The Significance of the 1976 Pacific Climate Shift in the Climatology of Alaska

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(Manuscript received 20 April 2004, in final form 25 February 2005)

ABSTRACT

The 1976 Pacific climate shift is examined, and its manifestations and significance in Alaskan climatology during the last half-century are demonstrated. The Pacific Decadal Oscillation index shifted in 1976 from dominantly negative values for the 25-yr time period 1951–75 to dominantly positive values for the period 1977–2001.

Mean annual and seasonal temperatures for the positive phase were up to 3.1°C higher than for the negative phase. Likewise, mean cloudiness, wind speeds, and precipitation amounts increased, while mean sea level pressure and geopotential heights decreased. The pressure decrease resulted in a deepening of the Aleutian low in winter and spring. The intensification of the Aleutian low increased the advection of relatively warm and moist air to Alaska and storminess over the state during winter and spring.

The regime shift is also examined for its effect on the long-term temperature trends throughout the state. The trends that have shown climatic warming are strongly biased by the sudden shift in 1976 from the cooler regime to a warmer regime. When analyzing the total time period from 1951 to 2001, warming is observed; however, the 25-yr period trend analyses before 1976 (1951–75) and thereafter (1977–2001) both display cooling, with a few exceptions. In this paper, emphasis is placed on the importance of taking into account the sudden changes that result from abrupt climatic shifts, persistent regimes, and the possibility of cyclic oscillations, such as the PDO, in the analysis of long-term climate change in Alaska.

1. Introduction

In 1976, the North Pacific region, including Alaska, underwent a dramatic shift to a climate regime that saw great increases in winter and spring temperatures, and lesser increases in summer and autumn, when compared to the previous 25 yr. This regime, for the most part, has persisted. The shift, experienced in Alaska as well as much of North America, was noted at the time as a series of very anomalous winters (Namias 1978). The persistence of the anomalous conditions was studied by Trenberth (1990) and the dynamics of the shift, both atmospheric and oceanic, were studied in detail by Miller et al. (1994). The shift in the climate regime now is known to have coincided with a shift in the phase of the Pacific Decadal Oscillation (PDO). The PDO index was developed by Mantua et al. (1997) in an examination of the relationship between Pacific climate variability and salmon production in Alaska and the U.S. Pacific Northwest.

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Multidecadal variability of North Pacific sea surface temperatures has been the focus of much research since the early 1990s, and its effects upon many atmospheric and oceanic variables (Graham 1994; Trenberth and Hurrell 1994; Zhang et al. 1997; Bond and Harrison 2000) and biological variables (Hare et al. 1999; Hare and Mantua 2000) are well documented. In specific relation to Alaska, winter temperature anomalies throughout the state were correlated with the PDO and El Niño–Southern Oscillation (ENSO) in conjunction with the Pacific–North American circulation by Papineau (2001), and a comprehensive review of historical work focusing on Pacific variability is found there.

In this paper, the effect that the regime shift has had on the long-term climatology of Alaska is examined. The climatologies of Alaska's climate regions in the negative and positive phases before and after the shift are compared and contrasted. The differences in sea level pressure (SLP), geopotential height, temperature, wind, cloudiness, and precipitation are examined to show the influence of the Pacific variability and response in the different regions of Alaska. Finally, it is shown that a significant amount of the warming trend seen throughout Alaska during the last half of the twentieth century is largely a result of the sudden shift in 1976. The temperature trends of the 25-yr climate periods that correspond to opposite phases of the Pacific decadal oscillation before and after the shift are not uniform, most often indicating cooling, and may contradict some ideas about long-term climate change as it relates to Alaska insofar as all of the regions in sub-Arctic Alaska have experienced a net cooling since 1977.

2. Data and methodology

The period of 1951–2001 was chosen to establish climatological periods of 25 yr with homogeneous data coverage on either side of the shift of 1976. The periods of 1951–75 and 1977–2001 (hereafter periods 1 and 2, respectively) were studied and compared on annual, seasonal, and monthly time scales. As the transition occurred during the year of 1976, it has been left out of the comparison analysis of the two periods. The exceptions are the winter seasons of 1975/76 and 1976/77, for which 2 months and 1 month, respectively, were used from 1976. Each of these winters clearly demonstrated the typical conditions of the regime of each respective period. The monthly values of the Pacific decadal oscillation index maintained at the University of Washington (http://tao.atmos.washington.edu/pdo/) are utilized in this study. Monthly anomalies in the sea surface temperature (SST) field of the North Pacific, poleward of 20°N, constitute the basis of the PDO index. An empirical orthogonal function (EOF) analysis is then performed on the SST data, and the leading principle component of the analysis yields the index value (for full details, see Mantua et al. 1997).

While it is admittedly impossible to completely exclude the aspects of ENSO and Arctic Oscillation (AO) variability and their contributing influence upon Alaskan climate, and it is not our intention to imply that they are not important factors, the focus of this study lies more toward demonstrating the influence of the singular steplike event in 1976 upon the long-term climatology than deciphering the complex connections that most certainly exist in the climate system. Statistical analysis shows that this shift is best reflected in the time series of the Pacific decadal oscillation index.

Climatological data from all first-order meteorological stations in Alaska, for which the best continuity of station location and data quality exists, are utilized in this study. First-order stations are defined as those operated by certified observers and most often are operated by the National Weather Service and include a full suite of instrumentation. These data include atmospheric pressure, temperature, cloudiness, total precipitation and snowfall, wind speed, and direction. The hourly wind direction measurements from the stations are analyzed and grouped into four categories of 90° segments centered on the cardinal directions (north, east, south, and west) to determine mean frequency distributions and then compared. Mean wind speeds for annual and seasonal time scales were calculated and compared for each region and season.

Missing data were managed by removing any month missing more than 10% of the daily observations and replacing the missing value with the full period monthly mean for that station. The stations are grouped into climate regions, which are shown in Fig. 1.

The mean annual, seasonal, and monthly values for the two periods, 1951–75 and 1977–2001, are detrended, and the differences in the means are analyzed for statistical significance using a Student's t test to determine whether the changes in temperature, sea level pressure, etc., are greater than can be explained by chance. In the analysis of temperature trends, a least squares linear regression trend analysis is used, and the statistical significance of the trends is evaluated again using the Student's t test.

Finally, the monthly and seasonal National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay et al. 1996) is accessed through the Climate Diagnostics Center Web site. Change in the sea level pressure and 500-hPa geopotential height fields over the Pacific Basin and mean temperature and sea level pressure fields over Alaska are generated and are presented to support the results from the station data and to grasp a better spatial picture of where specific centers of change occurred. The changes in these fields were examined for statistical significance with a Student's t test.

3. Results

a. PDO index

Figure 2 shows the time series of the monthly values of the PDO index from 1951 to 2001. The shift in phase from dominantly negative (blue) to dominantly positive (red) is clearly visible in 1976. The shift in the values of the index occurred between June and July 1976, with June having an index value of –0.67 and July having a value of +0.61.

Several exceptions to the dominant regime should be noted in the figure. For example, five of the six warmest winters in period 1 (cold regime) all correspond with the positive PDO index (1957/58 to 1960/61 and 1969/70). These periods can be clearly seen in Fig. 2. Conversely, the winters of 1989/90, 1998/99, and 1999/2000

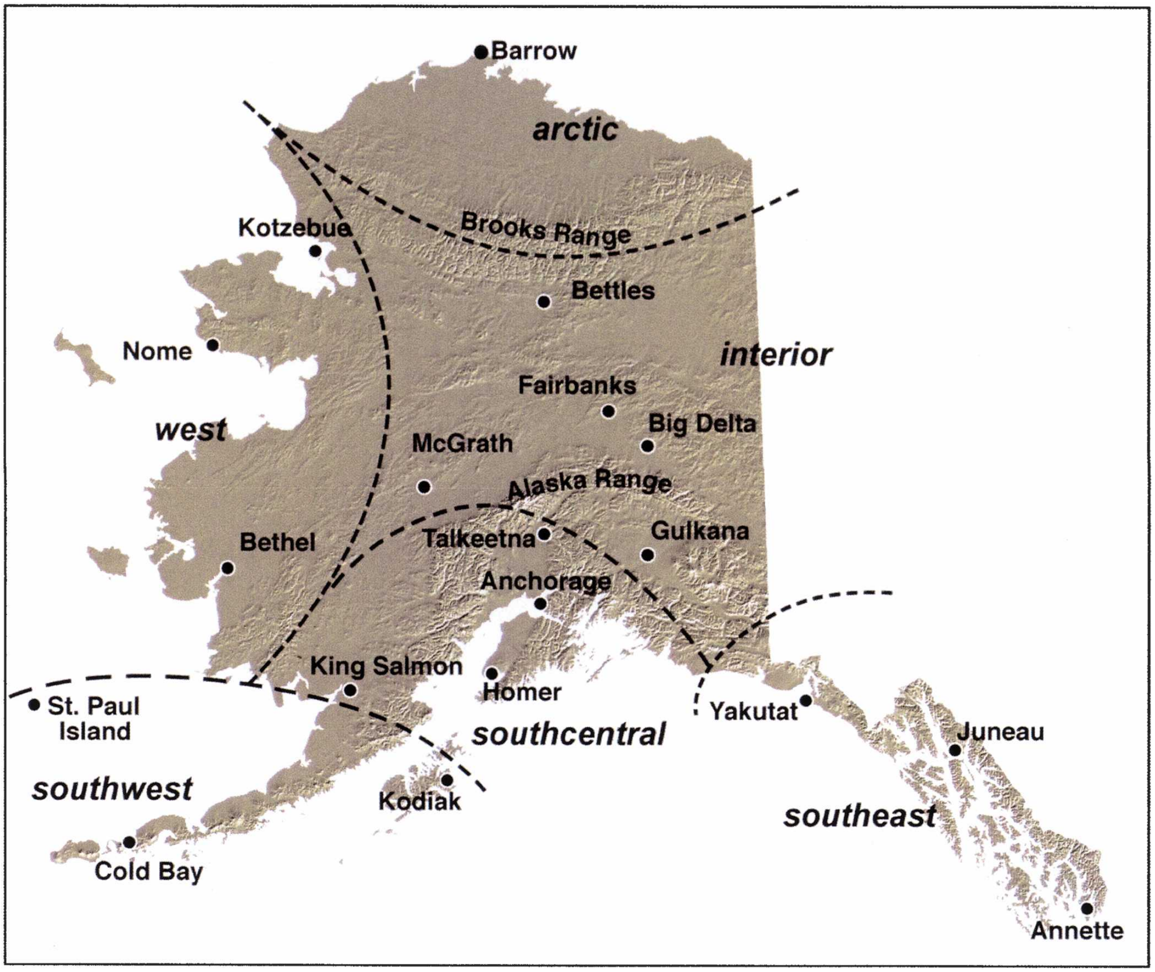


FIG. 1. First-order National Weather Service stations and the climate regions of Alaska.

were all under a negative PDO index and are all among the five coldest winters in period 2. Despite these exceptions, the persistence of the dominantly negative values before 1976 and dominantly positive values thereafter is clearly demonstrated.

On a whole, the correlation between the mean annual and seasonal temperatures and the corresponding PDO index values for each region was very good, with each season showing a statistical significance at a probability of greater than 95%. As can be seen in Table 1, the correlation coefficients of many of the regions showed correlation greater than 99% significance, with winter and spring showing the strongest correlation overall. The direct correlation coefficients in the Arctic region during the nonwinter seasons show the lowest values of all of the regions.

b. Sea level pressure and geopotential height

The variation in the depth and location of the Aleutian low and its effect on the circulation over the North Pacific region, and thus Alaskan temperatures, are well established from the literature (Namias 1969; Overland et al. 1999; Papineau 2001). The difference in seasonal and annual sea level pressure values for the climate regions of Alaska are presented in Table 2.

The changes in winter sea level pressure prove to be the greatest of all seasons, holding consistent with the assertion that the PDO seems to have its greatest effect in Alaska during the winter season. Of note in Table 2 is the regionality of the change, with the southeast region actually experiencing an increase in mean SLP to a magnitude of 0.8 hPa, while the deepening of the Aleutian low and its effects on the rest of the state during period 2 is also apparent. The mean SLP decreased by 2.2 hPa in the interior, by 2.8 hPa in the southwest region, and by 3.1 hPa in the west, all of which are significant at a probability greater than 95%.

Figure 3 shows the change in mean sea level pressure for each of the seasons from period 1 to period 2 from the reanalysis data. The results largely agree with those

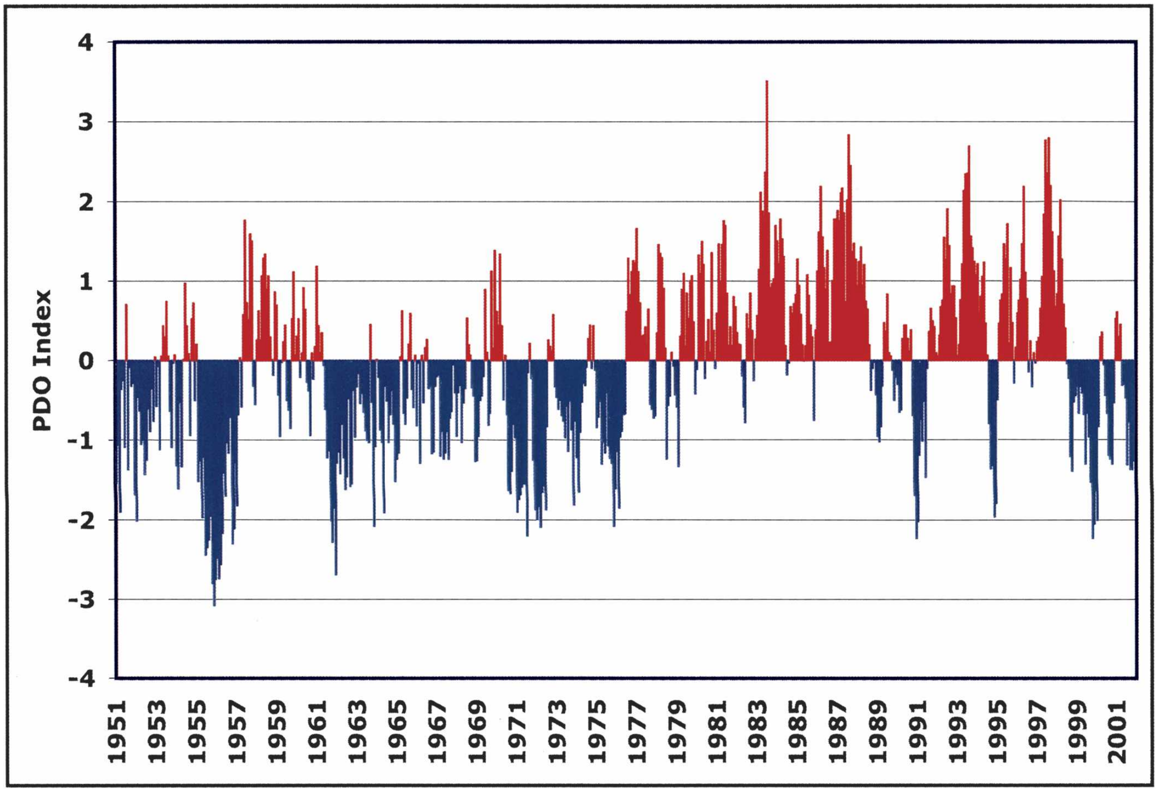


FIG. 2. Time series of the monthly values of the PDO index from 1951 to 2001.

found in the station data, both in magnitude and location of the change. Similar changes in 500-hPa geopotential height fields are shown in Fig. 4. The 500-hPa features in the winter plate [December–January–February (DJF)] of Fig. 4 highlighting the lowering of heights over the western North Pacific and concurrent increases in heights over western Canada are similar in nature to the patterns featured in Bond and Harrison (2000).

c. Mean surface temperature

The mean annual and seasonal temperature differences for each region are shown in Table 3. All of Alaska was warmer during the second period, with the greatest increases observed during the winter. Period 2 temperatures for all seasons except autumn were significantly different at a probability of greater than the 95% level. The southwest region was the only region that showed a significantly different signal during the autumn. It should be noted that winter temperatures are the most variable with a mean standard deviation of 2.6°C for the full period (1951–2001). This compares to a mean summer standard deviation of 0.9°C. The winter environment over Alaska is affected very little by solar radiation forcing, suggesting that advection of moisture and warm air into the state plays a dominant role, making the observed changes in circulation all the more important.

The greatest difference in mean seasonal temperature is found in the Interior during the winter (+3.1°C), followed by south-central and western Alaska. These three regions are more continental when compared to the southeast and southwest regions, which are much more influenced by the moderating effects of the oceans, and these latter two showed, not unexpectedly, the least amount of change. The Arctic region saw an increase in winter temperature of 2.0°C. All of the changes in mean winter surface air temperature are sta-

TABLE 1. Correlation coefficients (r) between mean annual and seasonal temperatures and the PDO index by region (bold indicates significance at a probability greater than 99%).

	Annual	MAM	JJA	SON	DJF
South-central	**0.740**	**0.707**	**0.553**	**0.567**	**0.753**
West	**0.603**	**0.490**	**0.486**	**0.454**	**0.577**
Interior	**0.663**	**0.540**	**0.430**	**0.522**	**0.684**
Southwest	**0.615**	**0.563**	**0.552**	**0.492**	**0.605**
Southeast	**0.715**	**0.815**	**0.581**	**0.568**	**0.672**
Arctic	**0.369**	0.278	0.299	0.229	**0.397**

TABLE 2. Difference (defined as 1977–2001 minus 1951–75) in mean SLP (hPa) (bold indicates significance at a probability greater than 90%).

	Annual	MAM	JJA	SON	DJF
South-central	−0.6 hPa	−1.3 hPa	**+0.5 hPa**	0.0 hPa	−1.6 hPa
West	**−1.0 hPa**	**−1.4 hPa**	+0.5 hPa	+0.1 hPa	**−3.1 hPa**
Interior	**−0.8 hPa**	**−1.3 hPa**	+0.4 hPa	+0.1 hPa	**−2.2 hPa**
Southwest	**−1.0 hPa**	**−1.9 hPa**	+0.4 hPa	+0.3 hPa	**−2.8 hPa**
Southeast	+0.2 hPa	−0.4 hPa	+0.3 hPa	+0.4 hPa	+0.8 hPa
Arctic	**−0.5 hPa**	−0.7 hPa	+0.3 hPa	+0.4 hPa	**−1.7 hPa**

tistically significant at a probability of greater than 99%. Of all of the seasons, autumn witnessed the least amount of change in mean temperatures. Fairly uniform increases in mean temperature were observed during the summer, the season with the least interannual variability. Several factors may contribute to this, including the minimum in the gradient of extraterrestrial radiation at high latitudes. However, the differ-

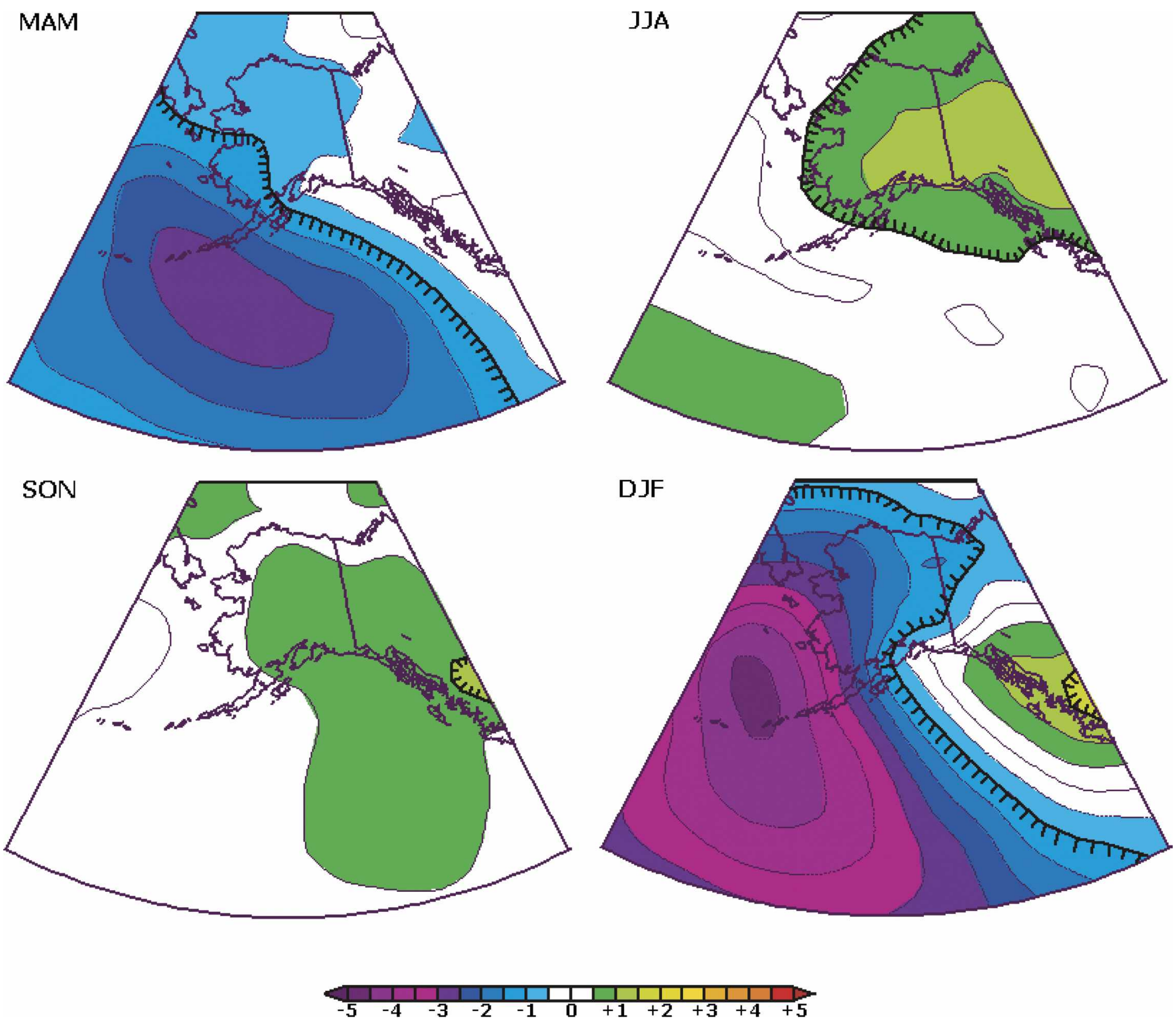


FIG. 3. Difference (1977–2001 minus 1951–75) in mean SLP (hPa) for (a) spring (MAM), (b) summer (JJA), (c) autumn (SON), and (d) winter (DJF) from the NCEP–NCAR reanalysis. Changes greater than the hatched contour indicates significance at a level greater than 90%.

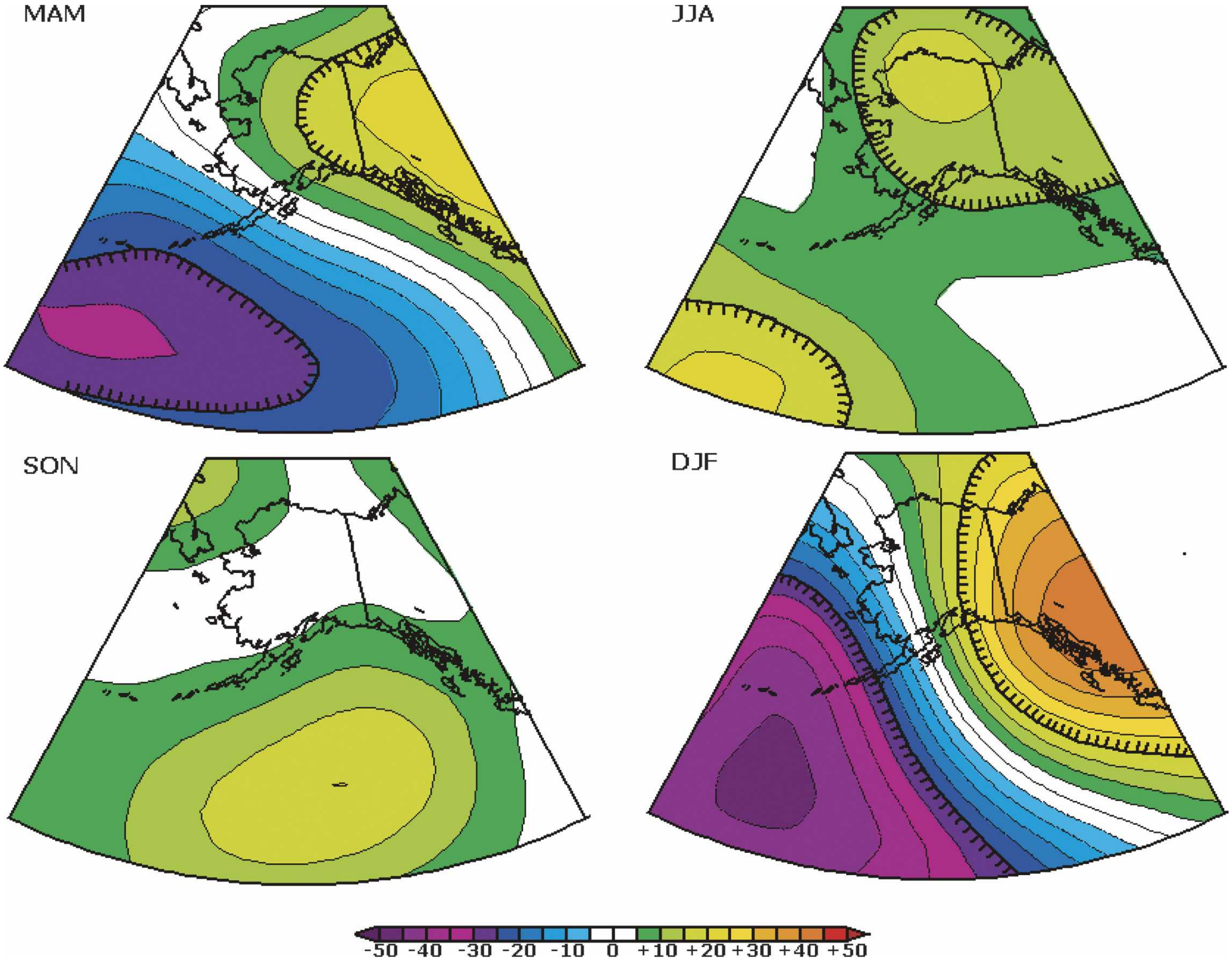


FIG. 4. Same as in Fig. 3, but for mean 500-hPa geopotential height (m).

ences in the summer, albeit small when compared to the winter, were still statistically significant at a level greater than 99% for all regions with the exception of the interior, which was significant at the 95% level. It should be noted that the seasons that experienced the least amount of temperature increase also witnessed the positive change in the sea level pressure field.

TABLE 3. Same as in Table 2, but for mean temperature (°C) (bold indicates significance at a probability greater than 95%; shading indicates significance at a probability greater than 99%).

	Annual	MAM	JJA	SON	DJF
South-central	**+1.5°**	**+1.9°**	**+0.6°**	+0.5°	**+2.9°**
West	**+1.3°**	**+1.4°**	**+0.8°**	+0.5°	**+2.8°**
Interior	**+1.4°**	**+1.7°**	**+0.5°**	+0.2°	**+3.1°**
Southwest	**+0.9°**	**+1.3°**	**+0.9°**	**+0.4°**	**+1.1°**
Southeast	**+1.1°**	**+1.4°**	**+0.7°**	+0.4°	**+1.7°**
Arctic	**+1.2°**	**+1.2°**	**+0.9°**	+0.4°	**+2.0°**

d. Wind

The changes in general circulation that would result from the changes in sea level pressure and geopotential height, shown in section 3b, can be partially observed in the changes of the surface wind fields. Increases in winds with a southerly component would advect more marine-moderated air into the region, which would be of particular interest in the winter by advecting comparatively warm air, and of lesser importance in the summer and autumn by possibly advecting comparatively cool air. Likewise, an increase in easterly winds would support the evidence of a decrease in the mean sea level pressure to the west of the state.

As is seen in Table 4, easterly winds increased in every region for every season from period 1 to period 2, with the exception of the southeast. Southerly winds increased up to 7% in the south-central and interior regions. In the southeast region, winds from the north and the south each decreased from 9%–26% in every

TABLE 4. Percent change [defined as (1977–2001 minus 1951–75)/1951–75] in the frequency of occurrence of winds by direction (bold indicates significance at a probability greater than 90%; shading indicates significance at a probability greater than 99%) (SC: south-central, Wst: west, Int: interior, SW: southwest, SE: southeast, and Arc: Arctic).

SC	ANN	MAM	JJA	SON	DJF	Wst	ANN	MAM	JJA	SON	DJF
North	−1	−1	+4	+1	−4	North	**−5**	+2	−4	**−8**	**−10**
East	**+30**	**+28**	**+16**	**+27**	**+47**	**East**	**+9**	+5	+7	**+7**	**+15**
South	**−5**	**−8**	**−9**	+2	+7	South	−1	−4	−1	+6	−1
West	**+11**	**+10**	**+18**	+6	+2	West	−4	−3	−1	−1	**−17**
Int	**ANN**	MAM	JJA	SON	DJF	SW	ANN	MAM	JJA	SON	DJF
North	−1	+2	+5	−3	−5	North	+3	**+9**	−4	+8	−1
East	**+5**	**+9**	−3	+4	**+13**	East	**+17**	**+17**	**+18**	+3	**+27**
South	0	+3	−2	+3	+1	South	0	+1	+1	−5	+4
West	−4	−7	+1	−2	−9	West	**−9**	**−16**	−6	0	**−13**
SE	ANN	MAM	JJA	SON	DJF	Arc	ANN	MAM	JJA	SON	DJF
North	−20	−19	−16	−26	−19	North	**−19**	**−28**	-8	**-17**	**-26**
East	−1	−3	+2	+1	−3	East	**+14**	**+16**	+3	+10	**+26**
South	−12	−9	−19	−13	−10	South	**−11**	−12	−14	−3	−16
West	+10	+14	+13	+9	+1	West	−2	+5	+7	−5	−12

season. The wind direction frequency in the southwest saw its greatest increase from northerly and easterly directions, with decreases from the south and west.

In addition, by taking into account the drop in overall sea level pressure and the increase in storminess that would accompany such a change, observed wind speeds might be expected to increase from period 1 to period 2. The exception is the southeast, where the mean sea level pressure and geopotential heights increased and where wind speeds might be expected to decrease.

As Table 5 shows, the mean wind speeds in the southeast region decreased during all seasons. The changes were all significant at a probability greater than 99%. Mean wind speeds increased in each season in the Arctic region in the south-central, except for the spring.

e. Cloudiness, precipitation, and snowfall

Changes in cloudiness between periods 1 and 2 were not large when analyzed on an annual and seasonal basis, as can be seen in Table 6. In the interior region, spring and summer saw decreases in cloudiness and increases during the autumn and winter. Summer cloudiness decreased or remained steady in all other regions as well. Cloudiness in the interior during autumn had a +4% change. Winter showed the greatest increases, with a 10% increase for the south-central and a 7% increase for the interior, both of which were statistically significant at greater than 99%. While the winter increases in cloudiness are not all statistically significant, the seasonal averaging masks month-to-month changes that are more pronounced, as will be discussed later.

The changes in mean annual and seasonal precipitation and snowfall totals are presented in Table 7 and show wide variation by season. The relative changes in precipitation during the summer were generally the lowest of all seasons, showing changes in total precipitation from −1% to +11%. Winter showed the most pronounced changes and the greatest range with −39% to +38%. It should be noted that summer is generally the time of the highest total precipitation amounts for most regions, thus the same absolute change in the mean precipitation totals during that period will result in lower percent changes when compared to winter and

TABLE 5. Same as in Table 2, but for mean wind speed ($m\ s^{-1}$) (bold indicates significance at a probability greater than 90%; shading indicates significance at a probability greater than 99%).

	Annual	MAM	JJA	SON	DJF
South-central	**+0.2 $m\ s^{-1}$**	+0.1 $m\ s^{-1}$	**+0.2 $m\ s^{-1}$**	**+0.3 $m\ s^{-1}$**	**+0.2 $m\ s^{-1}$**
West	−0.1 $m\ s^{-1}$	**−0.2 $m\ s^{-1}$**	**−0.2 $m\ s^{-1}$**	0.0 $m\ s^{-1}$	+0.2 $m\ s^{-1}$
Interior	**−0.1 $m\ s^{-1}$**	−0.1 $m\ s^{-1}$	**−0.2 $m\ s^{-1}$**	−0.1 $m\ s^{-1}$	−0.1 $m\ s^{-1}$
Southwest	0.0 $m\ s^{-1}$	−0.1 $m\ s^{-1}$	**+0.2 $m\ s^{-1}$**	0.0 $m\ s^{-1}$	−0.1 $m\ s^{-1}$
Southeast	**−0.5 $m\ s^{-1}$**	**−0.4 $m\ s^{-1}$**	**−0.4 $m\ s^{-1}$**	**−0.5 $m\ s^{-1}$**	**−0.8 $m\ s^{-1}$**
Arctic	**+0.4 $m\ s^{-1}$**	**+0.3 $m\ s^{-1}$**	**+0.3 $m\ s^{-1}$**	+0.2 $m\ s^{-1}$	**+0.6 $m\ s^{-1}$**

Table 6. Percent change [defined as (1977–2001 minus 1951–75)/1951–75] in mean cloudiness (bold indicates significance at a probability greater than 90%; shading indicates significance at a probability greater than 99%).

	Annual (%)	MAM (%)	JJA (%)	SON (%)	DJF (%)
South-central	**+2**	+1	−1	+1	**+10**
West	−2	**−6**	**−3**	0	+4
Interior	**+2**	−1	−1	**+4**	**+7**
Southwest	**+1**	+2	0	−1	**+3**
Southeast	−1	−2	**−2**	−1	+1
Arctic	0	−1	−1	0	+4

spring, the times of the year when the lowest total precipitation is observed.

On an annual scale, total precipitation increased in all regions during period 2 with the exception of the Arctic. Snowfall also increased for the south-central, interior, and western regions. However, despite the increase in total precipitation, snowfall decreased overall for the southeast and southwest regions in period 2. An important point to note here is that mean winter temperatures in the southeast and southwest are near the freezing point, so the observed increase in mean winter surface air temperatures from period 1 to period 2 (from −1.9° to 0°C in the southeast; from −2.5° to −1.4°C in the southwest) would result in a higher percentage of the total precipitation falling as rain rather than as snow in period 2. The observed decrease in mean total precipitation and snowfall in the Arctic region agrees with the decreasing trend in precipitation in the western Arctic discussed by Curtis et al. (1998).

Another highlight of the results is the increase in snowfall from period 1 to period 2 during the autumn in all regions, again with the exception of the southeast. The slight increase in snowfall in the Arctic was seen in period 2 despite a decrease in total precipitation of 21%. This increase in mean total autumn snowfall, in conjunction with the decrease in mean total spring snowfall, leads to an interesting point. Earlier snowmelt and decreased snow cover area during the spring throughout the high latitudes has been presented, and its impacts and implications as evidence of climate change are summarized well in Serreze et al. (2000). They state that the common thread in the studies of spring snowpack area and snowmelt is the reduction in spring coverage and earlier snowmelt, despite seasonal and spatial differences in the other seasons. In regards to this study, the decrease in snowfall from period 1 to period 2 during the spring season in combination with the increased temperatures would certainly support that assertion. However, increases in autumn snowfall and the increase in overall snowfall complicate the argument. Results from Shulski et al. (2003) over the period of 1950 to 2001 have shown that snowpack in the western, south-central, and interior regions of Alaska is being established earlier in the autumn and, despite the earlier spring melt that has been observed, the length of the continuous snowpack season has actually increased in length by up to 4 days, based upon a best-fit linear regression trend.

4. Long-term temperature trends

One of the more significant effects of a sudden climate regime shift, and an issue of particular interest in the field of climate change research, is the effect that a shift has on long-term temperature trends. Chapman and Walsh (1993) and Serreze et al. (2000) showed that the increases in temperature over land areas in the Northern Hemisphere since the 1960s were high in several locations, including over Alaska. A study of 50-yr surface air temperature trends over Alaska (Stafford et al. 2000) showed significant increases in temperature in all seasons and regions, with the exception of the autumn in the interior. Our analysis of the Alaskan annual and seasonal temperature records throughout the last half of the twentieth century (1951–2001) presented in Table 8 found the largest temperature increases in

Table 7. Percent change [defined as (1977–2001 minus 1951–75)/1951–75] in total precipitation (TP) and snowfall (SF) (bold indicates significance at a probability greater than 90%, shaded indicates significance at a probability greater than 99%).

	Annual (%)		MAM (%)		JJA (%)		SON (%)		DJF (%)	
	(TP)	(SF)	(TP)	(SF)	(TP)	(SF)	(TP)	(SF)	(TP)	(SF)
South-central	**+8**	+6	+3	−14	+2	—	+9	+20	**+20**	+12
West	**+15**	+13	**+20**	−5	+3	—	**+24**	+9	**+33**	**+27**
Interior	+7	+14	+4	−8	+7	—	+7	**+21**	+12	**+20**
Southwest	**+26**	−5	**+31**	−16	**+11**	—	**+24**	+8	**+38**	−1
Southeast	+7	**−36**	+4	**−49**	+6	—	+8	−18	+7	**−34**
Arctic	**−16**	−9	**−43**	−26	−1	−24	−21	+3	**−39**	−13

TABLE 8. Change in mean temperatures (°C) from 1951 to 2001 based upon linear least squares regression trend line (bold indicates significance at a probability greater than 90%; shading indicates significance at a probability greater than 99%).

	Annual	MAM	JJA	SON	DJF
South-central	**+1.9**	**+2.8**	**+1.1**	+0.3	**+3.6**
West	**+1.6**	**+1.8**	**+0.9**	+0.2	**+3.5**
Interior	**+1.7**	**+2.6**	**+0.8**	−0.4	**+3.7**
Southwest	**+0.8**	**+1.5**	**+1.0**	+0.3	**+0.8**
Southeast	**+1.3**	**+1.9**	**+0.9**	+0.3	**+2.1**
Arctic	**+1.9**	**+2.1**	**+1.4**	+0.7	**+2.8**

the winter followed closely by the spring. We show results similar to Stafford et al. in that interior Alaska saw the greatest temperature increases; autumn was the exception, with a temperature decrease in the interior and little or no warming elsewhere.

Figure 5 shows a plot of the time series of mean annual temperature for all of the six climate regions of Alaska in this study. It shows the temperature increases that are stated in Table 8 when the full time series departures are analyzed with a least squares linear regression. Additionally, the figure shows the least squares linear regression trend lines for the two shorter periods, 1951–75 and 1977–2001. The two 25-yr periods on either side of the regime shift show widely different trends from the total time series for all of the regions, with the exception of the Arctic region. Given the cooling trends during both periods, as well as the statistically distinct nature of the temperature regimes during the two periods (section 3c), it appears as though the long-term (1951–2001) warming trend is largely a function of the singular regime shift in 1976.

Calculating the trend values for the two shorter time periods yields the temperature change values shown in Table 9, which, when compared with the values in Table 8, shows the significance of the regime shift upon the long-term trend. For the different climatic regions of Alaska, a warming of between +0.8° and +1.9°C has been observed in the mean annual temperature for the time period of 1951 to 2001, all of which are significant at a probability greater than 95%. This results in a warming rate of +0.16° to +0.37°C per decade. However, for the two shorter time periods, 1951–75 and 1977–2001, respectively, we generally observe the opposite trend: *cooling*. The trend in mean annual temperatures for subarctic Alaska for both 25-yr time periods was −0.26°C per decade. The only exception is in the Arctic, where Barrow saw a trend of −0.28°C per decade from 1951 to 1975 and a warming temperature trend of +0.52°C per decade since 1977.

These results demonstrate both the importance of the time period chosen and the importance of making distinctions between climate regions when examining change in surface air temperature. Also of note is the fact that the warming in the Arctic region from 1977 to 2001 was the only short-period mean annual temperature series with a trend that was statistically significant and clearly demonstrates that the Arctic region is under different influence than subarctic Alaska, which might go toward supporting the idea of polar amplification of global climate change and underscores the importance of care that must be given when discussing the climate of Alaska as a state. Seasonally, the temperature trends of the two short periods follow the pattern of the annual trends for the most part. The slight cooling during autumn seen from 1951–2001 in the interior region was −0.4°C. However, the analysis of the two short periods shows temperature change of −1.3° and −1.7°C, respectively. The increase in the mean autumn temperatures from period 1 to period 2 in the interior of +0.2°C (Table 3) seems to have lessened the extent of autumn cooling that may have been experienced without the upward temperature shift.

The trends of mean winter temperature in both periods 1 and 2 almost all show cooling, though none of the trends were statistically significant. In Alaska, no gradual temperature increase can be observed over the last half of the twentieth century, for which time period homogeneous meteorological data exist. A gradual increase might be expected from the observed steady increase of greenhouse gases. However, much of the observed increasing temperature trend in subarctic Alaska, when examined for the last half-century can be explained by the sudden regime shift that occurred in 1976.

The trends in the mean annual and seasonal surface air temperature from 1979 to 1997 are shown in Figs. 8 and 9 of Rigor et al. (2000) and trends from 1977 to 2001 are shown in Fig. 8 of Jones and Moberg (2003) over hemispheric and global scales, respectively. When the trends over Alaska are examined in these other investigations, trends similar to those found during period 2 in this study are seen. The strongest positive trends in the spring occur in the Arctic region for Rigor et al. (2000) and are verified in our results. Likewise, Rigor et al. show the strongest summer warming over the south-central region, which is also found at a 90% significance level in our results. Jones and Moberg (2003) show the strongest cooling trends over Alaska in the autumn and winter, which is confirmed in our results. When these trends are compared to those of Chapman and Walsh (1993), Serreze et al. (2000), and Stafford et al. (2000), who show strongly positive trends

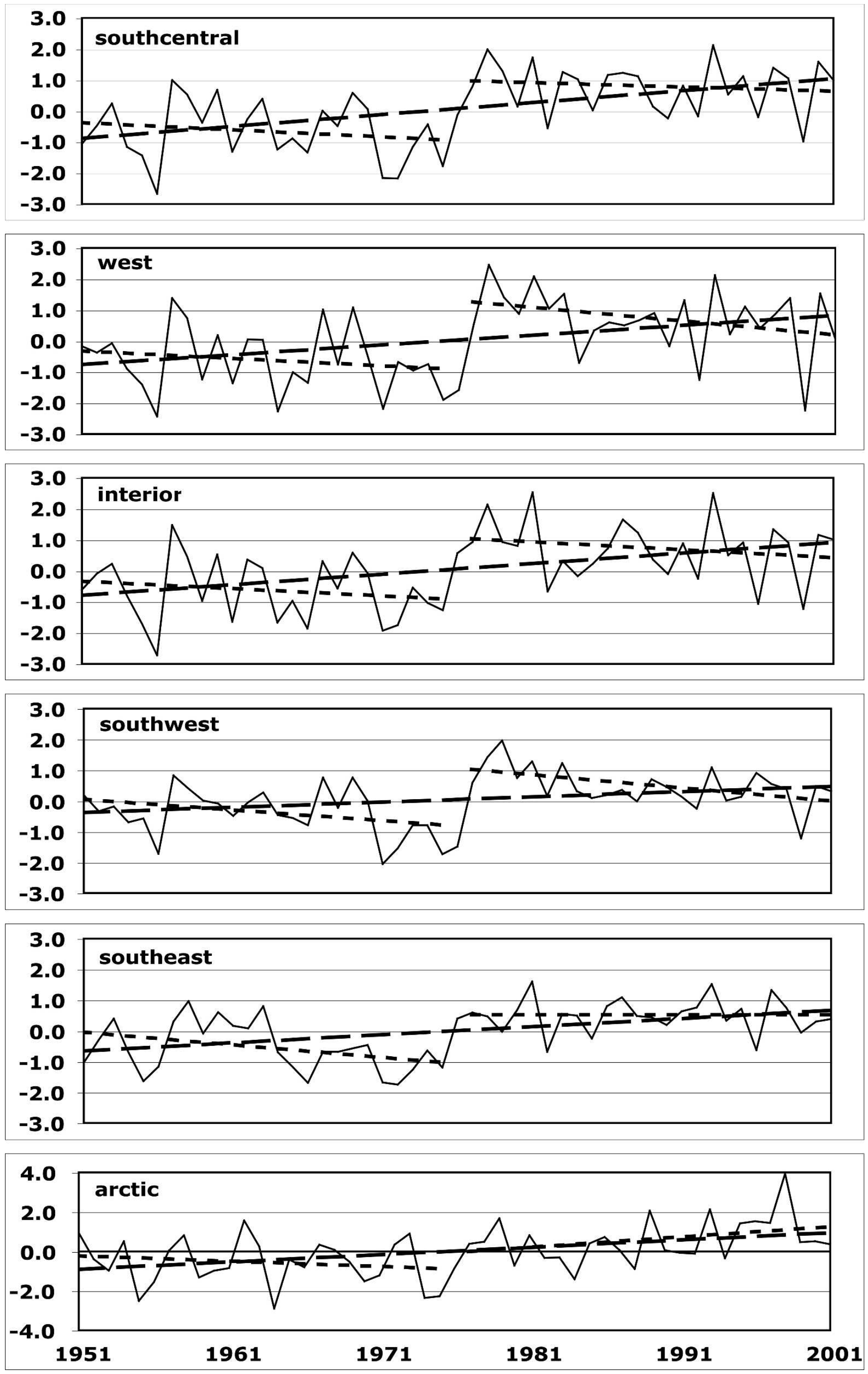


FIG. 5. Time series of the mean annual departure from average temperature of the six Alaska climate regions from 1951 to 2001. The least squares linear regression lines for 1951–2001, 1951–75, and 1977–2001 are included. Note that the scale is uniform except for the Arctic region.

over Alaska for their study periods (1961–90, 1966–95, and 1949–98, respectively), it can be seen that examining a trend in temperatures that straddles the 1976 shift generally yields an artificially high rate of warming over Alaska.

5. Discussion

The increase in temperature, especially during the winter and spring, can be seen as a result of the interrelation of the changes seen in many of the other dif-

TABLE 9. Change in mean temperatures (°C) from 1951 to 1975 [period 1 (P1)] and 1977 to 2001 [period 2 (P2)] based upon linear least squares regression trend line (bold indicates significance at a probability greater than 90%).

	Annual		MAM		JJA		SON		DJF	
	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
South-central	−0.6	−0.3	−0.1	+0.1	−0.3	**+0.7**	−1.0	−0.6	−1.1	−1.3
Interior	−0.6	−0.6	+0.1	+0.3	+0.3	+0.3	−1.3	−1.7	−2.0	−1.1
Southeast	−1.0	0.0	−0.3	−0.4	−0.6	+0.1	−1.1	−0.3	−2.0	+0.3
Southwest	−0.8	−1.0	−0.7	−0.9	−0.8	−0.4	−0.7	−0.7	−1.3	−1.7
West	−0.6	−1.1	−1.4	0.0	−0.3	−0.7	−1.2	−0.8	−0.5	−2.1
Arctic	−0.7	**+1.3**	−0.9	**+2.4**	−0.6	**+1.0**	−1.8	+2.1	−0.2	−0.2

ferent meteorological fields. The primary atmospheric "thumbprint" of importance to Alaska is the variation in the depth and location of the Aleutian low, to the southwest of the mainland and the analog high pressure center over western Canada.

Chen and Yoon (2002) showed that increases in the winter blocking high pressure pattern over western Canada linked with PDO variability have altered the storm track of Pacific cyclones, increasing the frequency with which these storm centers traverse into south-central and central Alaska. Typically, storms come ashore over south Alaska. The deepening of the Aleutian low is usually accompanied by a higher-than-normal pressure over western Canada and southeastern Alaska. Indeed, the whole of the Alaskan mainland and southwest experienced a net decrease in pressure while the southeast region witnessed an increase in pressure. Furthermore, a study by Graham and Diaz (2001) displayed an intensification of cyclones during the winter in the North Pacific and found a significant decrease in the mean sea level pressure of winter cyclones and concurrent increases in vorticity and wind speed around 1976.

During the winter, the temperature in Alaska is not influenced to any great extent by solar radiation due to short daylight hours and the low sun elevations experienced at such latitudes, as well as a high surface albedo. Longwave radiational cooling greatly influences the surface air temperature. Wendler and Jayaweera (1972) found that the infrared radiation loss under clear skies plays a very important role in the development of the surface-based temperature inversions, which are common in Alaska. The observed increase in cloudiness results in increased back radiation for the atmosphere, which leads to a much warmer surface temperature. In addition, the observed increases in the mean wind speeds increase the likelihood of the destruction or weakening of the surface inversion due to forced mixing, likewise resulting in warmer surface air temperatures. Conversely, the observed increases in sea level pressure experienced during the summer and autumn lend themselves to decreases in cloudiness and increased solar radiation, resulting in a higher temperature. The changes in these meteorological variables and their effect upon surface temperatures can all be related back to variation in the pressure field.

The general annual cycle for many of the meteorological variables can be deduced from the seasonal values. However, even within seasons, substantial differences can occur from month to month in the behavior of the anomalies. A previous study (Hartmann and Wendler 2003) demonstrated that the manifestations of the 1976 regime shift within the temperature were greatest in January, where the mean temperature for the 10 yr after the shift was as much as 10°C higher than for the 10 yr previous to 1976, while increases in December and February mean surface air temperatures were generally only one-third to one-half of that.

In this investigation, January is again seen to contribute the most to the overall changes observed during the winter season, with December and February sometimes showing changes that are quite different than those seen in January. Figures 6 and 7 show the difference in mean monthly surface air temperature and mean monthly sea level pressure from period 1 to period 2 from the regional station data as well as seen in the NCEP–NCAR reanalysis for the months of November through March. It can be seen that the months with the greatest increase in temperature (January and March) were also the months that had the greatest overall decrease in sea level pressure. November had very little in the way of change of both temperature and sea level pressure. The magnitude of the decrease in the pressure over Alaska in January and March is observed to have been much more pronounced than in December and February, and correspondingly, the temperature increases follow suit. The location of the greatest pressure difference is also of interest, being much farther to the east in January and March than in December and February. It should also be noted that during December, the southeast region saw an increase in mean SLP of more than 2 hPa, and its temperature increase was

	Nov	Dec	Jan	Feb	Mar
SC	+0.8	**+2.8**	**+3.9**	**+2.0**	**+3.2**
Wst	+1.0	**+3.1**	**+2.4**	**+3.1**	**+2.3**
Int	+0.6	**+2.8**	**+4.5**	+1.9	**+2.5**
SW	+0.2	**+1.0**	**+0.9**	**+1.4**	**+1.9**
SE	+0.6	+1.1	**+2.8**	**+1.3**	**+1.8**
Arc	+0.4	**+1.5**	+1.3	**+3.3**	**+1.7**

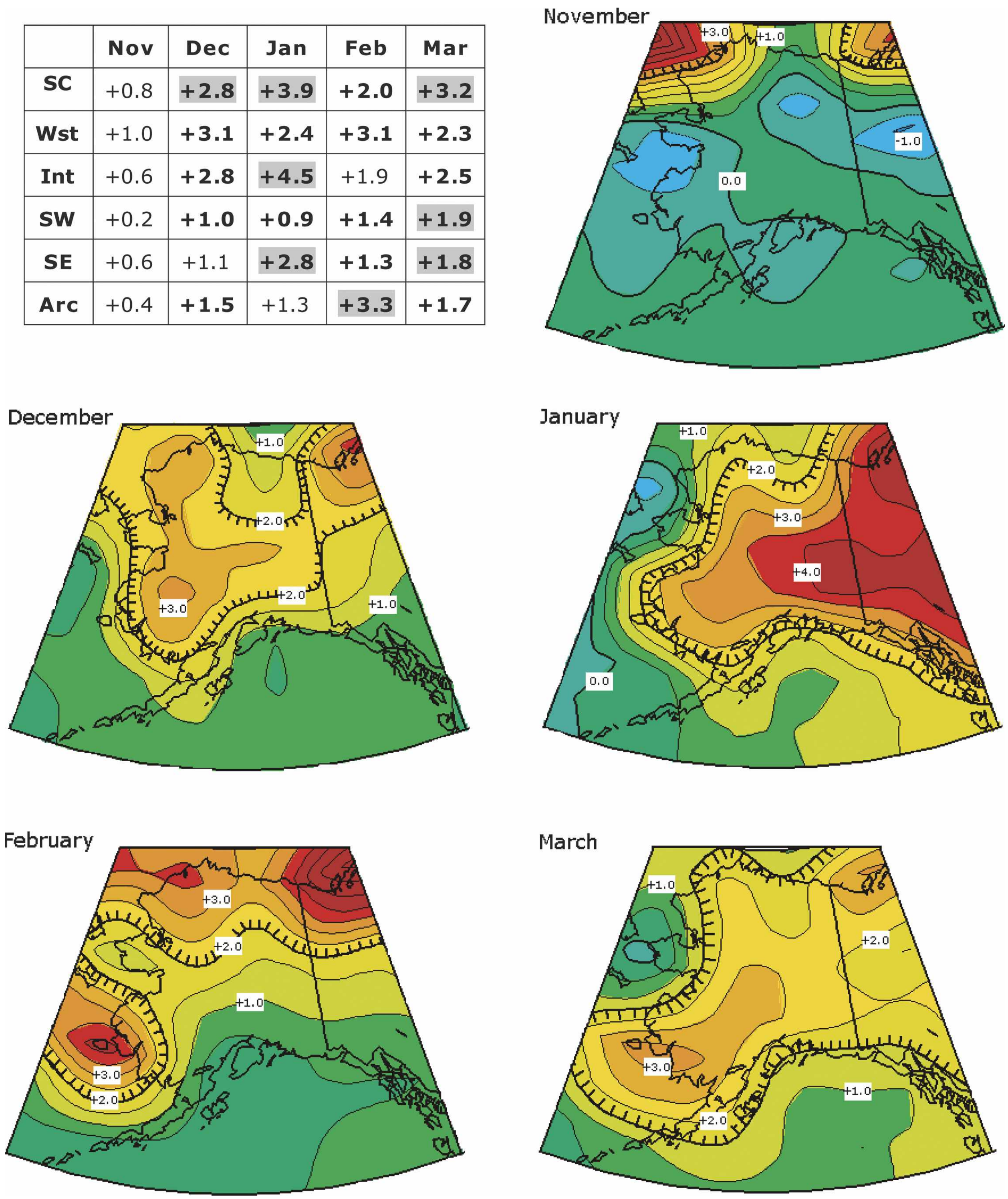
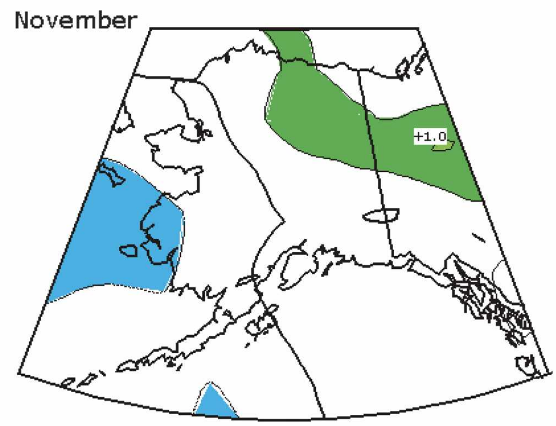


FIG. 6. Difference (1977–2001 minus 1951–75) of mean monthly surface air temperature (°C) for Nov to Mar from station data (in table) and from the NCEP–NCAR reanalysis. The hatched contour indicates significance at a level greater than 90% (SC: south-central, Wst: west, Int: interior, SW: southwest, SE: southeast, and Arc: Arctic).

	Nov	Dec	Jan	Feb	Mar
SC	-0.8	+0.1	**-5.1**	+0.2	**-2.3**
Wst	-1.0	-2.4	**-6.3**	-0.8	**-2.6**
Int	-0.6	-0.4	**-6.1**	-0.1	-1.9
SW	-0.6	-1.6	**-5.8**	-0.9	**-3.7**
SE	+0.3	**+2.7**	0.0	-0.4	0.0
Arc	+0.3	+0.4	**-4.1**	-1.4	-0.7



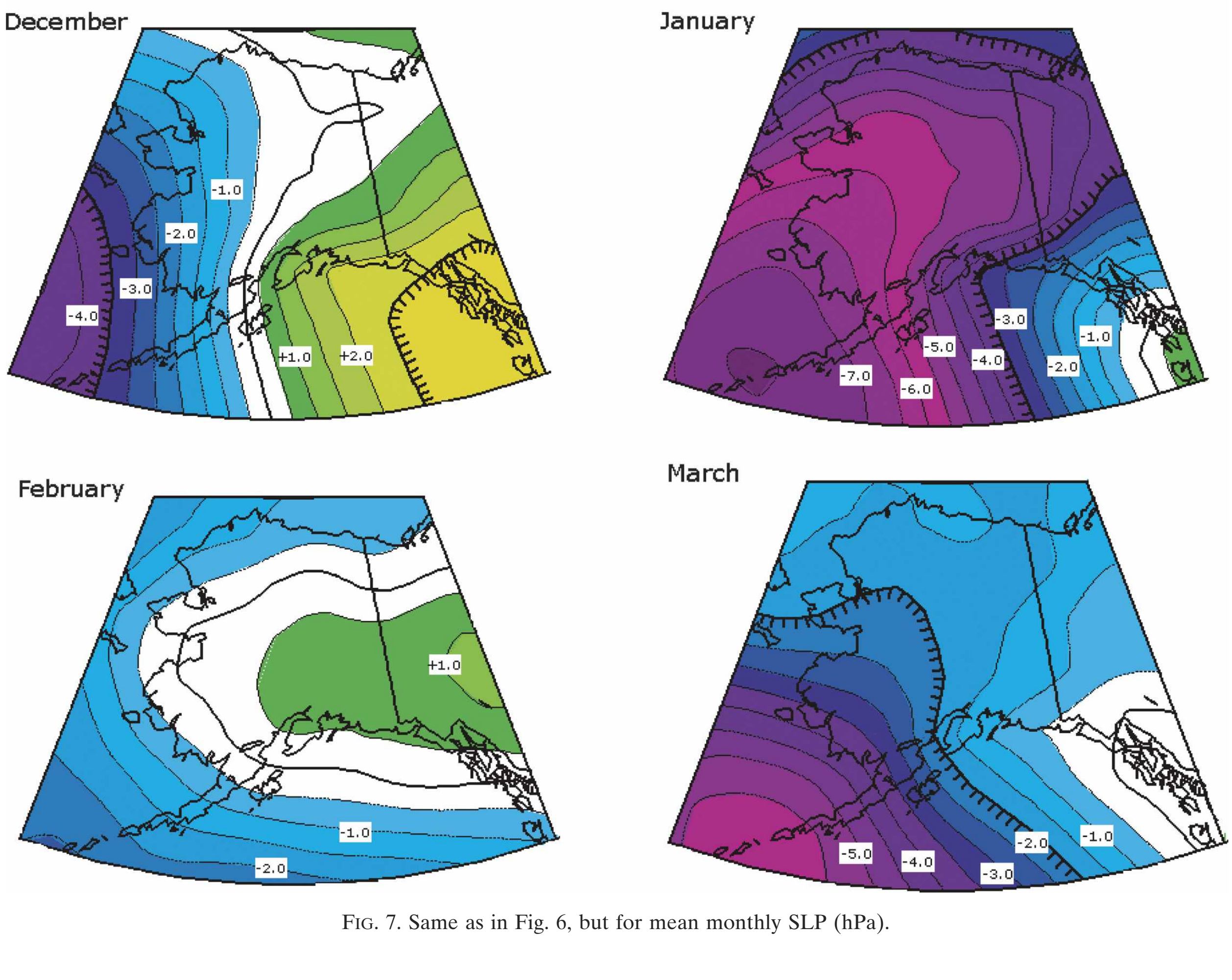


FIG. 7. Same as in Fig. 6, but for mean monthly SLP (hPa).

roughly one-third that of the increase experienced in the interior.

The disparity in changes from month to month within the same season is seen in other variables as well. The percent change of cloudiness showed increases from 1%–10% when examined for the winter season overall (Table 6). The greatest seasonal increase was seen in the south-central, but as can be seen in Table 10, the south-central saw widely different changes from month to month, with January again seeing the greatest change. Likewise, the interior region had an overall seasonal increase in cloudiness of 7%, with December

TABLE 10. Percent monthly change [defined as (1977–2001 minus 1951–75)/1951–75] in mean cloudiness (bold indicates significance at a probability greater than 90%; shading indicates significance at a probability greater than 99%).

	Nov	Dec	Jan	Feb	Mar
South-central	+3.6%	**+12.0%**	**+20.4%**	−0.5%	+1.5%
West	−4.7%	+8.6%	+6.3%	−4.6%	−8.6%
Interior	+4.5%	+6.3%	**+15.4%**	−1.2%	−0.7%
Southwest	+0.5%	+0.8%	**+6.6%**	+2.0%	+3.0%
Southeast	+0.6%	−1.2%	+5.6%	−1.8%	−1.3%
Arctic	−7.4%	+0.2%	+6.2%	+6.8%	+1.6%

showing an increase of 6.3% and February showing a decrease of 4.6%. Again, January is exceptional with a 15.4% increase in cloudiness. Likewise, in Table 11, subseasonal response in the frequency of occurrence of wind directions are demonstrated. Of note are the strong relative increases in the occurrence of easterly and southerly winds in the south-central and interior regions. Details of the changes in pressure and the resulting dynamic effects on advection, radiation, and thus temperature on the monthly level can sometimes be lost in studies that concentrate on the seasonal time scale.

The PDO index displayed a transition into the negative phase in 1999 but has rebounded to positive phase in 2002 and 2003. It is still unsure whether 1999 heralded another regime shift, and it will require a period of time to determine if the phase of the PDO has in fact changed, just as it took time for the full impact of the 1976 shift to be realized. Recent studies by Greene (2002), Minobe (2002), Chavez (2003), and Peterson and Schwing (2003) have discussed the possibility that the cycle has indeed shifted back to negative. However, Bond et al. (2003) suggest that another indicator may be at play in addition to the PDO and that it may have been governing the climate of the North Pacific since 1999. They showed an anomalously deepened Aleutian low in the end of our specific period (1999–2001), which has corresponded with a negative instead of positive PDO index. This current debate presents the fact that more work is needed to further define North Pacific climate indices and implications. If the phase does indeed continue toward negative PDO and that phase is persistent, the result of a weaker Aleutian low would likely move the state under a circulation regime similar to that of the 1950s to early 1970s, with substantial surface climate change from the present regime, which would include much colder winter and springtime temperatures and cooler temperatures overall.

Also, it is important to note that the Pacific decadal oscillation is not the only mode of variation that has influence upon the atmosphere–ocean system in the area of Alaska. ENSO, the AO, and other indices also have impact and the interaction of all of these modes with each other, which operate on varying time scales, complicates the matter of climate variability. Furthermore, recent research on the ENSO-forced variability of the Pacific Decadal Oscillation was published by Newman et al. (2003). They suggest that the long-lasting positive PDO period (1977–1998) may have been a result of the warm events in the Tropics and the slight dip in PDO values (1999–2001) could have been an integration of that period's cool east Pacific sea surface temperatures.

TABLE 11. Percent monthly change [defined as (1977–2001 minus 1951–75)/1951–75] in the frequency of occurrence of winds by direction (bold indicates significance at a probability greater than 90%, shaded indicates significance at a probability greater than 99%) (SC = southcentral, Wst = west, Int = interior, SW = southwest, SE = southeast, Arc = arctic).

SC	Nov	Dec	Jan	Feb	**Mar**	Wst	Nov	Dec	Jan	Feb	Mar
North	−2	**−6**	**−8**	+2	−3	North	−8	**−16**	−7	−6	**+15**
East	**+36**	**+53**	**+47**	**+41**	**+49**	East	+8	**+28**	+3	**+19**	+7
South	+3	+19	**+22**	**−15**	−9	South	+13	+8	+4	−11	−18
West	+4	+2	+6	0	+6	West	−11	**−24**	0	**−21**	**−19**
Int	Nov	Dec	Jan	Feb	Mar	SW	Nov	Dec	Jan	Feb	Mar
North	−3	−6	−6	−2	0	North	+8	−11	+1	+6	+4
East	+3	**+14**	**+10**	**+14**	**+21**	East	+1	**+28**	**+24**	**+29**	**+34**
South	−2	+4	+11	−7	+5	South	−8	**+20**	0	−5	+4
West	−5	−11	−2	−11	**−11**	West	+3	−11	**−11**	**−18**	**−20**
SE	Nov	Dec	Jan	Feb	Mar	Arc	Nov	Dec	Jan	Feb	Mar
North	**−23**	**−21**	**−28**	−6	**−21**	North	−20	**−34**	−19	**−24**	−11
East	−2	**−6**	−2	−1	−2	East	+15	**+46**	**+23**	+11	+7
South	−6	−11	−4	−13	−2	South	+4	**−30**	−20	+5	−9
West	+5	+5	+12	−7	+8	West	**−34**	−23	−14	0	+3

6. Conclusions

The interrelation of the variation in the sea level pressure field as driven by Pacific Ocean variability and its effect upon the temperature field observed in the different regions of Alaska is connected in several obvious ways:

1) The intensification of the Aleutian low during the winter and spring and the resulting flow yields an increase in the advection of more heat to the higher-latitude regions of Alaska, at times when solar radiation is very low.
2) Additional moisture is also advected into high latitudes resulting in increased cloudiness and precipitation. During the winter, increases in cloudiness result in increased longwave back radiation and a more positive radiation balance. Decreased cloudiness during the summer and autumn would result in more incoming shortwave radiation.
3) The increase in the frequency of higher wind speeds, along with the more positive radiation balance results in a decrease in the intensity and frequency of the surface-based temperature inversion, which plays an important role in the temperature regime of Alaska during the winter and spring.
4) The increase in winter and spring mean temperatures in the southeast and southwest regions where the mean temperature is near the freezing point results in a decrease in total snowfall, despite an increase in the total precipitation.

The influence of the shift in Pacific Ocean variability on temperature is more pronounced in the continental regions of Alaska (south-central, interior, and west) than in the maritime regions (southwest and southeast). The Arctic, while it showed some response, is most likely governed more by Arctic variation (i.e., the Arctic Oscillation), and the interplay of Pacific and Arctic circulation variation and its effect upon Alaska is a possible subject for further study.

Finally, the use of trend line analysis in climate change research depends greatly upon the time period studied, and results can be biased when an abrupt climate change is observed during the study period. It has been demonstrated that the sudden changes of 1976 observed in Alaska have a profound effect on temperature trends. Shifts and multiyear anomalies result in temperature trends over periods that can differ substantially (even in sign) from the trend of the full time period. The cooling trend throughout much of Alaska since 1977, though not statistically significant, is in contrast to some theories regarding the atmospheric warming in an increasing greenhouse gas environment.

Acknowledgments. This work was supported by State of Alaska funding for the operation of the Alaska Climate Research Center. The authors would also like to thank Dr. Martha Shulski and Dr. John Walsh, both of whom read the manuscript and provided valuable insight and contributions.

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