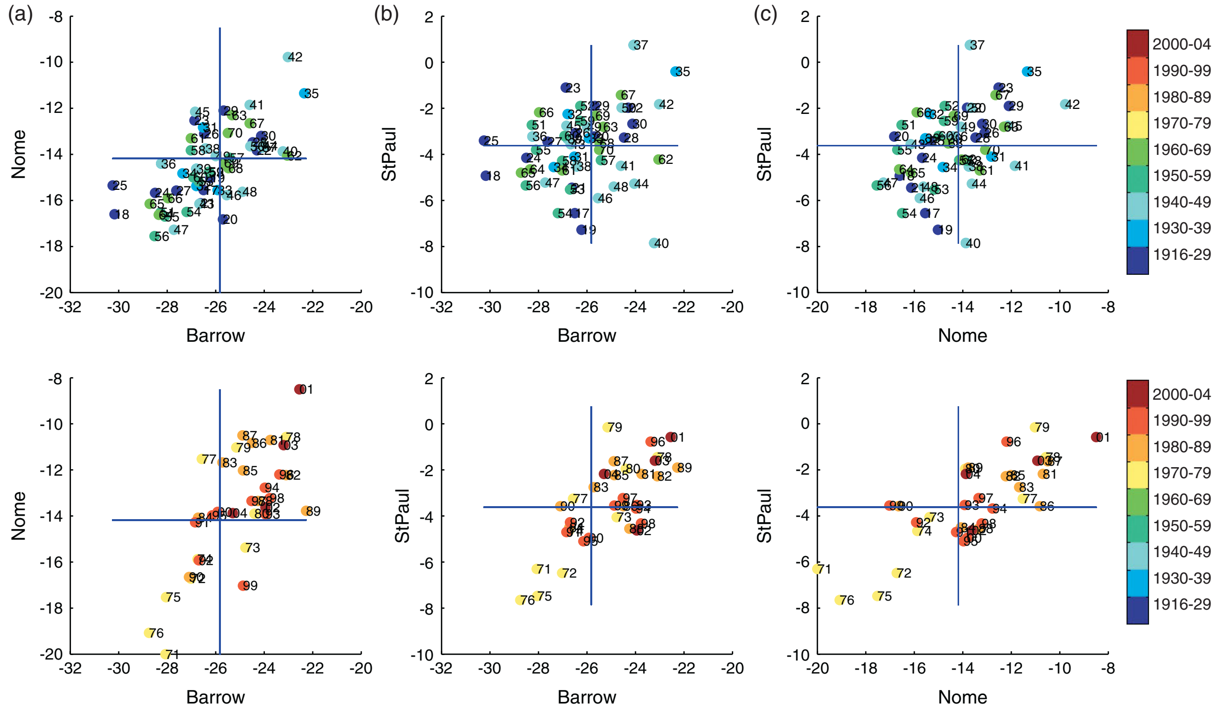


Figure 3. Scatter plot of the winter season covariability in SAT at Barrow–Nome (a), Barrow–St. Paul (b) and Nome–St. Paul (c) stations. The thin line in each plot indicates the climatological mean based on the entire record, and the color denotes the decade as shown in the legend. The 2-digit numbers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

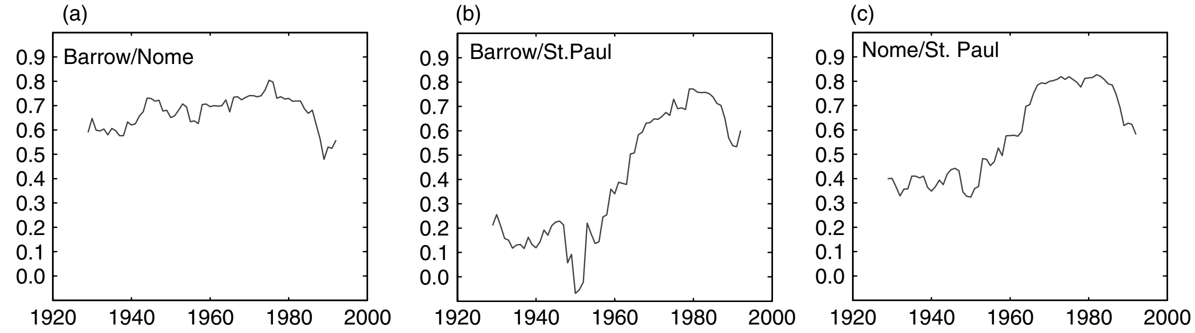
4. DECADAL CHANGES IN RELATIONSHIP AMONG NORTH/SOUTH STATIONS

Table I shows the correlation coefficients between the stations over the period of record for the four seasons. All but two (indicated by*) are statistically significant at the 95% confidence level. The low correlation in summer is not surprising, as the variability in the season is low. The correlations between Barrow and Nome are relatively high for the other three seasons, as is the correlation between Nome and St. Paul. The correlation between Barrow and St. Paul is lower than the other two pairs, with highest correlation occurring during the winter.

Except for the Barrow–Nome pair, the interpretation of these time-independent correlations can be misleading because of suggested time-dependent relationships in the north/south correlations. On the basis of an inspection of Figure 3, we investigated this time-dependent hypothesis objectively by computing running correlation coefficients over blocks spanning 25 years; deviations within a given block were recentered with the sample mean for the block rather than using the sample mean of the entire data record. The 25-year size was chosen to ensure a degree of statistical stability in the estimated correlations, while providing some localization in time. In winter (Figure 4, top panels), the running correlation coefficient is fairly constant

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



Histogram for 10,000 realization

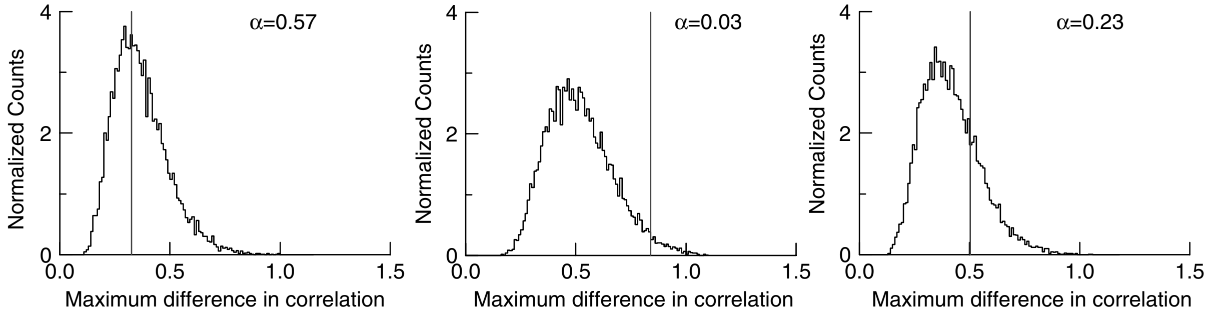


Figure 4. (Top) Running correlations with a 25-year window for winter between Barrow–Nome (a), Barrow–St. Paul (b), and Nome–St. Paul (c). (Bottom) The histogram for 10 000 realizations of maximum difference in correlation. Alpha (α) represents the level of significance and is the area under the curve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

between Barrow and Nome, but not, however, between Barrow and St. Paul and between Nome 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 (ε_t, η_t) is a bivariate Gaussian white noise process such that the correlation between ε_t and η_t is ρ for any given t; this implies that, when $\phi_X = \phi_Y = \phi$, the cross correlation between $\{X_t\}$ and $\{Y_t\}$ is $\rho\phi^{\tau}$ at lagτ. After fitting the above models to two time series, with ρ estimated with the observed instantaneous cross correlation, we generated simulations of $\{X_t\}$ and $\{Y_t\}$ of the same length as the observed 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 subjected to 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 under the null hypothesis. We can then use this distribution to assess the value of the statistic from the observed pair of SAT time series. If the observed value is in the upper tail of the distribution, we have evidence that the null hypothesis is untenable and that we should entertain the alternate hypothesis that the correlation between the two series has changed.

The lower panels of Figure 4 show the results of this study for the three time series. In each figure, we show the distribution of the inferred test statistic as a histogram, under the null hypothesis. The vertical line in each figure indicates the actual test statistic from the observed series. The observed level of significance, α, for each test is given by the area under the histogram to the right of the vertical line. We can interpret α as being the probability of obtaining a result at least as extreme as the observed value when in fact the null hypothesis is true. When α is small the null hypothesis is untenable. The values of α for Barrow–Nome, Barrow–St. Paul, and Nome–St. Paul are 0.57, 0.03, and 0.23 respectively. There is no serious reason to doubt the null hypothesis that there was no shift in correlation for the winter Barrow–Nome pairing, but there is strong evidence to reject the null hypothesis for the Barrow–St. Paul pairing. The value of α between Nome and St. Paul (0.23) does not allow us to reject the null hypothesis at a reasonable level of significance, but still suggests only a 1 in 4 chance that there is no shift in correlation.

The same technique was applied to the series for other seasons. Figure 5 shows the running correlations for the three pairs of stations with the same 25-year window length. In spring, we see that the correlation between Barrow and Nome is high from the 1940s to the 1960s, and slightly lower at both ends. The correlation has increased since the late 1960s between Nome and St. Paul, similar to the winter analysis. However, none of

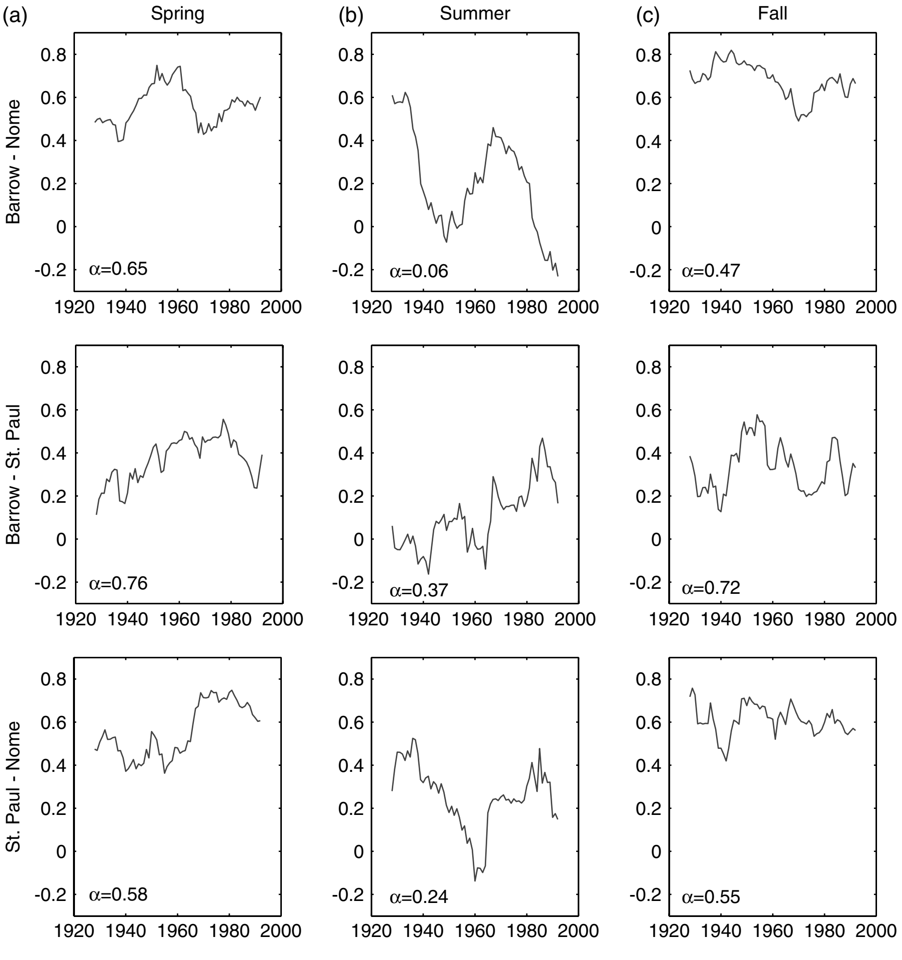
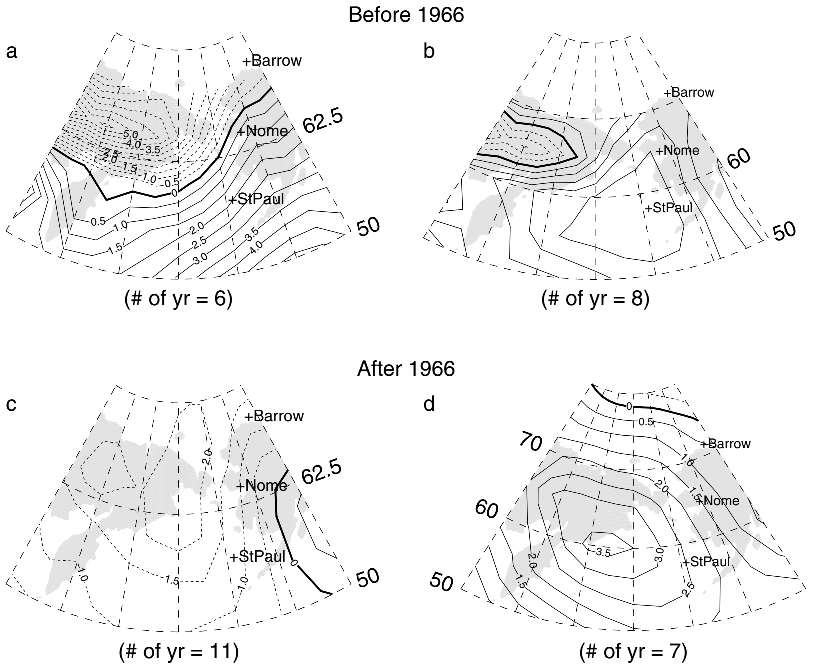


Figure 5. Same as in the top panels of Figure 4, but for the three remaining seasons: (from a to c) spring, summer, and fall. Values of α are given; none of the maximum differences in correlation (except Barrow–Nome summer) are accepted as significant

these changes are significant on the basis of our rigorous test; the values of α are near 0.6 or above for all three pairs. The running correlation for the summer season is not only small but is also negative for some periods. We do detect significant changes in the relationship between Barrow and Nome from the 1930s to late 1990s (top, Figure 5(b)), even though the average value of these correlations is small. The relatively high correlation between Barrow and Nome and between Nome and St. Paul for the fall season may indicate alternating Pacific and Arctic air masses at Nome in different years. No significant changes in correlations are found for the fall.

5. ATMOSPHERIC CIRCULATION PATTERNS ASSOCIATED WITH DECADAL CHANGE OVER THE BERING SEA

Regional atmospheric circulation changes are observed before and after the winter shift in correlation structure in the late 1960s. Figure 6 displays the composite plot of winter SLP anomalies for the years before and after 1966 (based on our statistical study) when absolute values of the SAT anomalies at both Barrow and St. Paul are larger than one-half of their standard deviation, based on the entire record length. Before 1966 the composites of SLP field show a combination of weak Siberian High and weak Aleutian Low, in both warm/warm (Figure 6(a)) and cold/cold cases (Figure 6(b)). The number of years that fall into the warm/warm category before 1966 (Figure 6(a)) are only half of those after 1966 (Figure 6(c)): 6 *versus* 11. For the cold/cold cases (Figure 6(b and d)) the number of years are nearly the same (8 *versus* 7), but the flow patterns are quite different. Before 1966, the anomalous high center located near St. Paul in the eastern Bering Sea blocks cold Arctic air from penetrating further south. After 1966 the Siberian High is stronger, which results in an anomalous high located over the western Bering, and northerly wind anomalies are established near the Bering Strait allowing the cold Arctic air to penetrate south to St. Paul Islands and beyond. The common feature of the composites for both warm/warm and cold/cold cases after 1966 is that anomalous atmospheric flows are more meridionally orientated than in the earlier period, although opposite in sign.



(# of yr = 6) (# of yr = 8)

(# of yr = 11) (# of yr = 7)

Figure 6. Composite of the winter sea level pressure (SLP) anomalies for the years before/after 1966 when absolute SAT anomalies are larger than one-half of their standard deviation (Figure 3). The warm/warm (a and c) and cold/cold (b and d) cases are separated to distinguish the SLP anomaly fields

The large number of recent warm/warm cases for the shorter interval after 1966 (Figure 6(c)) is particularly striking. When both Barrow and St. Paul experience warm SAT anomalies, the inferred anomalous wind flow is from the North Pacific to the Chukchi and Beaufort Seas. Overland *et al*. (2002) and Stone *et al*. (2002) report warm air temperatures and early snow melt in northeast Alaska in the last two decades.

6. SUMMARY AND DISCUSSION

There was a shift in the climatic relationship between the northern and southern Bering Sea during the last century. Increased covariability has been observed since the late 1960s. Statistical tests confirm the changing relationship between Barrow and St. Paul. There is also a suggestion, though at a weak level, of a change in correlation between Nome and St. Paul in winter and spring. This supports the concept that Arctic and Pacific air had fewer meridional excursions before late 1960s, as shown by the low and even negative correlation coefficients between Barrow and St. Paul during this period. After the mid-1970s, the warming in the Bering Sea is due in part to the deepening of Aleutian Low (Figure 6(c) and Overland *et al*., 1999) and reduced SLP in the Arctic (Savelieva *et al*., 2000), which allow warm Pacific flows to penetrate into the Arctic Basin.

However, more may be going on than simply a change in the Pacific North America/Pacific Decadal Oscillation climate patterns (Trenberth and Hurrell, 1994) associated with a deepening of the Aleutian Low. The increase in the north/south correlation structure does not begin near the well-known shift of 1976/7, but earlier, in the late 1960s, with a series of cold years at St. Paul. Thus, the increase in the north/south correlation in the Bering Sea may be more related to changes in the larger general circulation and shifts in the Siberian High.

On the basis of the abundance fisheries, benthic biomass and species composition, and marine mammal populations, Overland and Stabeno (2004) hypothesize that the southeastern Bering Sea shelf shifted from a more Arctic ecosystem to a more sub-Arctic ecosystem after the mid-1970s. The implications of the change in climatology documented in our paper support the hypothesis that the southeast Bering Sea was most likely an Arctic type ecosystem from the mid-1970s back to at least the early twentieth century.

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