1.11 CLIMATE TRENDS AND VARIABILITY IN ALASKA SINCE 1950

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1. INTRODUCTION

Many studies have investigated changes in global temperature records and results vary depending on the spatial and temporal scale studied. An assessment of the Intergovernmental Panel on Climate Change (IPCC) has shown an increase in the global mean surface temperature of approximately 0.6°C since the late 19^{th} century (Christy et al., 2001). In recent decades, the largest temperature increase has occurred over land areas in the Northern Hemisphere. It has been shown that since the mid 1960's, the area of greatest temperature increase was for Eurasia and northwestern North America (Chapman and Walsh, 1993, Jones, 1994). In addition, general circulation models (GCMs) predict an amplification of temperature increases at high latitudes due to feedback mechanisms. For the last two decades, the Arctic has shown a general warming trend, which is strongest for the winter and spring seasons (Christy et al., 2001). Temperature change in this region is also found to coincide with large-scale circulation changes such as the Arctic Oscillation and ENSO (Rigor et al., 2000, Serreze et al., 2000, Walsh et al., 1996, and Thompson and Wallace, 1998).

Although long-term precipitation records are more difficult to analyze due to problems with observation technique and undercatch in windy environments, studies have shown a precipitation increase for the autumn, winter, and spring seasons for southern Alaska (Stafford et al., 2000) and an overall decrease in the western Arctic and northern Alaska (Curtis et al., 1998). Frozen precipitation type as well as snow cover is particularly important in the Arctic and subarctic because of the influence on the water budget and dramatic changes in the surface energy budget during and after ablation (e.g. Robinson et al., 1992). Snowfall time series data for northern Canada (55°N to 70°N) show an increase of 20% since 1950 (Groisman and Easterling, 1994) while in the Canadian high Arctic there has been a slight decrease in snow depth (Warren et al., 1999.)

Changes in the frequency distribution of both temperature and precipitation is lesser known, however, it is often the extreme events that result in the greatest societal impact. Such information could provide insight in regard to climate change impacts on society (Zhang et al., 2001). In this study, changes in temperature and precipitation means as well as the frequency distribution are investigated for Alaska.

2. METHODS

Data used in this study were obtained from the National Climate Data Center's summary of the day for the 21 first- order observing stations in Alaska for the period 1950 to 2001 (Fig. 1). The stations are located such that they are representative of the three climatic regimes in the state (maritime, continental, and arctic). Individual stations were grouped by region similar to that outlined by Stafford et al. (2000). Six regions were utilized in this study, southeast, south central, southwest (all maritime climates), interior and west, the latter having both continental and maritime influences, and arctic. The spatial representation is not uniform in each region, in which 7 locations are in the south central region and only one station, Barrow, in the arctic. Additionally, these observing stations are all at low elevations.

Daily values of maximum and minimum temperature, precipitation, snowfall and snow depth were obtained for each station and checked for cases of missing data. Months with greater than 10% missing data were excluded from the analyses. Unalakleet was the only station completely excluded from all analyses due to frequent missing data. Snowfall and snow depth measurements for the purpose of a trend analysis were not analyzed for Barrow because of the problem of undercatch in this windy environment and are considered suspect. In addition, snow depth measurements on the tundra landscape are subject to extreme spatial variability due to frequent drifting snow events throughout the season and landscape characteristics (Sturm et al., 2001).

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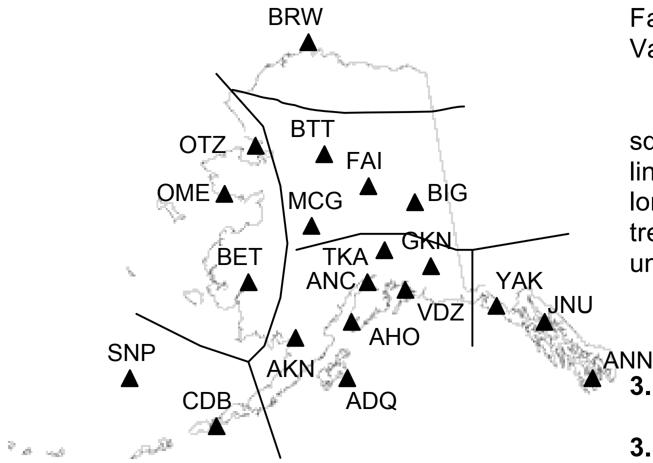

Figure 1: Locations of first-order observing stations in Alaska and the six climate regions.

Average daily temperature was computed from the mean of the daily maxima and minimum temperatures. Month and seasonal means of average, maximum, and minimum temperature were computed along with precipitation and snowfall totals. In addition, the daily maximum and minimum for each month were ranked and the 90th and 10th percentiles, respectively, were computed. Similarly, statistics for the daily precipitation totals for each month were found. The maximum and mean daily total and frequency of days with precipitation were computed, along with the monthly total.

While no statistics of daily snowfall events were calculated, monthly snowfall totals were determined. In addition to the 20 first order stations, snowfall was also analyzed for an additional three cooperative observing locations in the southeastern Alaska panhandle (Petersburg, Sitka, and Wrangell). Daily snow depth data were also obtained and the onset and end dates defining the period of continuous snow cover were determined. For several locations, the time period with snow on the ground was discontinuous due to ablation events, particularly for the southern regions. Additionally, locations in western Alaska (Bethel and Nome) experience a high frequency of strong wind speeds that induce blowing snow and redistribute the seasonal snow cover. Therefore, locations by which temperature or wind results in a discontinuous snow cover for the winter were excluded from the analysis. In all, 9 locations were analyzed for snow cover statistics (Kotzebue, Bettles, Big Delta, McGrath, Fairbanks, Gulkana, Talkeetna, Anchorage, and Valdez).

For each parameter or statistic, a least squares method was utilized to determine the best fit linear trend for the time series data, representing the long term change for the period 1950 to 2001. Most trends are reported in units of change per decade unless otherwise stated.

3. RESULTS

3.1 Temperature Means

For much of Alaska the mean annual temperature is below 0°C, except for southern portions of the state (Table 1). For the long-term trend, all regions show an average increase in the mean annual temperature on the order of 0.28°C per decade since 1950. The southwest shows the least warming and note that this region consists of coastal locations. The strongest warming is observed for the interior and southcentral.

Table 1: Annual mean temperature for each region and the long-term temperature trend since 1950.

	Annual Temp	Change (°C / decade)
S.east	5.5	0.25
S.cent.	1.7	0.36
S.west	-0.3	0.14
Interior	-3.5	0.36
West	-3.5	0.25
Arctic	-7.9	0.33

On a seasonal basis, all regions except the southwest show the strongest warming in the winter (December, January, February) and spring (March, April, May) seasons (Table 2). Interior locations show the greatest increase in the average temperature for winter of almost 0.8°C per decade for the 50-year period. Other regions average approximately 0.56°C per decade, and except for the arctic and southwest, the change in the minimum temperatures is greater than that for the maxima. Other studies have found similar results in which minimum temperatures have warmed at a greater rate than the maxima, resulting in a decrease in the DTR (Stafford et al., 2000). Spring temperatures also show a strong general warming trend over the last five decades. For this season, the average temperature increase is in the range of 0.19 to 0.48°C per decade. Additionally, as with the winter season, the change in minimum temperatures is greater than the maxima, except for the southwest. The trend for summer is generally lower, with average increases from 0.15 to 0.31°C per decade for the last 50 years. The only months with a long-term temperature decrease were found in autumn, in which the interior, west, and southwest all show slight negative trends. Interior locations show an overall temperature decrease for the maximum, minimum, and average temperature, albeit minor.

Table 2: Change per decade (1950 – 2001) in the seasonal maximum (Tmx), minimum (Tmn), and average (Tav) temperatures for the six regions. Boldface italicized type indicates significance at the 95% confidence level.

		Winter	Spring	Summer	Autumn
S.east	Tmx	***0.39***	***0.38***	0.10	0.06
	Tmn	***0.52***	***0.46***	***0.28***	0.18
	Tav	***0.42***	***0.41***	***0.18***	0.11
S.cent.	Tmx	***0.44***	***0.39***	***0.19***	0.04
	Tmn	***0.70***	***0.57***	***0.30***	0.19
	Tav	***0.58***	***0.48***	***0.24***	0.12
S.west	Tmx	0.12	***0.47***	***0.42***	0.10
	Tmn	0.01	0.25	***0.21***	-0.14
	Tav	0.06	***0.36***	***0.31***	-0.02
Interior	Tmx	***0.72***	***0.39***	0.10	-0.10
	Tmn	***0.81***	***0.47***	***0.20***	-0.02
	Tav	***0.78***	***0.46***	***0.16***	-0.06
West	Tmx	***0.53***	0.19	0.13	-0.01
	Tmn	***0.67***	0.46	***0.17***	0.03
	Tav	***0.61***	0.32	0.15	-0.03
Arctic	Tmx	***0.65***	0.34	***0.37***	0.07
	Tmn	***0.57***	***0.37***	***0.17***	0.05
	Tav	***0.65***	***0.36***	***0.27***	0.07

3.2 Temperature Frequencies

The frequency of extreme temperature events was also studied in regard to high maxima and low minimum temperatures. The locations were again grouped into the six climate regions. In this analysis the trends were determined for each month rather than season and the results to follow will be discussed by region.

There are three main features to the temperature frequency trends: 1) strong increases for the winter and spring months, 2) weak increases for summer and slight decrease for autumn, and 3) a greater shift in the extreme minimums than the maxima. The southeast (Fig. 2) and south-central regions exhibit seasonal variability as well as a greater trend for the extreme minimum temperatures. The winter and spring months show a strong positive shift in the extreme minimum temperatures on the order of 0.7°C per decade. For the southwest, trends in the minimum are also of greater magnitude than those for the maximum, However, the trends are of lesser magnitude than for those of all other regions, which is likely due to the moderating effect of a strong maritime influence.

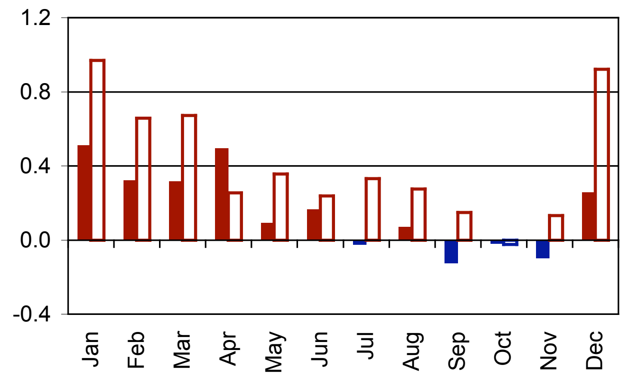

Figure 2: Trend (°C per decade) in the 90th percentile (Tmx, closed symbols) and 10th percentile (Tmn, open symbols) for southeast Alaska.

Western Alaska shows a similar pattern of variability with a strong increase in the extreme minimum temperatures. From December through April, there is a positive trend in the range of 0.6 to 1.8°C per decade. In addition, the change in extreme temperatures is significantly less for the summer months, and in the autumn season the trend is slightly negative. Similarly, stations in interior Alaska exhibit a positive shift in the extreme minimum temperatures, particularly through winter and spring. The trend in the minimum temperatures is approximately twice the magnitude of that for the maxima. During the autumn season, a negative trend is also found for both extremes, which corresponds to the period with an overall temperature decrease (Table 2).

For the Arctic region the most prominent feature in the temperature frequency distribution is a strong increase in the extreme minimum temperatures in January. The increase is on the order of 1.0°C per decade. A negative trend in the percentiles is shown for both the maximum and minimum temperature extremes in November, specifically for the maximum.

3.3 Precipitation

Mean annual precipitation (Jan – Dec) and snowfall (Jul – Jun) for each region are given in Table 3. Locations in southeastern, Alaska have the highest precipitation and snowfall totals of greater than 250 cm. Several locations in these regions experience a high frequency of orgoraphically-enhanced precipitation events. In contrast, the arctic region shows a low annual precipitation total of only 12 cm, and 75 cm for snowfall. Locations in the interior average almost 33 cm of precipitation annually with 180 cm of snowfall.

Each region shows an increase in annual precipitation total except for the Arctic (Table 3). The average increase is less than 5% per decade of the long-term annual mean for each region and the interior shows the smallest increase. In the Arctic there is an decrease of almost 6% per decade since 1950, which is similar to the decrease found in other areas of the western Arctic region (Curtis et al., 1998).

Table 3: Mean annual precipitation and snowfall for each region (cm) and the long-term trend (% change per decade).

	Precipitation	Snowfall
S.east	261.7 / 3.2	282.6 / -9.8
S.central	83.3 / 3.3	254.9 / 3.9
S.west	77.6 / 4.6	154.7 / 9.1
Interior	32.9 / 1.3	181.5 / 6.1
West	35.5 / 2.5	141.2 / 5.4
Arctic	11.6 / -5.9	75.7

As with total precipitation, the trend in snowfall is also found to increase for most regions. The average increase per decade is on the same order and varies from 3.9 to 9.1% of the respective mean annual total. However, for the southeast region there is a general decrease in annual snowfall of almost 10% per decade.

Precipitation statistics were also computed on a seasonal basis. Total precipitation in winter has increased for all regions except for the arctic, which shows a decrease of approximately 16% per decade since 1950 (Table 4). The other regions show an average increase in the range of 2 to 9% per decade. For summer, the southern regions and interior show a slight increase, while the west and arctic show a decrease. Locations in the interior and southeast show the least change overall, with minor increases in total precipitation.

Table 4: Trend (% per decade) in the seasonal total precipitation (top value) and snowfall (bottom value) for 1950 – 2001. Boldface italicized type indicates statistical significance at the 95% confidence level.

	Winter	Spring	Summer	Autumn
S.east	2.0	1.2	2.6	1.6
	-9.0	***-19.9***		-3.7
S.cent.	***9.3***	6.3	1.2	3.5
	9.0	4.3		***10.0***
S.west	***6.6***	1.5	0.8	2.9
	9.0	1.2		***8.3***
Interior	3.0	1.5	2.0	1.4
	7.5	0.8		***9.1***
West	6.2	2.0	-1.6	3.9
	10.2	-0.9		5.3
Arctic	***-16.3***	***-13.1***	-1.6	***-8.3***

The southeast shows a decrease in snowfall of 9 and 20% per decade (based on the long-term mean) for winter and spring, respectively. This coincides with an overall increase in total precipitation for these seasons. For the other regions, the change in snowfall during winter and autumn is positive and in the range of 3 to 10%. The smallest change found in the long-term trend is for spring, except for the southeast region as mentioned previously.

3.4 Precipitation Frequencies

As with temperature, total precipitation was also studied in regard to frequency of occurrence. The maximum daily, mean daily, number of days with precipitation, and total precipitation was examined for each month and region.

The southeast and southcentral both show increases in total precipitation for all months. Also, the increase in the maximum daily amount is significantly greater than that for the mean daily total (Fig. 3). This is especially the case for the southeast in which, for example, December shows an increase in the maximum daily total of over 3 cm since 1950.

The trend in extreme daily events for the southcentral region is consistently lower than that for the southeast, however both regions show corresponding trends. Annette, located in the far southeastern panhandle shows an overall decrease in total precipitation, most notably for October and the spring months. Saint Paul and Cold Bay, in the southwest, exhibit similar seasonal variability, with the change at Cold Bay consistently higher than that for Saint Paul. For these locations, the change in maximum daily precipitation is greater than the change in mean daily total, as was the case for the other maritime locations of the southeast and southcentral.

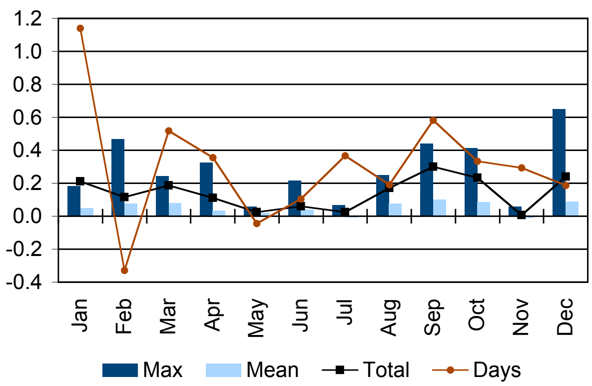

Figure 3: Changes in precipitation total and frequency (cm per decade) and number of days with precipitation (days per decade) for the southeast region (1950 – 2001).

Precipitation frequency changes in the west and interior are the lowest magnitude of all regions and there is little change in the maxima or mean daily precipitation totals. These regions also exhibit a greater change in the maximum daily total rather than the mean. For these regions, the spring months show the highest correlation between the change in the frequency of days with precipitation and total precipitation. Precipitation totals are normally lowest at this time of year therefore the dependence of total precipitation on the frequency of days is strongest.

The Arctic shows an overall decrease in precipitation and the change appears to be largely due to a decrease in the mean daily precipitation total, rather than the maximum. However, it is important to note that in the arctic, precipitation events are generally rather light. Also, all months except September show a decrease in the number of days with precipitation, with the trend on the order of 0.5 days per decade, or 2.5 days over the last 50 years.

3.5 Solid Precipitation and Snow Cover

A significant feature in the southeast precipitation trends (excluding Annette) is the strong decrease in snowfall coinciding with a slight increase in total precipitation. As mentioned previously, autumn, winter, and spring all show an increase in total precipitation along with a strong decrease in frozen precipitation. To obtain a more enhanced spatial representation of precipitation in the southeastern panhandle region, the cooperative stations of Petersburg, Sitka, and Wrangell were also studied, along with Juneau and Yakutat. Monthly precipitation and snowfall totals for these five locations were averaged and the long-term trend was obtained from the best-fit linear regression. October and November show only slight changes in both total and frozen precipitation, while December through March show strong decreases in snowfall on the order of 6 cm per decade (Fig. 4). Conversely, the total precipitation trend for October through April is positive, but only a fraction of the magnitude. Therefore, there appears to be a general shift from frozen to liquid precipitation type in this region of Alaska. Recall that these observing stations are near sea level, and this region is characterized by mountainous terrain, therefore this trend may not necessarily be the case for locations at higher altitudes.

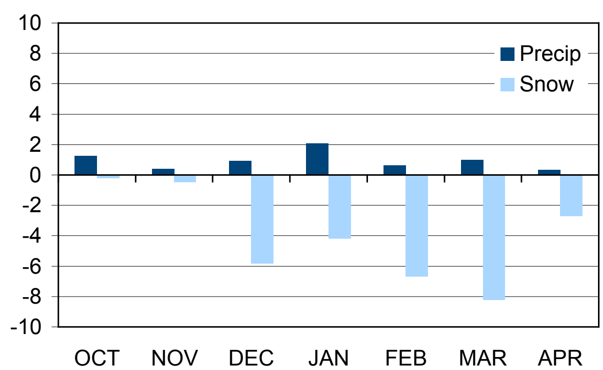

Figure 4: Trend (cm per decade) in the monthly precipitation and snowfall totals for southeast Alaska (1950 – 2001).

The snow cover period was also studied for 9 locations in the interior, west, and southcentral regions. The onset of the period with continuous snow cover for all locations shows a negative trend on the order of 1 to 2 days per decade (Fig. 5). Therefore, the snow season is beginning earlier in the calendar year. Also, the end of snow cover, and ablation, is occurring earlier in the spring. For the interior and southcentral regions, the trend is such that there is an overall increase in the number of days with snow on the ground on the order of 1 to 10 days. Although for locations in southern Alaska, this increase is quite low. Nevertheless, these regions exhibit a shift in the snow season toward an earlier onset as well as an earlier ablation period.

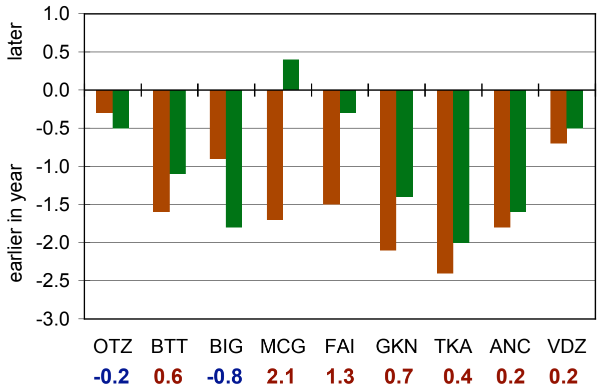

Figure 5: Trend (days per decade) in the onset (orange) and end (green) of continuous snow cover (1950 – 2001). Negative values indicate trend toward earlier in year and positive indicates later. Change in number of days (per decade) with continuous snow cover given at bottom of figure.

4. DISCUSSION AND CONCLUSIONS

Although each region studied shows an increase in the mean annual temperature, the nature of the overall temperature change in each climatic region in Alaska exhibits a seasonal dependency. The six regions studied showed the greatest warming for the winter and spring months, with either small positive, or negative trends in the autumn season. Other studies suggest that these temperature changes in the cold season reflect shifts in synoptic-scale circulation patterns (Hurrel, 1996). To coincide with these temperature changes, one might expect similar seasonal trends in other variables such as sea level pressure (SLP) or humidity.

When the change in SLP for each region and month are examined there is also a corresponding seasonal variability. On average, the SLP trends exhibit a decrease from December through March that is generally greatest for January. Recall that this is the time when most locations show a strong temperature increase, especially for the minimum and extreme low temperatures. At this time of year in the arctic and subarctic, the occurrence of clear skies associated with high pressure systems can result in very low minimum temperatures due to radiational cooling. A decrease in pressure would likely lead to a higher frequency of cloud coverage and at this time of year, this would result in a temperature increase with less of a net longwave radiation loss. This trend is also seen for much of the Arctic with a decrease in the Jan – Feb mean SLP for the last two decades, which is associated with an increase in the mean central pressure of the semipermanent Aleutian Low (Overland et al., 1999). There is very little change in SLP during the late spring and summer months and recall that at this time there is little change in temperature for most regions.

In addition, atmospheric moisture (dewpoint) has also increased for most regions in the winter and spring months, most notably for the arctic and interior Alaska from December to February. This increase in humidity would also account for the strong increase in minimum temperatures, more so than the maxima. Also, the autumn months show a decrease in humidity, which corresponds to a temperature decrease. Changes in humidity levels would indicate circulation changes and advection of more moist air at the surface. Again, both trends in SLP and humidity agree with the seasonal temperature changes observed over the last several decades and suggest a change in the atmospheric circulation pattern, most notably for the winter and spring season.

The trend in the monthly total precipitation and snowfall for locations in the southeast show a slight increase in the former and a large decrease in the latter, which are unlike the precipitation trends for the other regions. In terms of mean temperature, this region of Alaska has annual temperatures above 5°C, with temperatures in the winter months just below 0°C. However, the positive temperature trend mentioned previously appears to allow for a higher frequency of above freezing temperatures. This is resulting in a shift from frozen to a higher occurrence of liquid precipitation type in this region, which has occurred for the autumn, winter, and spring, most significantly for the winter months. One consequence of this shift would be implications for the water budget in this region.

There is also a shift in the seasonal snow cover with an earlier onset as well as an earlier melt season. Interior and southcentral Alaska show a slight increase in the snow season length. In these regions the onset of continuous snow cover is changing more quickly than the end, however both are occurring earlier in the calendar year. Recall that these regions have experienced a snowfall increase, specifically in the winter months, therefore more energy would be required for ablation, which could account for the differences in these trends. A trend toward an earlier melt date and disappearance of snow cover was also observed in arctic Alaska by Stone et al. (2002). On the larger scale, a decline in snow-covered area by 10% has been observed in the Northern Hemisphere since the early 1970's, with the largest change occurring in the spring and summer (Groisman et al., 1994).

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