Theor. Appl. Climatol. 67, 33–44 (2000)

Theoretical
and Applied
Climatology

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Temperature and precipitation of Alaska: 50 year trend analysis

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With 8 Figures

Received August 30, 1999
Revised March 21, 2000

Summary

Temperature and precipitation records from 1949 to 1998 were examined for 25 stations throughout the State of Alaska. Mean, maxima, and minima temperatures, diurnal temperature range, and total precipitation were analyzed for linear trends using least squares regressions. Annual and seasonal mean temperature increases were found throughout the entire state, and the majority were found to be statistically significant at the 95% level or better. The highest increases were found in winter in the Interior region (2.2 °C) for the 50 year period of record. Decreases in annual and seasonal mean diurnal temperature range were also found, of which only about half were statistically significant. A state-wide decrease in annual mean diurnal temperature range was found to be 0.3 °C, with substantially higher decreases in the South/Southeastern region in winter.

Increases were found in total precipitation for 3 of the 4 seasons throughout most of Alaska, while summer precipitation showed decreases at many stations. Few of the precipitation trends were found to be statistically significant, due to high interannual variability. Barrow, our only station in the Arctic region, shows statistically significant decreases in annual and winter total precipitation. These findings are largely in agreement with existing literature, although they do contradict some of the precipitation trends predicted by the CO_2-doubling GCM's.

1. Introduction

In recent decades, increasing air temperature has been found throughout much of the Northern Hemisphere; it has been most pronounced in the Arctic and Sub-Arctic regions (IPCC, 1992). This rate of climate change at higher latitudes has been attributed in part to increased levels of greenhouse gases (Environment Canada, 1995), and is predicted by the General Circulation Models (e.g., Weller et al., 1995). Support for these predictions is provided by Chapman and Walsh (1993), while Stone et al. (1992) state for a shorter time period (1958–1986) that a potential greenhouse warming signal is not yet distinguishable from natural interannual climate variations.

Decreases were found in precipitation during the past few decades over northern Alaska and the Arctic (Curtis et al., 1998; Warren et al., 1999); increases in temperature have been detected over northern latitudes by Weller et al. (1995); further Walsh and Chapman (1990) found a rise in Arctic sea level pressures. Such climate changes could have potentially severe consequences for many aspects of life at high latitudes. Fluctuations in sea ice, found by Chapman and Walsh (1993), could have a substantial impact on the fishing industry and local wildlife. Likewise, permafrost thawing (Osterkamp et al., 1987) could cause many engineering difficulties, in addition to altering the ecological balance in affected areas (Weller et al., 1995). Although many recent temperature and precipitation trend studies have focused on the entire Arctic or Northern Hemisphere (Wallace et al., 1996; Chapman and Walsh, 1993; Karoly,

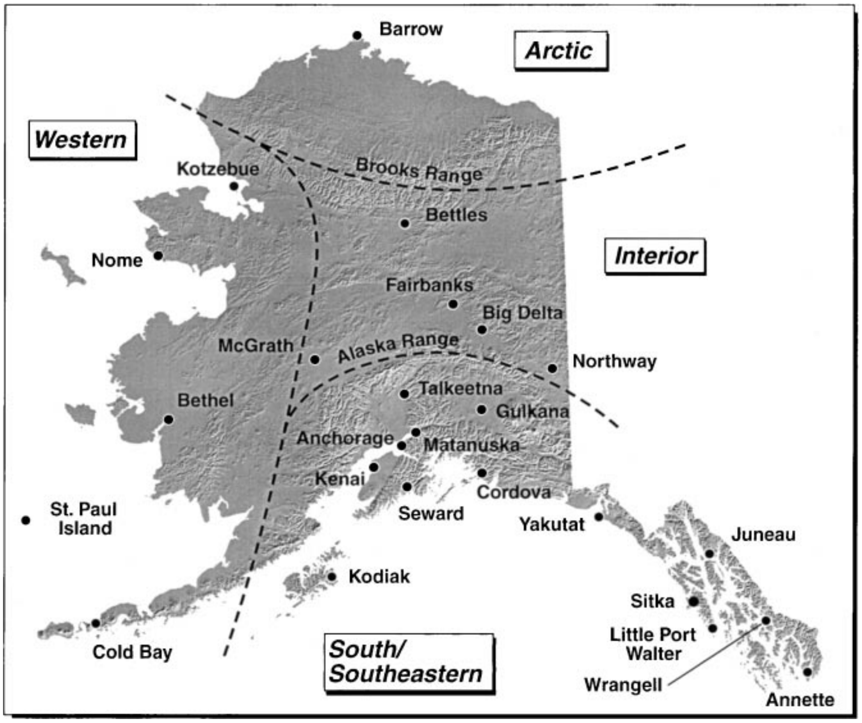

Fig. 1. Meteorological stations, climatic zones and aereal relief of Alaska

1989), or on small regions within Alaska (Magee et al., 1999; Curtis et al., 1998), our study examines the trends for the entire State of Alaska.

Alaska encompasses 1.5 million km^2 of land (Searby, 1968) and spans approximately 20 degrees of latitude (Fig. 1). Consequently, its climate is dominated by large seasonal variations in the amount of solar radiation received at the surface. Local topography and proximity to oceans are also important factors that determine Alaska's climate (Benson et al., 1983). Additionally, throughout the year, several permanent and semi-permanent pressure systems of varying intensity alter Alaska's atmospheric circulation. These systems include the Arctic and Siberian highs, which affect the northern and interior portions of the state, and the Aleutian low (Overland et al., 1999), which affects the southern and western portions (Martyn, 1992). The El Niño-Southern Oscillation (ENSO) has also been shown to cause large interannual variation in Alaska's climate (Hess et al., in press). Due to these varying conditions and influences throughout the state, we have divided Alaska into four climate regions: South/Southeastern, Western, Interior, and Arctic.

The Arctic region is the coldest and the driest, with a Köppen classification of ET and frequent high winds. Snow accounts for approximately 75% of the total annual precipitation in the Arctic region (Searby, 1968). In the Interior (Sub-Arctic) region, classified as Dfc, the summer temperatures can reach as high as 30 °C or higher, while the winter temperatures are frequently below −40 °C with common strong shallow inversions. The Western region is transitional between continental and coastal, and is influenced by cold interior air, fluctuations in sea ice extent, and low pressure systems from the Bering Sea. Severe winters bring high winds, and summer temperatures rarely reach higher than 10 °C. For most of Alaska, precipitation is higher in summer and autumn than in winter and spring. The reverse is true in portions of the South/Southeastern region, although the region is generally wet all year. The coastal/maritime climate moderates both winter and summer temperatures in this region, and station climate classifications within the region range from Cfb to Dfc.

Our regional divisions, shown in Fig. 1, were based primarily on latitude, longitude, and geographic boundaries. Two mountain ranges, the Alaska and Brooks ranges, provide the principle boundaries between the South/Southeastern and Interior regions, and between the Interior and Arctic regions, respectively. Somewhat less natural was the definition of the fourth, the Western region, which is not based on clearly established topographic boundaries. This region is affected at times by the continental climate of Interior Alaska, at other times by the maritime climate of the adjoining Bering Sea. However, statistical analyses of the temperature showed that it did not fit well in either of two climatic zones, the South/Southeastern and Interior regions. These regions were more uniform in regard to temperature without the Western stations; hence, it deserved to be a zone by itself. Now, cross correlations between the stations for each climatic zone gave the relatively high mean annual values between 0.8 and 0.9. For all regions, the stations were most uniform in winter, and least in summer. This is to be expected given the increased geographical variability of temperatures during the summer and fall, when solar radiation and cloudiness are primary factors, as opposed to winter and spring, when there is little or no solar radiation throughout the state and cloudiness is at an annual minimum (Dissing and Wendler, 1998). Snow cover also contributes to the uniformity of the temperatures during the winter season. The Arctic region was not included in this analysis, given the fact that Barrow is our only Arctic station. Barter Island, the other long-term meteorological station in the Arctic, ceased operating in 1988, and hence is not included in our study. Intercomparing the established climatic zones, the interior of Alaska displayed the least degree of temperature variation between the stations. This is understandable, as this area is sheltered from both the South (Alaska Range) and North (Brooks Range), hence the climate is more uniform.

Figure 2 is a contour plot of the mean annual air temperatures for Alaska and shows the 25 stations used in this study. Over the oceans, lines were extrapolated, given the absence of oceanic data. It should be noted that none of the stations are at high altitude, thus alpine influences are eliminated in the figure. The isotherms run largely along lines of latitude and are approximately parallel the two mountain ranges, lending support to our choice of regional divisions.

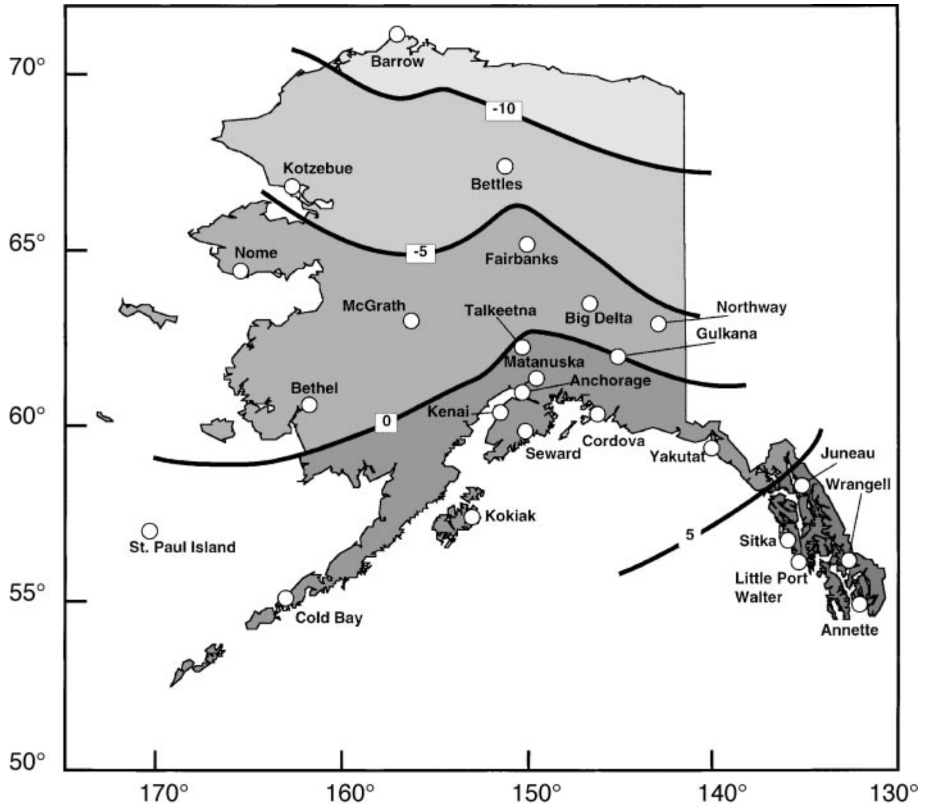

Fig. 2. Mean annual air temperatures (°C) for the State of Alaska based on the 25 study sites. Note that none of the stations are mountainous (highest elev. Northway at 527 m), thus eliminating alpine influences in the figure

2. Analyses

2.1 Data sets

Temperature and precipitation data sets used in this study were compiled from the following sources: Alaska Climate Research Center, NOAA National Data Center, National Weather Service Forecast Office, Western Regional Climate Center, and NOAA Local Climatological Data. Our data sets represent the 50 year period from 1949 through 1998. The 50 year period of record represents the longest period for which relatively good quality data are available for a large number of stations. Of course, some location and instrumentation changes have occurred throughout this period; nevertheless, trends in climatic variables within regions were consistent, lending trust to the quality of the data.

Our choices for the 25 stations were based on the quality and continuity of the data. Data were gathered in the form of monthly maxima, minima and mean temperatures, and monthly total precipitation (rain plus water equivalence of snow). For temperature, no month was used if more than ten days of data were missing (no more than three days for the transitional months: March, April, September, and October, which could have rapid short-term warming or cooling). For precipitation, no month was used if even one day was missing. In the final temperature data set, less than 1% of the months were missing (with 2% being the highest value for a single station), and approximately 1% were missing from the precipitation record (with 7% being the highest value for a single station). In the case of missing temperatures, the mean value for the month over the period of record was calculated and inserted in place of the missing value. Missing precipitation data were treated somewhat differently. A nearby station was used as a proxy by calculating the mean difference between the stations for the month in question, adjusting the value for the proxy site accordingly, then inserting it in place of the missing value.

2.2 Variables and statistics

Several climatic variables were analyzed in this study: mean, maxima, and minima temperatures, diurnal temperature range, and total precipitation. Temperature and precipitation are two major climate variables which display a relatively high reliability and availability in climatic records. Monthly values were averaged or summed (for temperature and precipitation, respectively) to arrive at seasonal and annual values. Seasons were defined using the standard meteorological definition (i.e. winter = Dec–Feb, spring = Mar–May, etc.).

For each variable, seasonal and annual time series graphs were plotted for our 50 year period of record. A linear least-squares regression line was then fitted to each time series, and the change was calculated from the end points of the regression line. Throughout this study, ΔT_{Mean} refers to the change over the past 50 years in the mean temperature, DTR refers to the change over time in diurnal temperature range, and ΔP refers to the change over time in the total precipitation. In the case of the precipitation, percent changes ($\Delta P_{\%}$) were also calculated. Finally, two-way analyses of variance (pure model I ANOVA's with replication) were carried out to check for seasonal and/or regional effects in ΔT_{Mean}, DTR, and $\Delta P_{\%}$. The Arctic region was omitted from the ANOVA's due to its lack of multiple sites. For the sake of establishing equal sample sizes among the regions, five stations were randomly sampled from the 14-station South/Southeastern region. Three different samples were taken, and the tests were repeated for each sample.

3. Results

3.1 Mean temperature

Figure 3 is a plot of the mean annual maxima, minima, and mean temperatures for Talkeetna, AK. Notice that the increases are generally linear over time, with scatter due mainly to interannual variability. The increase in mean temperature shown here is significant at the 99.9% level. Note that the temperature increase of the minima is more pronounced than the maxima, a result expected due to increased greenhouse gases. Talkeetna is presented as an example, and in Figs. 3 and 4 contour plots for all of Alaska are presented, showing the ΔT_{Mean} annually and seasonally, respectively. Figure 4 shows that the increases are highest in the interior of the state (2.2 °C), with a secondary but less extensive high

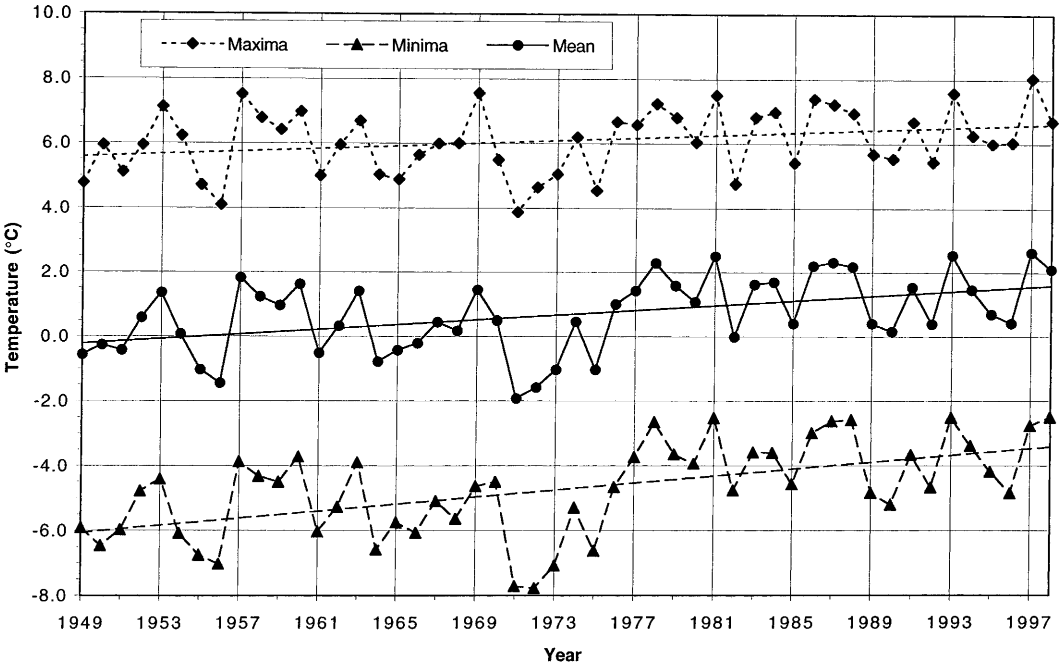

Fig. 3. Annual mean maxima, minima, and mean temperatures for Talkeetna, AK from 1949 to 1998 with linear least squares regression lines. Maxima and minima trend lines are converging, resulting in a decreasing diurnal temperature range. Temperature increase and decrease in range are both statistically significant at the 99.9% level

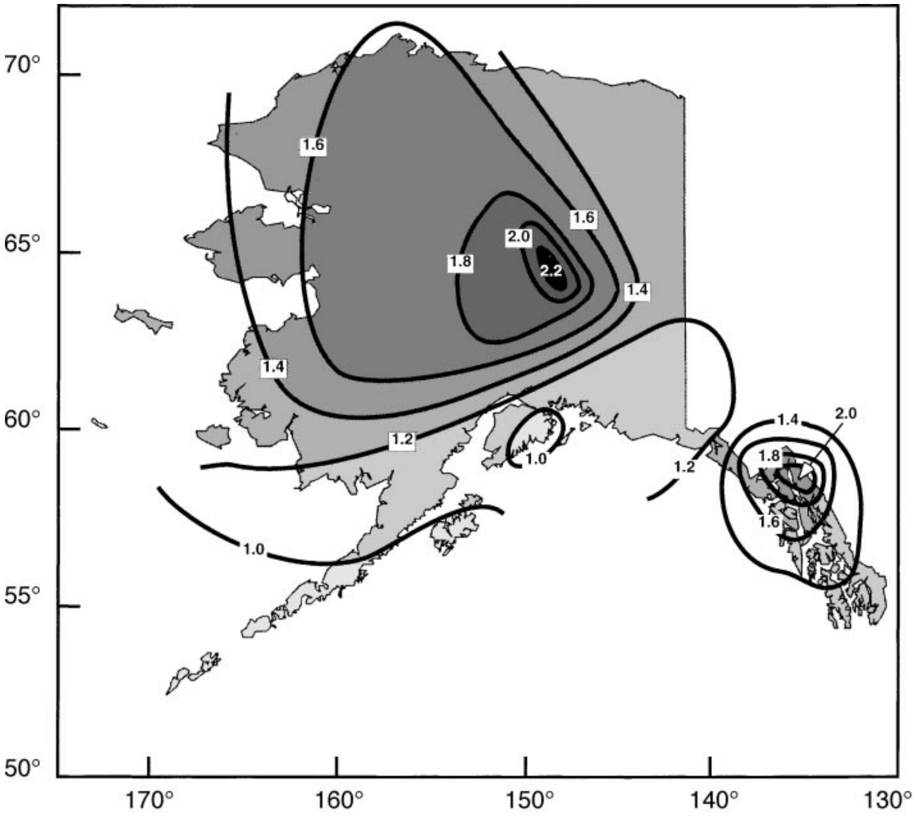

Fig. 4. ΔT_{Mean} (°C) for annual temperature over the 50 year period from 1949 to 1998. Highest increases are found in the Interior region (2.2 °C), with a secondary high point in the South/Southeastern region (2.0 °C). Contours are derived using a simple interpolation between stations and does not consider terrain (i.e. land or water)

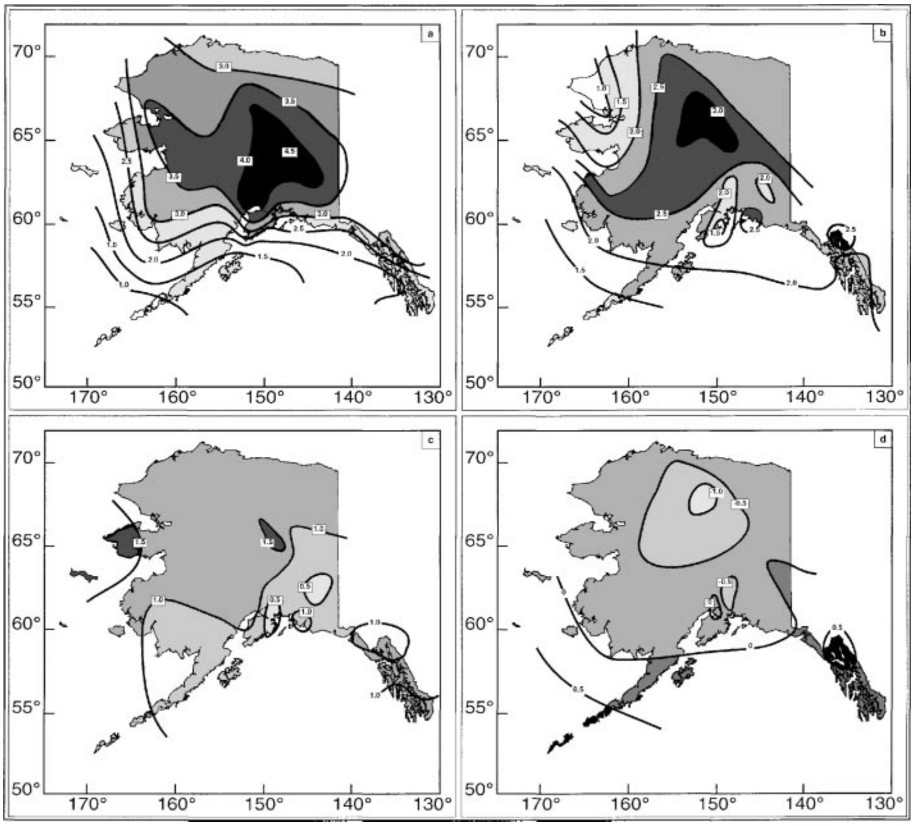

Fig. 5. As with Fig. 3, but for seasonal temperatures. Winter (**a**) shows the highest increases, followed by spring (**b**) and summer (**c**). Negative values (decreases in temperature) are shown for autumn (**d**)

in the southeast (2.0 °C). The average value for the Interior region was 1.9 °C, while the Western region showed the lowest average increase of 1.3 °C. Similar trends are shown on the winter and spring maps (Fig. 5a and 5b): winter, 4.1 °C and 2.2 °C, spring, 2.9 °C and 1.7 °C, for Interior and Western regions, respectively. In the summer season (Fig. 5c), the South/Southeastern region displays the lowest average temperature increase (0.9 °C), but the ΔT_{Mean} is low throughout the entire state. Autumn (Fig. 5d) is the only season in which negative temperature trends are found, and all of the trends were of very small magnitude. The state-wide average ΔT_{Mean} for autumn is -0.2 °C.

Significance tests of the individual regression lines for each station yielded mixed results. In the case of mean annual temperature (Fig. 4), all but one of the stations showed a significant increase at the 95% level or better. St. Paul Island was the exception, but this is not surprising due to the extremely strong oceanic moderation of the climate there. For the winter season, all but four of the sites showed significant regression lines (exceptions were Kodiak, Wrangell, Cold Bay and St. Paul Island, which are all relatively coastal). All stations showed significant regressions for spring, except for the Western region where none of the regression lines were significant. For summer, approximately 66% of the stations showed significant regression lines, and the non-significant sites were scattered throughout the South/Southeastern and Interior regions. None of the stations showed significant regression lines for autumn, most likely due to shallow slopes, rather than excess scatter in the data. A two-way ANOVA of the ΔT_{Mean} showed a significant (99% level or better) seasonal effect as well as a significant regional effect. The interaction term was also significant at the same level. Each of the three repetitions of the ANOVA (as described above) yielded the same results, showing homogeneity among the stations in the South/Southeastern region.

3.2 Diurnal temperature range

By subtracting the mean monthly minima temperatures from the corresponding maxima temperatures, then averaging them annually and

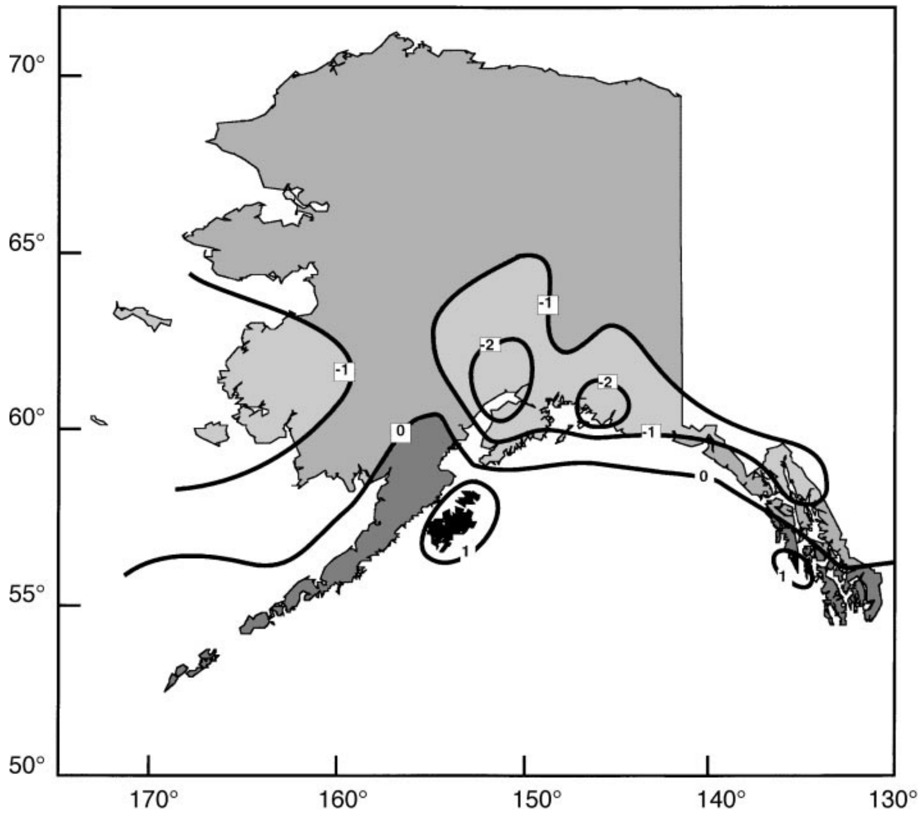

Fig. 6. DTR (°C) for winter over the 50 year period form 1949 to 1998. The greatest decrease can be seen in the South/Southeastern region (−2 °C), but increases are also seen in the same region

seasonally, we obtained mean diurnal temperature ranges. These ranges were tested in the same manner as the mean temperatures. In Fig. 3, notice that both the maxima and minima temperatures are increasing, but that the minimum temperature is increasing slightly more rapidly than is the maximum. Consequently, the annual mean diurnal temperature range for Talkeetna, AK is decreasing with time. This decrease is significant at the 99.9% level. As with mean temperature, DTR was calculated annually and seasonally for each of the 25 stations. Winter displayed the most pronounced decrease in diurnal temperature range (Fig. 6). From the DTR at the individual stations, regional means were calculated (Table 1).

Winter is the only season in which all regions showed a decrease in diurnal temperature range; the South/Southeastern region had the highest value, with a decrease of 1.8 °C. However, Fig. 6 shows that this region is not uniform, and for Kodiak- and Baranof- Islands, the diurnal temperature range increased. For all other seasons, as well as for the annual values, there are both positive and negative DTR values present among the regions. The state-wide annual average DTR is −0.3 °C.

Upon testing the regression lines for significance, we found that only about half of the stations showed significant trends in the DTR, at the 95% level or better, for any given season. Winter, for example, showed 11 significant regres-

Table 1. DTR (°C) from 1949 to 1998: Annual and seasonal means for each region

	Annual	Winter	Spring	Summer	Autumn
South/Southeastern	−0.9	−1.8	−0.6	−0.8	−0.5
Western	−0.5	−0.9	−1.1	0.2	0.0
Interior	0.0	−0.6	0.5	0.1	0.2
Arctic	0.4	−0.9	−0.2	1.8	0.7

sions and 14 non-significant. Two of these significant trends, Kodiak and Little Port Walter, were increases while the rest were decreases. Only four stations, Anchorage, Juneau, Seward, and Talkeetna, showed significant decreases for all seasons. Kodiak and Little Port Walter both showed significant increases for all seasons. The non-significance of so many of the DTR values, may be explained by the fact that normally the maxima and minima trend lines show parallel slopes, accentuating the ΔT_{Mean}, and minimizing the DTR. Therefore, we suggest that the non-significance is due to the small magnitude of the slopes, rather than to a large amount of scatter. A two-way ANOVA of the DTR was performed, but no significant regional or seasonal effects were detected.

The decrease in the DTR for Alaska over the last 5 decades is in general agreement with results found for the Northern Hemisphere (Karl et al., 1993). They found that the decrease in the DTR is approximately equal to the increase in mean temperature. In our case the observed warming was somewhat larger than the decrease in the DTR. Further, the maximum temperature increase with time was found in the interior, while the maximum decrease in DTR was found in the Talkeetna area, south of the Alaska Range. Hansen et al. (1997a, b) examined the sensitivity of climate models to a wide range of radiative forcings, and Rebetez and Beniston (1998) studied the decreases in sunshine duration and DTR for Switzerland. The latter found a good correlation between increased cloudiness and decreased DTR for low lying stations. There is no systematic study on cloudiness trends of Alaska, however, in northern Alaska (Barrow) (Curtis et al., 1998) and Interior Alaska (Fairbanks) a decrease in cloudiness has been observed. The observed decrease in DTR is small for both climatic zones. In contrast to this, South Alaska (Anchorage) experienced an increase in cloudiness. The mean cloudiness increased for the 50 years from 68% to 72%. This is also the region with the largest decrease in DTR.

Nevertheless, to explain a decrease in DTR for Interior and Northern Alaska with decreasing cloud amount, other radiative forcing mechanism, most likely increased CO_2, changes in the intensity of Arctic haze (Shaw, 1995) and the concentration of ozone have contributed to the observed decrease in DTR. Another possible culprit might be the atmospheric circulation. For Northern Alaska, we observed a temperature increase with a decrease in cloudiness, a trend was also well pronounced in winter and spring, when clouds tend to warm the surface. We explained this counterintuitive result by changes in circulation (Curtis et al., 1998). A higher amount of water vapor in the atmosphere could be responsible for the observed temperature increase at a constant cloudiness; such an increase in water vapor would also decrease the DTR.

3.3 Precipitation

Figure 7 is a smoothed contour plot similar to Fig. 2, but for mean annual total precipitation. Note the dramatic difference between the northern portion of the state (< 200 mm) and the high point in the southeast at Little Port Walter (5577 mm). Of the 25 stations used in this study, Barrow and Little Port Walter represent the extremes of precipitation, with the latter receiving about 50 times the amount recorded at the former. The majority of this difference results from the large amount of moisture brought into the southern coastal regions by low pressure systems. Coastal uplift in the southern portion of the state further increases the precipitation there, while decreasing the amount of moisture that can reach into the Interior and Arctic regions. Precipitation values for the Interior region range from approximately 200 mm to over 400 mm, small values to be sure, yet not as small as the 114 mm observed in the Arctic. Time series plots for total precipitation were generated, and the changes were expressed as percentages of the mean for the 50 year period. Annual and seasonal means were calculated for each region (Table 2), although we observed much variability among the stations. Precipitation in most of Alaska has increased over the past 50 years, with the largest increase (25%) found in winter in the Western region. Only in the Arctic region is a decrease in precipitation found throughout the year (−36% for the total annual amount), while the Interior generally displays the smallest changes. The absolute measurements of precipitation, especially at Barrow in winter, where the wind is moderate to strong, is often underestimated. This has been shown by Clagett (1988), who used Wyoming windshield gauges. However, the data set from the

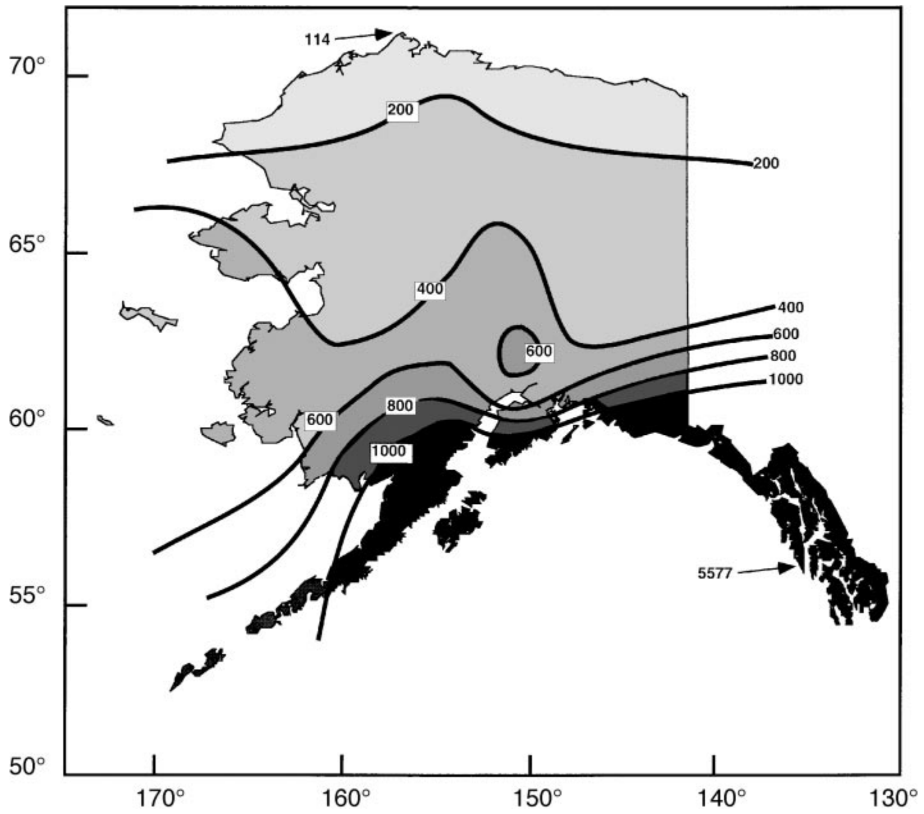

Fig. 7. Mean annual total precipitation (mm) for the State of Alaska based on the 25 study sites. Notice the dramatic contrast between the northern coast (< 200 mm) and the high point in the southeast at Little Port Walter (5577 mm)

Table 2. $\Delta P_{\%}$ from 1949 to 1998: Annual and seasonal means for each region

	Annual	Winter	Spring	Summer	Autumn
South/Southeastern	10	22	12	−1	10
Western	9	25	17	−11	21
Interior	7	3	6	1	19
Arctic	−36	−106	−57	−16	−36

standard 8-inch precipitation gauge is all that is available for Barrow for the entire 50 year period used in this study. Given that the instrumentation has been consistent, we have much more confidence in the trend analysis than in the absolute precipitation values.

Figure 8 is a comparison of the total annual precipitation at two of our study stations, the most northern (Barrow) and a southern station (Seward) at approximately the same longitude. Barrow displayed a decrease of 36%, while Seward displayed an increase in precipitation of 17% for the 50 year period; the mean increase of the South/Southeastern region is 10%. Notice the large amount of interannual variability in both of the time series plots, as well as the opposing slopes of the regression lines. At the 95% level of confidence, the Barrow regression line is significant, while the one for Seward is not.

In the vast majority of cases, significance tests of the trends in total precipitation yielded non-significant results. Significant decreases were found for Barrow in the annual and winter totals. Yakutat is the only station for which significant trends were found for every season; all of them were positive. In light of this large amount of non-significance in the individual regression lines, it is not surprising that the ANOVA also yielded non-significant values for the differences among regions and among seasons. Excess scatter, caused by high interannual variability is believed to be the primary cause of the non-

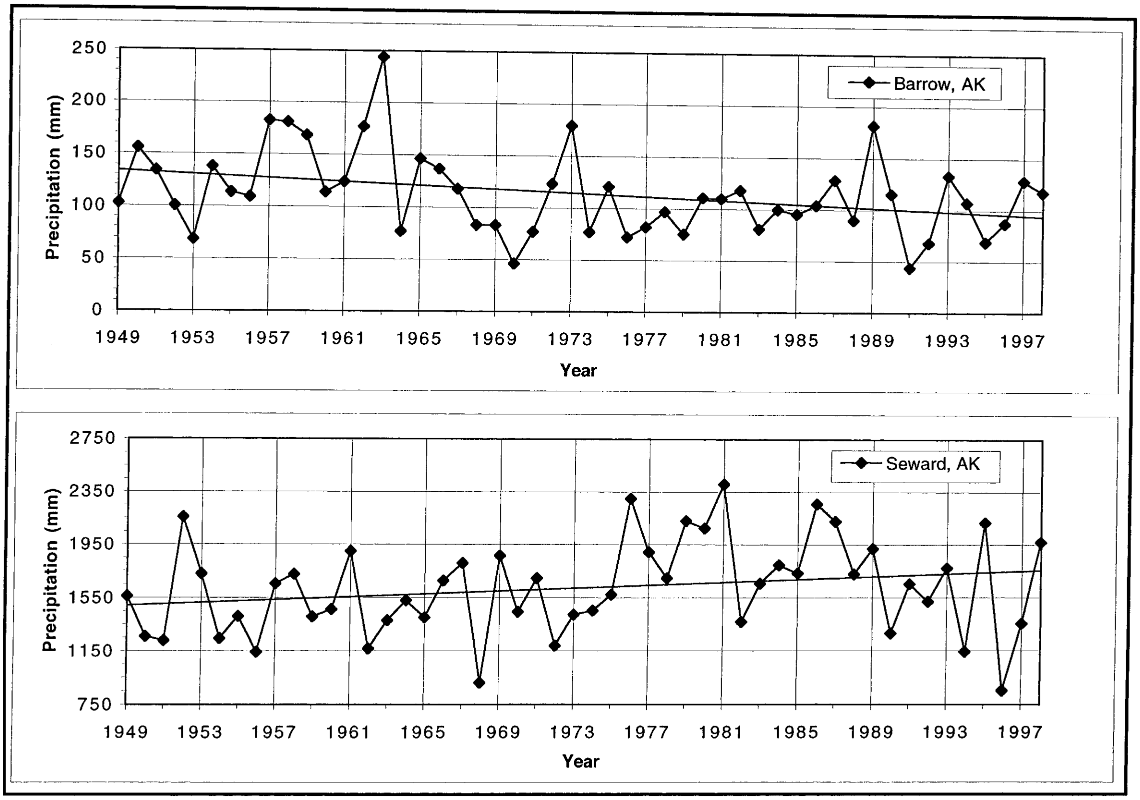

Fig. 8. Comparison of time series plots (1949 to 1998), with linear least squares regression lines, of total annual precipitation (mm) for Barrow and Seward, AK. Note the large amount of interannual variability at both stations, as well as the opposing slopes of the regression lines

significance in the precipitation trends. Precipitation is also highly variable geographically (Fig. 7), as it is dependent on many local factors such as proximity to the ocean, relative position of mountain ranges, and local topography. These all tend to increase the variance within subgroups in our ANOVA, and thus prevent significant results.

4. Discussion

Our findings regarding mean temperature are in good agreement with recent research. Chapman and Walsh (1993) also found warming to be most pronounced in winter and spring, and least in summer. This pattern is also predicted by GCM's based on a doubling of CO_2 (Weller et al., 1995). Karoly (1989) also found evidence that could support anthropogenic climate forcing via increases in greenhouse gases, but he concedes that there are other factors that could have produced similar results. Our findings of decreasing temperature in autumn cannot be explained in terms of greenhouse warming. The results of the ANOVA suggest that the ΔT_{Mean} is not homogeneous throughout the state, and that the regional effects differ by season.

Analyses of diurnal temperature ranges have yielded mixed results, such as those seen in this study, and in previous literature as well. The IPCC (1992) reported findings of increases in the daily minima temperatures, and little or no increase in the daily maxima temperatures, resulting in a decrease in the diurnal temperature ranges for the Arctic. However, findings of increases in diurnal ranges were also reported in the same publication. Our results are roughly consistent with the proposed pattern of decreasing DTR, although we found several cases in which the decrease resulted from decreases in both the maxima and minima temperatures, or from decreases in maxima but not minima.

GCM's based on a doubling of CO_2 predict that increases in Arctic temperatures will be accompanied by increases in precipitation for both summer and winter (Weller et al., 1995; Environment Canada, 1995). Our results partially support this prediction. We found precipitation increases in winter for 3 of our 4 regions (South/Southeastern, Western and Interior), but we also found decreases in summer precipitation for 3 of our 4 regions (South/Southeastern, Western and Arctic). Our findings of decreased winter precipitation on the Arctic coast are consistent with findings reported by Warren et al. (1999) and by Curtis et al. (1998). Additionally, Tao et al. (1996) found a significant inverse correlation between summer temperature and summer cloud cover over the Arctic Ocean, lending credence to our finding of decreased summer precipitation throughout much of Alaska.

Incomplete agreement between the CO_2-doubling GCM's and the observed atmospheric changes forces us to search for other possible sources of variability that could either mask or augment the effects of anthropogenic greenhouse gas increases. Zhang et al. (1996) proposed one such source when they reported cycles in Arctic temperature and precipitation on a roughly decadal scale. Similar cyclical patterns were found by Juday (1984). Urban heat islands can enhance the possible effects of greenhouse warming (Benson et al., 1983), and can account for up to 20 percent of the observed warming in certain locations (Magee et al., 1999). Additionally, interrelationships and feedback between sea ice extent and the corresponding air temperatures are another source of variability in the climatic records. Sellers (1969) found a substantial feedback at work in the Northern Hemisphere, and he also found that albedo changes in the Southern Hemisphere could have potentially severe repercussions in the Arctic. However, Ingram et al. (1989) caution us that the method used to estimate the surface albedo feedback can alter the apparent strength of the mechanism.

5. Conclusion

Increases in mean annual air temperature over the 50 year period from 1949 to 1998 were found for all stations in this study, with the highest increase located in the Interior (2.2 °C). Seasonally, the increases were highest in winter and lowest in summer. Autumn was the only season in which temperature decreases were observed. The majority of the annual and seasonal increases were statistically significant at the 95% level or higher. None of the autumn decreases were statistically significant.

Diurnal temperature range has generally decreased over the period covered in this study, with a decrease of 0.3 °C found in the state-wide annual mean. Approximately 50% of the stations showed statistically significant trends for any given season, but not all of these followed the expected pattern of slowly increasing maxima temperatures and more rapidly increasing minima temperatures.

In the precipitation record, the majority of stations showed increases for winter, spring, and autumn. Decreases in summer precipitation were found for many stations, which, although not statistically significant, can be at least partially corroborated with existing literature. Statistically significant precipitation decreases were found for the Arctic region in the annual and winter totals.

Acknowledgments

This study was supported by a grant to the Alaska Climate Research Center at the University of Alaska by the State of Alaska and by a National Science Foundation REU Grant to the Geophysical Institute. Blake Moore helped with the graphics and Gunter Weller read the manuscript: thanks to both of them. Further, our thanks go to the two to us unknown reviewers of this paper; their kind and knowledgeable comments improved the manuscript.

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