CLIMATE VARIABILITY FOR ARCTIC ALASKA

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1. INTRODUCTION

Barrow, the northernmost community in North America, is located on the Chukchi Sea coast, 10 miles south of Point Barrow from which it takes its name. It is 1160 kilometers north from Anchorage and lies close to sea level at 71°17' N, 156°14' W. Due to its high latitude, the sun remains below the horizon from about 19 November to 22 January and continuously above the horizon from 11 May to 1 August. Barrow's climate classification after Köppen is ET (tundra climate) which implies it as having an average temperature during its warmest month between 0° and 10°C. High to moderate wind speeds (mean annual value 5.3 m/s) are observed predominantly from an easterly direction and snowfall accounts for about 75% of the total annual precipitation (Searby 1968). Monthly climatological averages (1958-1999) are shown in Table I.

Table I. Average temperature, precipitation, and cloudiness for Barrow, Alaska (1958-99).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
TEMP (°C)	-25.5	-27.0	-25.8	-18.3	-6.6	1.3	4.3	3.4	-0.8	-9.9	-18.3	-24.0	**-12.2**
PREC (mm)	4	4	4	5	4	7	22	26	16	12	6	4	**113**
CLD (%)	49.4	47.8	45.1	54.2	82.0	79.1	76.9	89.1	91.2	83.5	62.0	50.5	**67.6**

It can be seen from the table that a) nine months of the year have a temperature below the freezing point, b) precipitation is light with a maximum in summer, and c) cloud amount is high. The minimum cloudiness occurs in spring (March, 45 %), but becomes very high in summer and early autumn, when semi-permanent Arctic stratus are present. In September a value of over 90% cloud cover is observed.

Stafford et al. (2000) studied the climate change of Alaska for the last 5 decades (1949-1998). For this period, they found for Barrow, the only long term climatological first class weather station in Arctic Alaska, a temperature increase of 1.6°C, while for the same time period the annual precipitation decreased by 36%, with the largest decrease occurring in winter. This is a counter-intuitive result, as with increased temperature an increase in precipitation would be expected.

It should be pointed out that the precipitation at Barrow as recorded by the National Weather Service is biased, a fact known for a long time (Black 1954). Solid precipitation accompanied with moderate to strong wind speeds is difficult to measure and is normally underreported (Stone 1997). However, the relative trend as measured at Barrow should be valid, as Curtis et al. (1998), who studied the climate of the western arctic with special emphasis on Barrow, showed. It is also in agreement with the trend of decreasing snow cover in the Arctic Ocean (Warren et al. 1999). In general, Curtis et al. (1998), studying a slightly different time period to Stafford et al. (2000), found similar trends both for temperature and precipitation. However, the authors were unable to offer a plausible explanation of these opposing trends relying solely on surface observations.

2. RELATIONSHIP BETWEEN SURFACE TEMPERATURE, PRECIPITATION AND CLOUDINESS

To better understand the relationship among surface weather and conditions aloft, correlation coefficients between monthly averages of temperature, precipitation and cloud amount were calculated by season and annually; they are presented in Table 2. Positive correlation coefficients were found between temperature and precipitation for all seasons and the annual value.

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On the average, a warmer than normal season brought above normal precipitation. For fall and the annual values, this relationship was significant at the 99% confidence level, and for summer and winter at the 95% confidence level. Only in spring was the relationship weak and not significant; this might be caused by the fact that in spring the precipitation is very light, with an average of 13 mm water equivalent for the three months.

High positive correlation (>99% confidence level) occurred between temperature and clouds for all seasons except summer. In other words, cloudy days were on average warmer than clear ones. This is understandable, as the solar radiation is weak for all seasons but summer (Wendler and Eaton 1990). Additionally, due to the snow cover, which lasts for about 9 months and has a high surface albedo, most of the incoming radiation is reflected back to space. Hence, for most of the year the slightly increased positive short wave radiation budget on clear days is overcompensated by the more negative long wave radiation budget, due to the lack of additional IR back radiation from the clouds (Weller and Holmgren 1974, Wendler et al. 1981). Only in summer, when the surface albedo is low and the incoming short wave radiation relatively large, were no significant correlation coefficients between cloudiness and temperature found, indicating that for clear days, the increased short wave radiation budget is in balance with the more negative long wave radiation budget.

Table II. Correlation coefficients [r] between temperature, precipitation and total cloud amount for Barrow, AK (1958-1999) based on seasonal averages (i.e., winter = (DJF)). r > |0.30| represent a statistical significance >95% and r> |0.41| represent a statistical significance >99%; they are highlighted.

CORRELATION COEFFICIENTS	year	winter	spring	summer	fall
temperature vs precipitation	**0.54**	0.31	0.04	0.39	0.52
temperature vs clouds	**0.83**	0.56	0.87	-0.01	0.85
precipitation vs clouds	**0.51**	0.47	0.15	0.43	0.52

The correlation coefficients between precipitation and cloud amount are positive for all seasons and the year, a result to be expected. Clouds are necessary for precipitation, but on the other hand, there are many days with total cloud cover and no precipitation. The correlation coefficients are all significant at the 99% confidence level with the exception of spring; again, as with the correlation coefficient with temperature, the light precipitation in spring might be the cause.

3. RAWINSONDE DATA

The change of atmospheric circulation over Barrow, Alaska for the period 1958-1999 was investigated by examining the mandatory levels of the rawinsonde record up to the 100 hPa level. For the 42 year study period, Barrow's rawinsonde data record is substantial considering the harsh environment experienced during balloon launchings. Successful launches were available for 95% of the time; the day observation (00 Z or about 1.5 hours after solar noon) being available 1.2% more often than the night sounding. The only extended time period for missing data was October 1972. If one observation during the 24 hour period was missing, we used the remaining one for this day and for calculating the monthly average. The 1000 hPa level was not included if sea-level pressure was below this value. As the station has a height of 9 m asl, the station pressure was only 1.1 hPa less than the sea level pressure. Monthly sea level pressure below 1000 hPa occurred 5.4% of the time; data were missing more frequently in winter than in summer. The 925 hPa height was added as a mandatory level only in the 1990's and therefore could not be used in our study.

As would be expected, the highest and lowest geopotential heights for each level occur in July and January, respectively (one month lag from maximum and minimum in solar elevation). The only exception occurs at 850 hPa (lowest in December) and at 1000 hPa (highest in March, lowest in August). Standard deviations (SD) were also calculated but are not presented in the table. The highest deviations in height were found at 100 hPa from October to April and at 250 or 300 hPa from May to September, the latter being near the height of the tropopause.

Table III. Barrow, Alaska monthly geopotential average heights (ht in m) and temperatures (T in °C) for mandatory rawinsonde levels between 100 to 1000 hPa. Average surface temperatures are based on daily observed maxima and minima for the period 1958-1999.

Pressure level		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
100	ht	15576	15628	15709	15871	16131	16345	16450	16339	16084	15785	15657	15542
hPa	T	-54.9	-52.7	-50.3	-48.4	-47.4	-45.8	-45.4	-46.7	-49.3	-52.2	-53.6	-56.3
150	ht	12989	13009	13065	13200	13447	13644	13773	13651	13423	13156	13047	12961
hPa	T	-54.4	-52.9	-50.9	-48.2	-46.9	-45.5	-45.9	-46.6	-48.8	-51.5	-53.3	-55.5
200	ht	11154	11158	11196	11308	11543	11727	11832	11744	11534	11292	11198	11130
hPa	T	-55.5	-54.3	-52.1	-49.2	-47.7	-46.4	-47.1	-47.7	-49.7	-52.2	-54.2	-56.2
250	ht	9743	9736	9759	9853	10080	10258	10369	10284	10084	9857	9773	9717
hPa	T	-57.1	-56.7	-54.7	-52	-51.2	-50.4	-50.3	-51.1	-53.1	-55.3	-56.1	-57.5
300	ht	8590	8579	8596	8677	8897	9066	9169	9091	8906	8695	8614	8563
hPa	T	-55.4	-55.9	-54.8	-53.1	-50.7	-47.9	-45.7	-46.9	-50.7	-54.4	-55.1	-56.2
400	ht	6724	6713	6725	6793	6981	7116	7195	7127	6981	6808	6739	6701
hPa	T	-45.7	-46.7	-46.5	-44.6	-39.4	-34.8	-31.7	-33	-38.2	-43.2	-45.3	-46.7
500	ht	5209	5201	5213	5267	5416	5519	5578	5519	5409	5270	5217	5187
hPa	T	-36	-36.9	-36.9	-34.6	-28.3	-23.2	-20	-21.7	-27.2	-32.7	-35.2	-36.7
700	ht	2805	2801	2812	2840	2924	2973	3001	2961	2906	2824	2798	2784
hPa	T	-22.1	-22.8	-22.7	-19.9	-12.7	-7.1	-4.3	-6.3	-11.8	-18	-20.8	-22.4
850	ht	1361	1360	1370	1380	1420	1435	1447	1419	1396	1354	1345	1341
hPa	T	-17.3	-18	-17.5	-13.9	-5.7	0.7	3.5	1.1	-4.6	-12.1	-15.5	-17.6
1000	ht	160	162	163	152	148	126	122	110	117	119	135	145
hPa	T	-22.7	-23.9	-23.1	-17.4	-7.1	0.7	4.2	3.1	-1.1	-9.4	-16.9	-22
SFC	T	-25.5	-27.1	-25.8	-18.3	-6.6	1.3	4.3	3.4	-0.8	-9.9	-18.4	-24

Average minimum temperatures occur at 250 hPa for all months except March and April, when they occur at 300 hPa level. This is, of course, the region of the tropopause. Largest SD in temperature occur at the highest levels in January and March but generally below 700 hPa during the remainder of the year.

4. SURFACE INVERSIONS

Normally, the temperature decreases with height. However, in polar regions, colder temperatures are observed frequently at the surface than for the air above, as the radiation balance of the surface is negative. When analyzing the frequency of surface inversions, we did allow a lower layer to be up to 0.4°C warmer than the layer above, to account for the rawinsonde sensor error of ± 0.2°. For example, if the surface was more than 0.4°C warmer than the immediate layer above, no surface inversion was counted. If, however, the value was less than 0.4°C, but warmed above that level, exceeding the surface temperature, then it was counted.

Surface inversion can occur any time of the year. In summer (May through September) they are quite shallow, as at this time the monthly mean temperatures at the surface are higher than at 850 hPa. Table IV summarizes the monthly average surface inversions for 1958-99.

It can be seen that winter has in general more frequent, more intense, and deeper inversions, a result to be expected. Nevertheless, the frequency in winter is lower than for Interior Alaska (Bilello 1966, Wendler and Nicpon 1975), a result which is at the first surprising considering that Barrow is located in the Arctic. However, Interior Alaska is sheltered to the South by the Alaska Range, and to the North by the Brooks Range. Hence, wind speeds in winter are low. In contrast to this, Barrow is much more exposed to the general circulation, as it is located on the shore of the Arctic Ocean. The surrounding topography is flat with a low surface roughness. These higher wind speeds can erode the surface inversions due to forced mixing. The table shows further, that the inversions are more frequent and generally thicker during night time (12 Z), especially for the summer months. This is also pronounced in spring, when the cloud amount is relatively low, and nightly cooling due to outgoing long wave radiation is substantial. The average depth of the inversion in winter is about 900 m, and reduced to about half this value in summer. The average intensity in winter is about 10°C, which reduces by more than half in summer.

Table IV. Monthly average numbers, frequency (FREQ in %), thickness (ΔZ in m), and intensity (ΔT in °C) of surface inversions (SFC IN) for Barrow, Alaska (1958-1999).

	00Z	SFC IN	FREQ	Δ Z	ΔT	12Z	SFC IN	FREQ	Δ Z	Δ T
JAN	959	633	66.0	850	10.4	924	602	65.2	816	10.8
FEB	892	548	61.4	927	10.9	864	591	68.4	943	11.4
MAR	979	399	40.8	893	9.0	961	731	76.1	895	10.4
APR	932	150	16.1	705	5.5	931	657	70.6	757	7.9
MAY	968	63	6.5	500	3.8	958	320	33.4	516	6.8
JUN	917	126	13.7	421	3.7	901	363	40.3	438	6.4
JUL	975	197	20.2	439	3.7	944	498	52.8	410	5.8
AUG	972	103	10.6	446	3.0	979	369	37.7	368	4.5
SEP	936	64	6.8	260	2.7	939	222	23.6	271	3.8
OCT	956	228	23.9	424	4.7	960	303	31.6	375	5.2
NOV	919	422	45.9	595	6.9	919	466	50.7	596	7.4
DEC	977	599	61.3	820	9.0	956	581	60.8	786	9.2

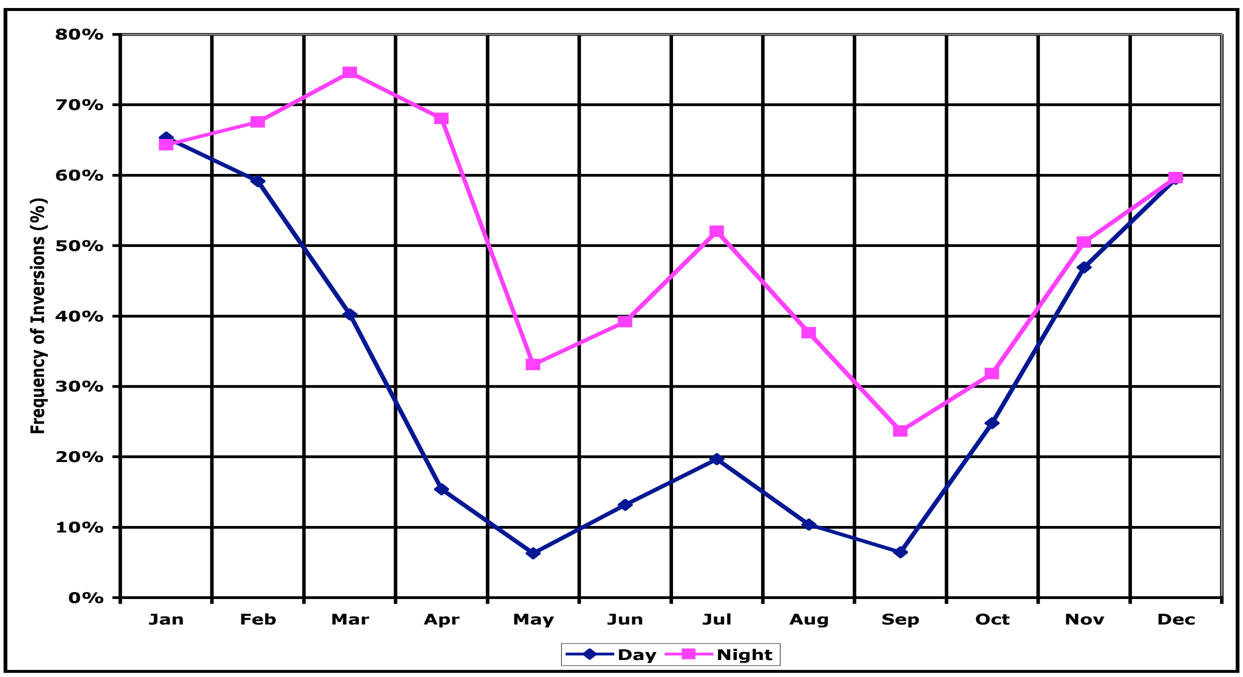

Figure 1. Frequency of surface inversions for Barrow, Alaska, 1958 to 1999

In Figure 1 the frequency of the inversions by month is presented. The typical annual course, with high occurrence rate of about 70% in winter, and low values in summer, were observed. Further, there is little difference between day and night rawindsonde ascents in winter, when solar elevations are low or the sun is below the horizon. In summer, when the global radiation is more substantial, a marked difference in the frequency can be observed; for the day ascents, the inversions are only half as common as for the night ascents. On average, over the year, 41% of the time surface inversions are observed. Such inversions de-couple the surface conditions from the conditions aloft. This might, in part, explain why Curtis et al. (1998) were unable to explain the observed precipitation changes, which were most pronounced in winter, with surface climatological data from Barrow. An interesting point of Fig. 1 is the secondary maximum of inversions in July. At the first glance, we were surprised by this, as this is the warmest month of the year. However, it might be explained by the fact that at this time the land is substantially warmer than the ocean and a sea breeze develops. Kozo (1982) has reported on these events for the North Slope. Cold, marine air is advected and forms a surface inversion. Hence, in contrast to most of the year, this inversion is not caused by a negative radiation budget, but by advection.

5. HUMIDITY AND WIND SPEED

Humidity data were available for less than 50% of the study period due partially to past recording procedures that did not report relative humidity under 20%, dew point depressions greater than 30°C (Schwartz and Doswell 1991) and dew point temperatures which fell below -40°C. Humidity values were available for the 700 and 850 hPa levels from 1963. Data for October 1972, November 1979, and June 1986 were missing. The monthly averages are provided in Table V.

Table V. Average monthly dewpoint depressions (DD) in (°C) and relative humidity (RH) in (%) at 700 and 850 hPa for Barrow, Alaska (1963-1999).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
700 DD	7.2	7.1	7.6	8.0	9.9	10.1	9.5	8.8	9.1	7.7	7.6	7.0	**8.3**
700 RH	51.8	52.1	49.7	48.7	43.2	44.2	47.4	49.6	46.6	50.7	50.3	52.7	**48.9**
850 DD	6.2	5.7	6.4	6.8	8.8	8.9	8.0	6.7	6.7	5.3	5.9	5.5	**6.7**
850 RH	58.3	60.8	57.2	56.3	49.8	51.3	55.8	60.9	64.3	64.5	60.4	62.0	**58.5**

The relative humidity has its minimum in May with a secondary minimum in midwinter. The maxima are observed close to the autumn equinox. Note further, that a substantial drying occurs between the lower and higher layer, the 700 hPa level being about 10% less humid than the 850 hPa level.

Wind data were available 90.8% of the time. Data were missing for October 1972 and April and June 1983. Winds were separated into bins of non-overlapping quadrants, centered on each cardinal direction (Table VI).

Table VI. Barrow, Alaska annual average wind speed (u in ms^{-1}) and frequency of occurrence (f in %) for significant rawinsonde levels between 100 to 1000 hPa for 1958-1999 (all soundings) by quadrant (i.e., East=045°-134°, South=135°-224°).

		100	150	200	250	300	400	500	700	850	1000
EAST	u	1.3	2.0	3.5	7.3	10.2	10.5	9.0	8.0	8.9	7.6
	f	4.7	3.8	5.3	7.9	10.8	13.2	15.5	26.8	38.5	52.1
SOUTH	u	8.5	9.6	10.7	13.1	14.7	13.4	11.2	7.9	6.7	5.0
	f	25.4	27.1	29.3	29.5	28.8	28.9	28.8	25.5	19.3	12.3
WEST	u	12.5	12.2	13.4	16.3	18.1	16.3	13.3	9.3	8.1	6.0
	f	60.8	57.9	51.9	46.2	41.9	38.9	36.9	30.7	26.7	19.8
NORTH	u	5.2	6.8	9.1	13.1	15.1	13.5	10.8	7.3	5.9	4.8
	f	9.3	11.0	13.7	16.5	18.4	18.8	18.8	17.1	15.3	15.3

The total frequency from these four quadrants approximates 100% with rarely occurring calm wind events not included in our statistics. The level with the highest average wind speed generally occurs at 300 hPa except at 400 hPa during the coldest months for east winds when winds are generally lighter and occur less often. It should be noted that the 100 hPa level is based on fewer observations, as not all rawinsondes reach this height. However, these failures do not occur often enough to skew the long term averages since their occurrence is randomly distributed. Specific level averages may not show smooth continuity (transition) with immediately adjacent levels, and higher SD usually reflect this. This apparent discontinuity is caused in part by the latitudinal and altitude shift in the jet stream. Characteristically, the easterly frequency of occurrence, the most common direction at the 1000 hPa level, rapidly decreases with height; southerly frequency is broadly even at all but the lowest and highest levels where it occurs less often; westerly frequency rapidly increases with height; and northerly frequency slowly decreases with height.

To see if wind aloft had any significant effect on precipitation, surface temperature, and cloud cover, we calculated the wind way by multiplying the wind speed by frequency of occurrence. This represents best the advection and will be discussed in more detail later.

6. CLIMATOLOGICAL TRENDS

a.) Temperature

Barrow has experienced warming during the last decades. In Figure 2, the annual and winter values of the temperatures of Barrow are presented for 1958-1999. Assuming a linear trend, a warming of 2.0°C for both values can be observed for the 42 year time period. For comparison to the other seasons, see Curtis et al. (1998).

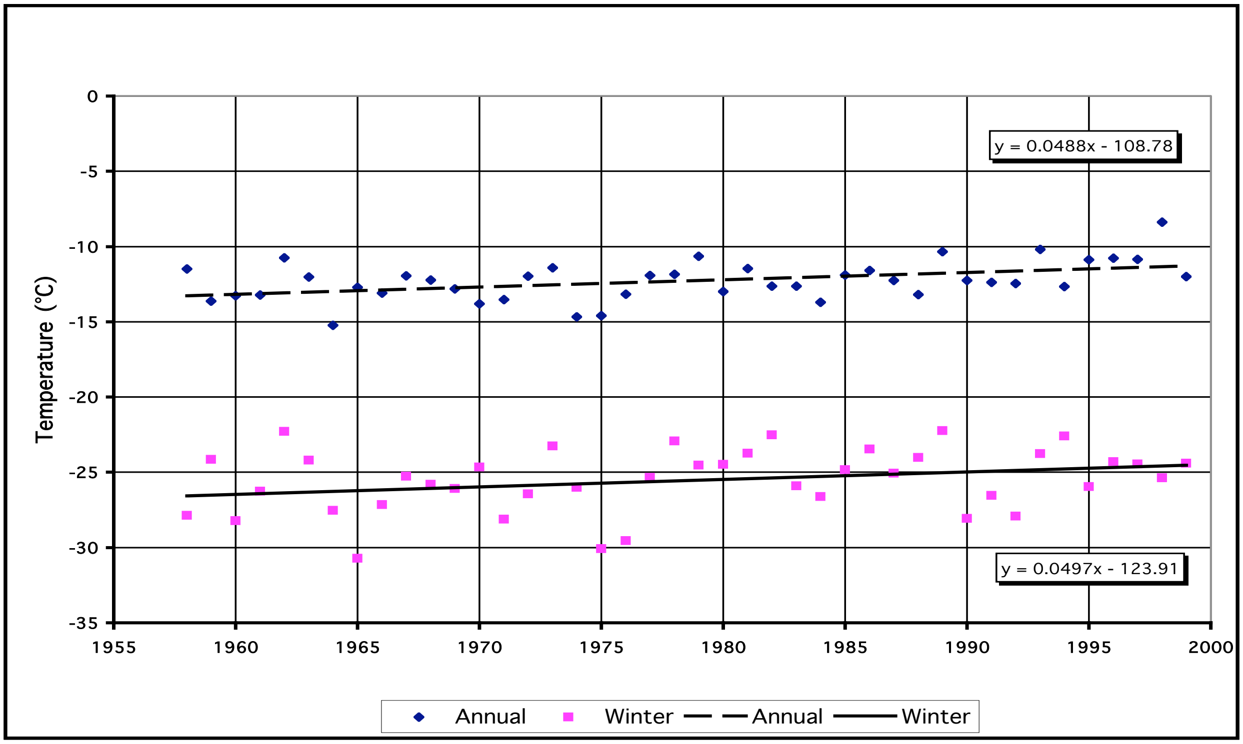

Figure 2. Annual and Winter temperature trends for Barrow, Alaska, 1958-1999

Looking at the rawinsonde data, it can be seen that this warming is most pronounced at the surface. This is a result which is not in agreement with GCM's, which predict the maximum warming in the lower troposphere, but not at the surface. However, it is in agreement with satellite derived trends, which showed maximum warming at the surface (IPCC 2001). In Fig. 3 Barrow's winter temperature change is presented as function of height for the 42 year period. It can be seen that the warming is quite limited to the lowest layers of the atmosphere. At the surface we observed the above mentioned 2.0°C, at the 1000 hPa level, which has on the average a height of 120 m, this value is already reduced to half of the surface value, at 850 hPa it is less than 0.3°C, and at the 700 hPa level cooling is observed. The cooling increases when going further up in the atmosphere, and reaches in the lower stratosphere a similar magnitude to the surface warming. On a decadal time scale, only the 1990's shows a warming trend at all levels with the 1970's showing the greatest warming trends in the lowest half of the atmosphere.

The observed warming of the layer close to the surface should have an effect on the surface inversion. If the inversions are strong, it should weaken it, and weak inversions might disappear altogether. In Fig. 4 we plotted the frequency of inversions both for annual and winter conditions against time. For the mean of the year, the frequency declined from 43% to 39%, a relative decline in frequency of 10%. In winter, the frequency declined even sharper, from 68% to 57%, a relative decline of 16%. It is interesting to note this stronger decline in frequency, both in absolute as well as relative terms, occurred more strongly in winter than for the average of the year. At the first glance, one would expect the opposite, as in winter the inversions are stronger, and hence less easy to eliminate. However, an explanation might be found in the fact that the observed surface warming in the summer season was less pronounced than for winter. It is interesting to note that, while during the summer season the frequency and height of the inversions has decreased, the temperature gradient, when expressed in °C/100 m, has increased. Furthermore, a more substantial decrease in depth than in frequency was observed. The surface inversions decreased on the average in depth 26% for the annual value, and a large 36% over the winter value for the 42 year study period. The decrease in frequency of surface inversion in winter and the increase in surface temperature over the last decades does not only hold true for the Alaskan Arctic, but was found for much wider areas, including the Canadian Arctic (Bradley et al. 1993).

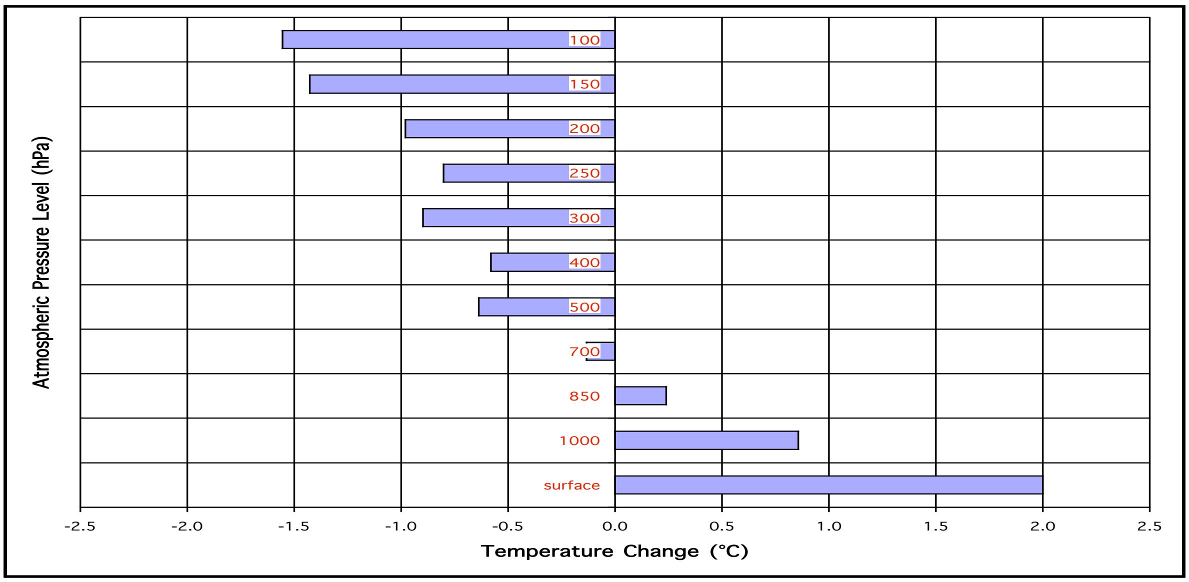

Figure 3. Temperature trends in winter as a function of height for Barrow, Alaska, 1958-1999

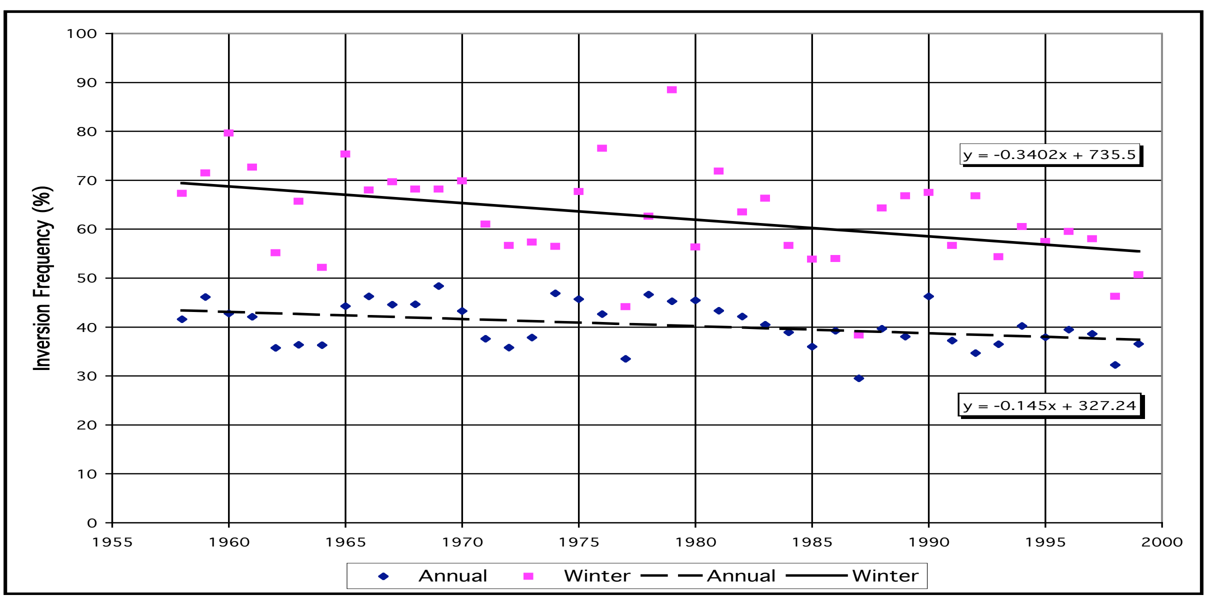

Figure 4. Trend in the frequency of surface inversions in winter and for the year for 1958-1999

A decrease in stability of the air between 1000 hPa and 700 hPa of 0.8°C was found for the mean annual value for the study period. Increased instability was also found most of the time for greater heights. The greatest change was observed in the upper troposphere (500 hPa to 250 hPa level) in spring. An explanation of these trends is that the lower atmosphere, which has warmed for at least the last 42 years, is transferring its excessive heat into the upper atmosphere that has been cooling. Increased instability would normally increase precipitation; we observed the opposite, which can be taken as an indication that convective dynamics is only a minor contributing factor to precipitation in the Arctic.

b. **Precipitation**

As mentioned in the introduction, precipitation has decreased on the North Slope of Alaska over the last few decades. In Fig. 5 we plotted this decrease for the winter and for the annual value as measured for Barrow for 1958 to 1999. The trend line is strongly negative, especially in winter. However, the magnitude of the decline is influenced by a single year (1963), and the intensity of the decline would change, if a different time period would be selected. In addition, solid precipitation is difficult to measure, especially when winds are strong, as frequently experienced at Barrow. Nevertheless, we believe that the decrease in precipitation is real. There are for a 40-year time period simultaneous measurements at Barrow and Barter Island. Barter Island is located some 500 km to the East of Barrow but in a similar geographic setting on the shoreline of the Arctic Ocean. Barter Island showed an even more dramatic decrease, and the year of maximum precipitation at Barrow (1963) was a normal one for Barter Island, hence it is unconvincing to put too much importance on this single year.

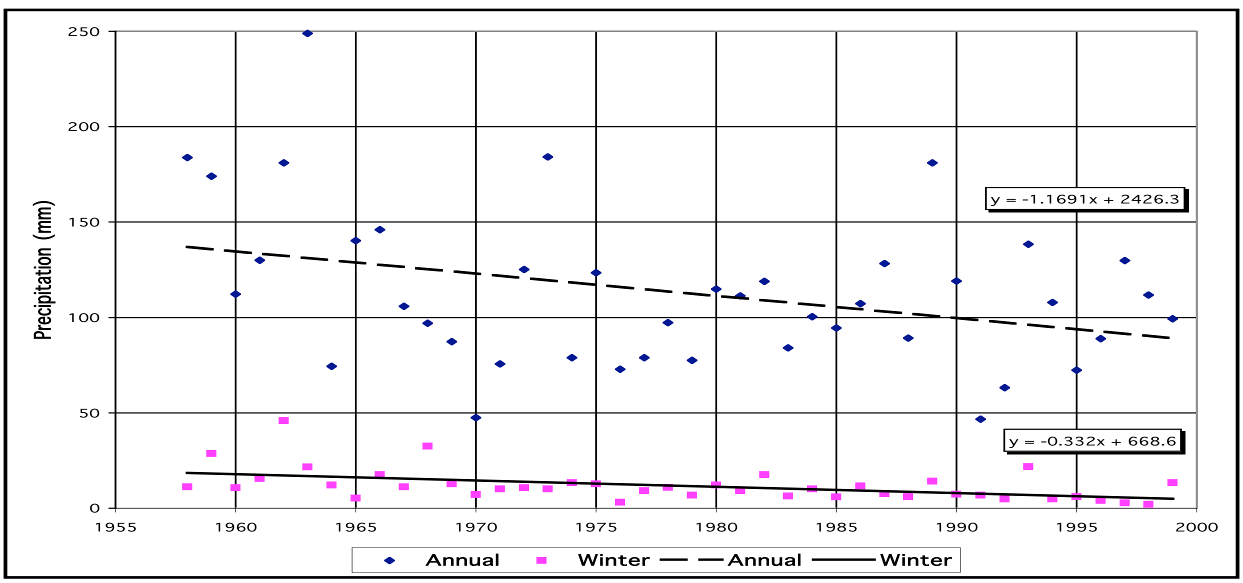

Figure 5. Precipitation trend in winter and the year for Barrow, Alaska, 1958-1999

As stated previously, Curtis et al. (1998) observed the precipitation decrease already, but was unable to offer a convincing explanation when using the surface data. In general one would expect increased precipitation with increasing temperature. It can be argued that the advection of moist air occurs dominantly at an elevated level, e.g. 700 hPa, a level at which, at least for the winter, a small amount of cooling occurred. This might explain why no increase in precipitation was observed, however, a decrease, which took place for 3 of the 4 seasons, cannot be explained in this matter. In Fig.6 we plotted the observed temperature change from 1958 to 1999, assuming a linear relationship of change for the time period, as function of month and height. It can be seen from this figure, that while in late winter/early spring the surface warming is limited to the lowest level of the troposphere, it extends higher for the other seasons.

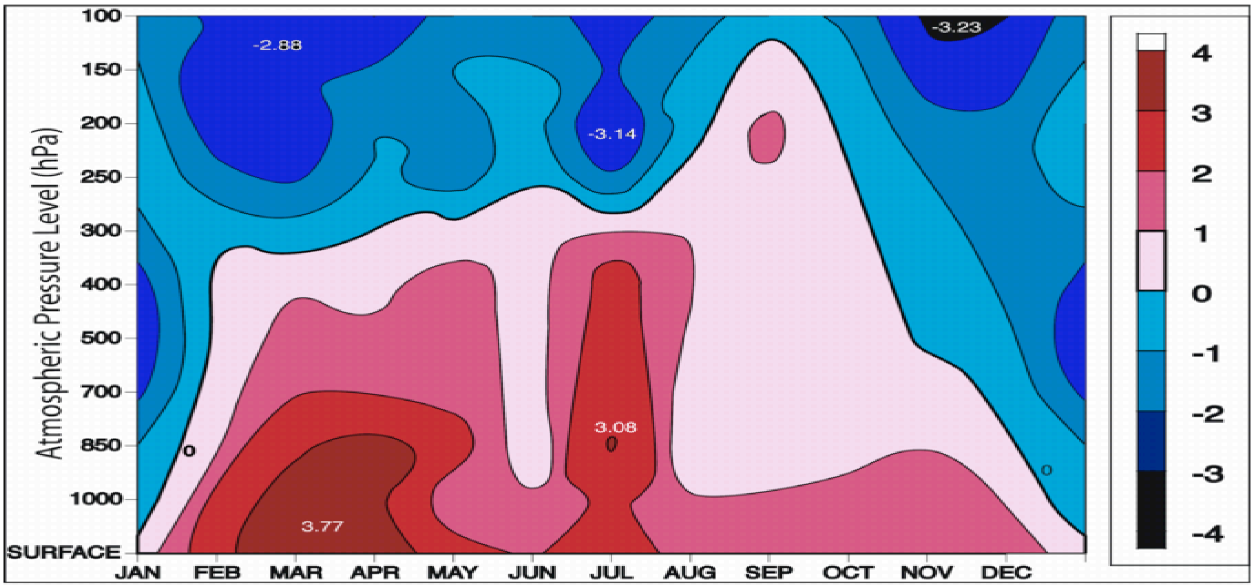

Figure 6. Temperature change from 1958 to 1999 as a function of season and height for Barrow, Alaska

c. Wind

Another explanation might be found in change of the wind directions which might have occurred at Barrow. Curtis et al. (1998) showed from surface wind data, that southerly and westerly winds are more likely to be associated with precipitation than easterly or northerly winds. Their results were not very conclusive, but one might argue that surface observations represent a relatively poor presentation of moisture advection to Barrow. Hence, for different elevations of the atmosphere we correlated annual values of the precipitation with frequency wind directions. Fig. 7 shows clearly that in years in which the frequency of southerly or westerly winds is above normal, precipitation is above normal, too. This holds true for all lower levels. Close to the surface (1000 hPa), southerly winds are best correlated with precipitation, while at the 500 hPa level westerly winds and precipitation show the highest correlation coefficients. Easterly winds, and to a lesser degree winds from a northerly direction bring below normal precipitation.

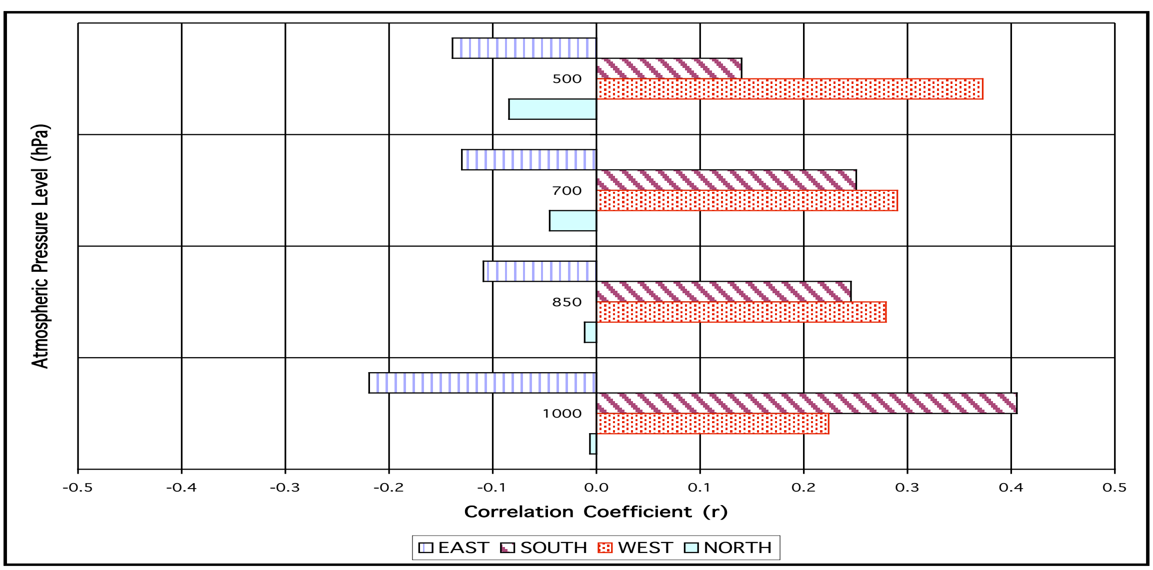

Figure 7. Correlation coefficient between annual precipitation and wind direction for different levels of the atmosphere at Barrow, Alaska. A correlation coefficient >0.3 is significant at the 95% level.

The wind speed record was fairly complete and was analyzed at the different mandatory levels of the atmosphere for the four cardinal wind directions. A least square linear analysis was applied to all monthly averages for all levels up to 100 hPa to detect changes from 1958 to 1999. Such an analysis can be done for frequency or wind speed. We chose the product of the two, which represents the wind way, in other words the amount of air advection within a certain time period to Barrow at a specific level.

In Fig. 8, the change of air advection from the west is presented as a function of height for the 42 year observational period. Westerlies bring, on average, the most precipitation. It can be seen that in winter there is a well developed minimum in the upper troposphere, which reaches to below the 850 hPa level, but is not visible at the surface, and hence, could not be detected from the surface winds. This decrease in westerly advection can explain the observed decreased precipitation in winter. A second minimum can be observed in late spring, early summer, while March and August gave positive values. The extremes in March and June were located in the stratosphere and should not have much bearing on moisture advection, while the August maximum is like the winter minimum in the upper troposphere and should influence the moisture advection and indeed, the August precipitation has increased over the 42 year period. August and to a lesser extend September were the only two months of the year, which showed an increase.

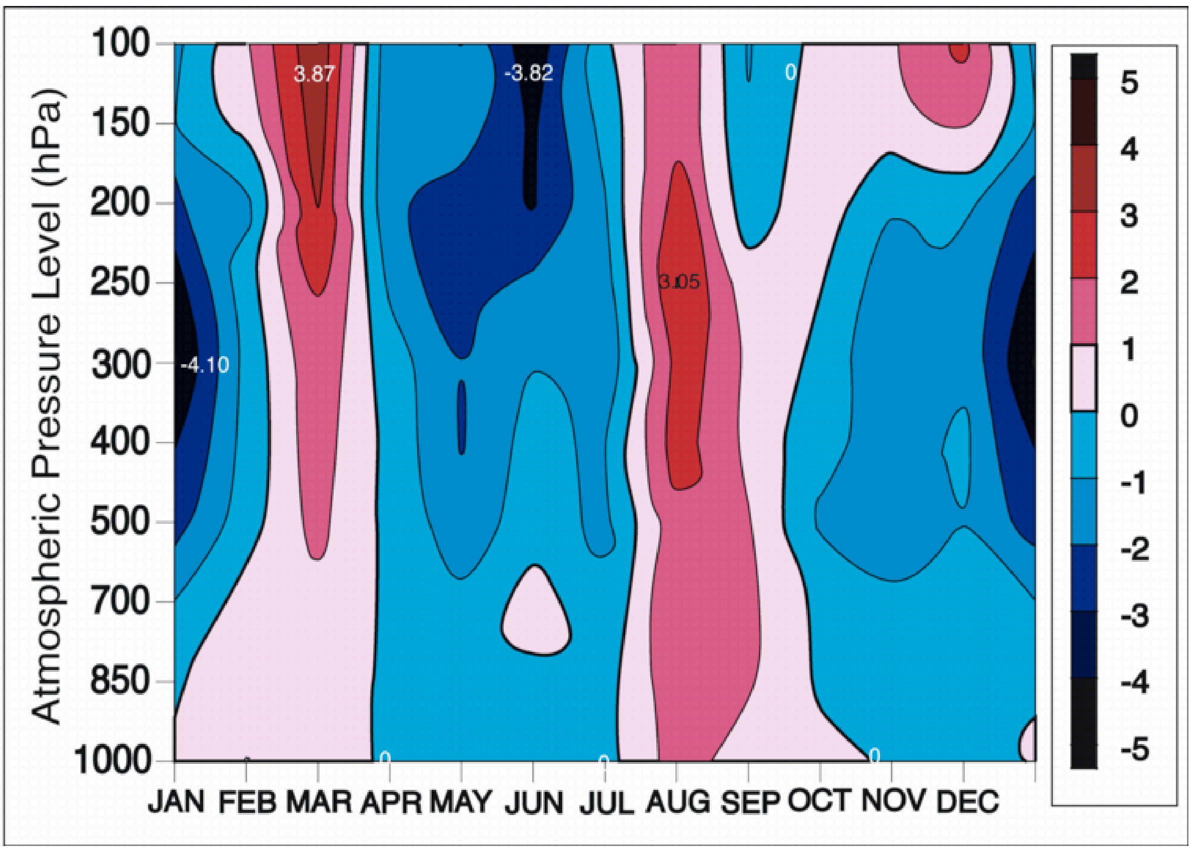

Figure 8. Annual course of the change of air advection from the west as a function of altitude for Barrow, Alaska

We also examined the dew point depressions and their trends for the 850 and 700 hPa levels, which were available from 1963 to 1999. An increasing dew point depression would, of course indicate a drying of this layer. These two levels were judged especially important for the advection of moisture to Barrow. The seasonal data are presented in Table VII.

Table VII. Annual and seasonal dew point depression values and trends for the 850 and 700 hPa levels and their changes for Barrow, Alaska (1963-99). The values given for 1963 and 1999 represent the end points of the best linear fit.

700 hPa	1963 °C	1999 °C	□T °C	Change %	850 hPa	1963 °C	1999 °C	□T °C	Change %
Ann	8.12	8.44	0.32	3.9	Ann	6.74	6.76	0.02	0.2
Win	6.38	7.83	1.45	20.4	Win	5.34	6.32	0.97	16.7
Spr	8.92	8.10	-0.83	-9.7	Spr	7.56	7.15	-0.41	-5.5
Sum	9.83	9.09	-0.74	-7.8	Sum	8.31	7.51	-0.80	-10.1
Fal	7.37	8.78	1.41	17.5	Fal	5.74	6.13	0.39	6.6

Significant increases (drying) were found in winter and fall at the 700 hPa level. Drying trends aloft in the region of precipitation cloud types from October to February are consistent with the decrease in winter and fall precipitation that has been observed.

7. Atmospheric Indices

Atmospheric indices describe the state of the general circulation. They might be derived from different parameters such as sea surface temperatures, pressure differences between different latitudes, solar sun spot cycle and others. Changes in these indices, be it cyclic or semi-linear, will have an effect on the surface climate at a certain point. Our special goal is to obtain a better understanding of the decrease in precipitation observed in Northern Alaska. There have been a number of investigations on the precipitation changes and cycles in the Northern Hemisphere (Bradley et al. 1987, Brown 2000, Dai et al. 1997, Groisman and Easterling 1994). Ye (2001) discussed the winter precipitation characteristics in Eurasia and their connections to sea surface temperatures in the Pacific and Atlantic Oceans. Here, we examined a number of indices, namely the Arctic Oscillation (AO), North Pacific (NP), Western Pacific (WP), Pacific Decadal Oscillation (PDO), Pacific North America (PNA), North Atlantic Oscillation (NAO), Nino 3.4, Nino 4, and 10.7cm solar indices.

We used the total data set (504 monthly values) as well as the 60 highest, 60 lowest and 60 most neutral values to correlate these with the surface conditions at Barrow, namely surface temperature, precipitation and cloud amount. The extreme indices were also included in this study, as precipitation is a parameter, which is much more influenced by extreme events than by the mean. Correlation coefficients were calculated between the different indices and the surface parameters in Barrow not only for identical time periods, but also for lag times for the Barrow observations from 1 to 6 months. The reasoning behind this was the fact, that a deviation in the sea surface temperature in the Pacific will affect the general circulation over a time, but might not have an immediate effect at Barrow.

Two of the above mentioned indices displaying the most promising relationship with the Barrow data are the North Pacific index (NP) and the Pacific Decadal Oscillation (PDO). For the other ones no systematic correlation coefficients with the Barrow surface observations, which were significant, could be found.

In Fig.9 time series of the North Pacific index (NP) is presented; it is defined as the area-weighted sea level pressure over the region 30-65°N, 160°E to 140°W and can be found on the net under http://www.cgd.edu/-jhurrell/np.html. A detailed desciption is given by Trenberth and Hurrell 1994. Substantial variations from year to year can be observed, but altogether a decrease over the whole time period was found. When correlating this index with the surface data of Barrow, well established correlation coefficients could be found (Table VIII) for 0 to 6 months lag times. Note, that most of the correlation coefficients have significance level of 99% or higher.

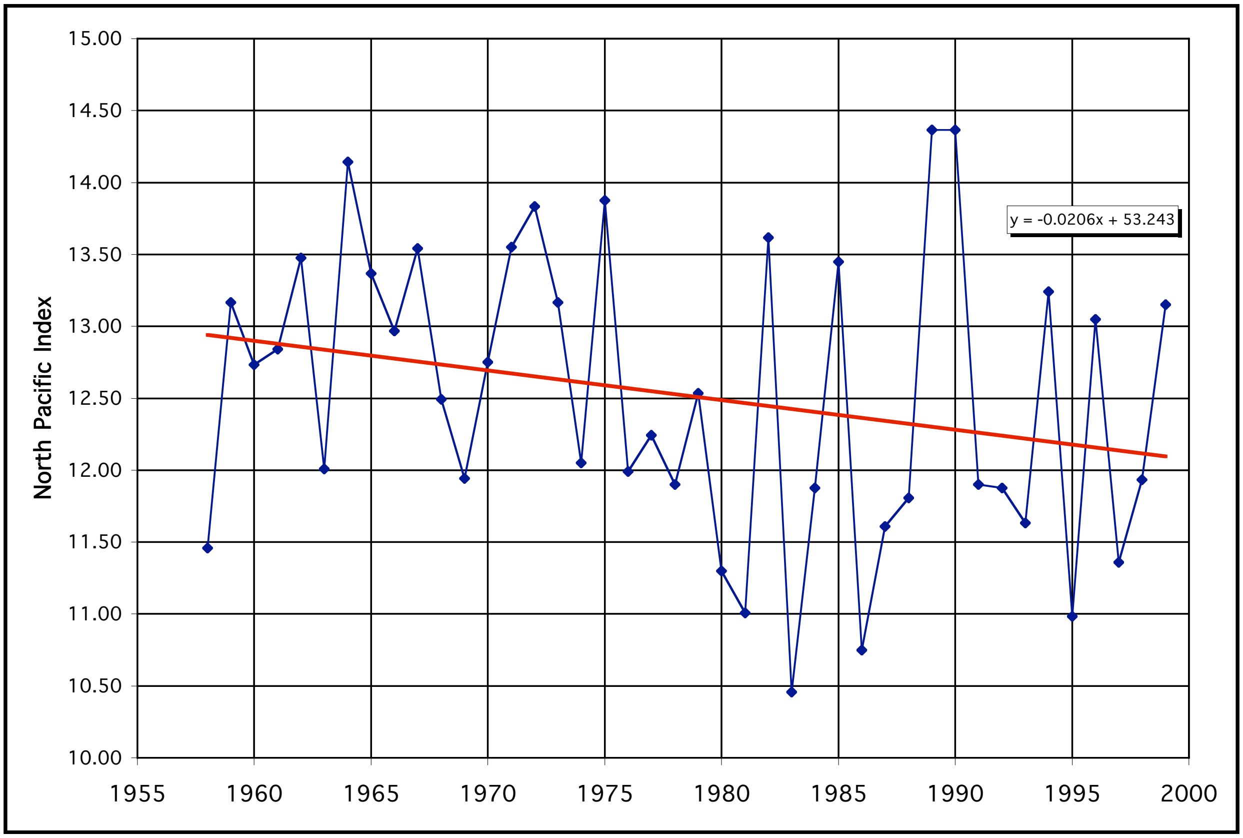

Figure 9. Time series of the annual values of the North Pacific (NP) Index.

Table VIII. Correlation coefficients of the North Pacific (NP) index with the surface data (temperature, precipitation and cloud amount) of Barrow, Alaska for lag times of 0 to 6 months. Heavy shade 99% significance level, lighter shade (95%).

	0	1	2	3	4	5	6
Precipitation	**0.39**	**0.39**	**0.34**	**0.30**	**0.15**	**-0.10**	**-0.38**
Sfc. Temp	**0.64**	**0.71**	**0.57**	**0.25**	**-0.15**	**-0.49**	**-0.69**
Cloudiness	**0.50**	**0.66**	**0.55**	**0.29**	**-0.02**	**-0.25**	**-0.46**

In Fig.10, a scatter diagram of the monthly NP indices against precipitation at Barrow for a one month time lag are presented; for this lag time the highest correlation coefficients with the surface observations at Barrow were found. It can be seen from the graph that, on the average, lower NP values are associated with a lower amount of precipitation. Hence, as the NP values decreased over the 42 year time period (Fig.9), the observed decreasing trend in precipitation makes sense, at least statistically. A meteorological hypothesis might be that with decreasing atmospheric pressure values, the Aleution Low increases in intensity. This establishes a stronger pressure gradient with the semi-permanent anticyclone, which is observed over the Beaufort Sea. This anticyclone causes the Beaufort Gyre, indicating, on the average, easterly winds off the shore of Northern Alaska. An increase in frequency of these winds should lead to a decrease in precipitation, as winds from an easterly direction bring the least moisture.

The Pacific Decadal Oscillation is defined as the leading principal component of North Pacific monthly sea surface temperature (SST) variability poleward of 20°N. The monthly mean global average SST anomalies are removed to separate this pattern of variability from any “global warming” signal that may be present in the data. More details are given by Zhang et al. (1997) and Mantua et al. (1997). Climate anomalies associated with PDO are similar to ENSO (Latif and Barnett 1996). The warm phase (El Nino) of the PDO is associated with warmer and drier winter/spring over northern North America while its cool phase is more like La Nina. Standardized values of the PDO index can be found on the internet: ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/ INDICES/PDO.latest

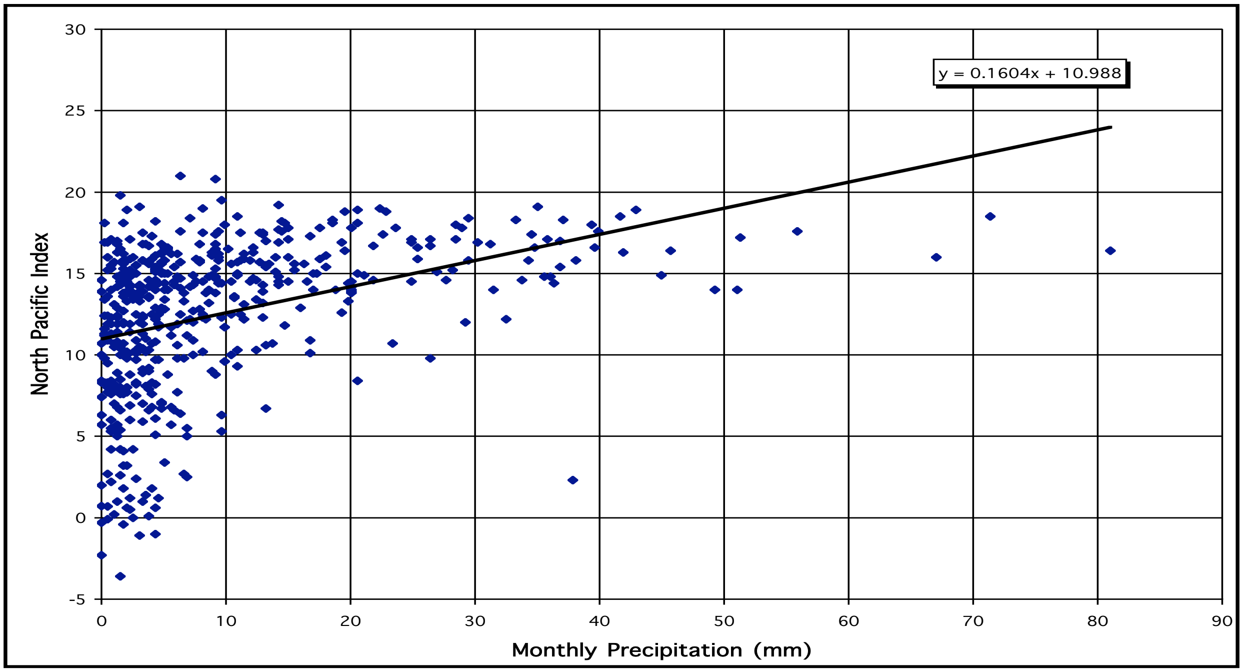

Figure 10. Scatter diagram of monthly values of the NP Index against precipitation (temperature and cloud amount) at Barrow with a time delay of one month

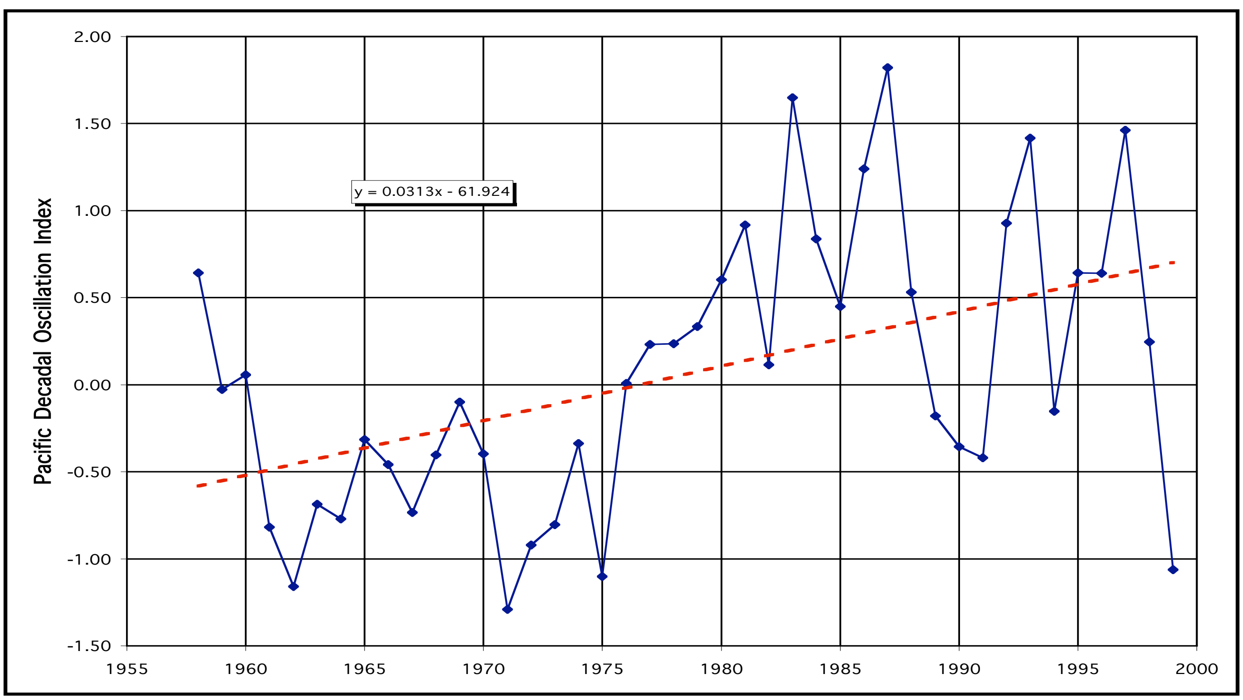

Figure 11. Time series of the annual values of the Pacific Decadal Oscillation (PDO) Index.

The PDO increased over the 42 year time span (Fig.10), however, it is more cyclic than linear. The length of the period appears rather to be 40 years (or 20 years for the half cycle) than one would have expected from the name of this index. Presently, we are starting a downward trend. Correlation coefficient (not given) with precipitation and cloudiness were not significant. However, above normal values in the PDO resulted in above normal temperatures at Barrow with a time lag of 1-3 months with a significance level of above 99%. We also correlated the monthly PDO values with the wind way (wind speed x frequency) observed at Barrow at different levels of the atmosphere for time lags up to 6 months. In Table IX these values are presented for the mandatory levels from 1000 hPa to 500 hPa level, which represents the lower troposphere, in which most of the moisture is advected. It can be seen from the table that easterly wind ways are positively correlated with the PDO index for the 850 and 1000 hPa level and all time lags for the surface. As the index increased for the 42 year time period, more air was advected from an easterly direction. We have shown previously (Fig. 7), that easterly winds brought below normal precipitation, which is able to explain the decreased precipitation at Barrow.

Table IX. PDO index and wind ways correlation coefficients based on 504 months from 1958-1999 for Barrow, Alaska. Darker shade is 99% significance level and lighter shade is 95% significance level. Monthly lags from 0 to 6 months.

WIND WAY	LEVEL (hPa)	0	1	2	3	4	5	6
EAST	500	-0.03	-0.07	-0.05	-0.03	-0.03	0.01	0.02
	700	0.04	0.00	0.01	0.03	0.05	0.09	0.09
	850	0.12	0.05	0.06	0.07	0.09	0.11	0.11
	1000	0.19	0.11	0.11	0.10	0.10	0.11	0.10
SOUTH	500	0.08	0.05	0.04	0.04	0.02	0.00	0.02
	700	0.07	0.04	0.03	0.03	0.01	-0.02	-0.03
	850	-0.03	-0.03	-0.01	-0.03	-0.04	-0.09	-0.08
	1000	-0.18	-0.11	-0.05	-0.04	-0.03	-0.04	-0.03
WEST	500	-0.08	-0.11	-0.11	-0.11	-0.09	-0.06	-0.09
	700	-0.08	-0.07	-0.07	-0.06	-0.07	-0.05	-0.06
	850	-0.10	-0.07	-0.06	-0.04	-0.06	-0.03	-0.06
	1000	-0.14	-0.09	-0.07	-0.06	-0.06	-0.03	-0.04
NORTH	500	-0.17	-0.10	-0.12	-0.12	-0.07	-0.08	-0.06
	700	-0.20	-0.16	-0.15	-0.16	-0.10	-0.11	-0.08
	850	-0.21	-0.16	-0.15	-0.15	-0.10	-0.10	-0.08
	1000	-0.05	-0.05	-0.07	-0.04	-0.03	-0.04	-0.03

On the other hand, the index was negatively correlated for all other three cardinal wind directions. While northerly winds brought a slight decrease in the precipitation, southerly and westerly advection increased the precipitation amount. This is especially pronounced at the lowest levels of the atmosphere with no or one month time lag. These winds bring above normal precipitation. A negative correlation means that with the observed increasing PDO index, less advection from southerly and westerly direction occurs, the direction from which normally above normal moist air is advected, again supporting the decreased precipitation amount observed at Barrow. It is interesting to note, that the PDO is on the downward cycle, and if the above trend holds, increased precipitation at Barrow should be observed over the next decade.

A meteorological explanation is similar to the one found for the decreasing NP values. Increasing PDO values mean a deepening and eastward movement of the Aleutian Low, establishing a more steady pressure gradient with the semi-permanent Beaufort Sea anticyclone, causing more frequent easterly winds.

8. CONCLUSION

Barrow, as most of the arctic (Serreze et.al 2000), has experienced a warming over the last 4 decades. This warming was most pronounced at the surface, decreasing to about half its surface value at the 1000 hPa level, and had reversed sign (cooling) in winter at the 700 hPa level. This predominantly warming in the boundary layer caused the often occurring surface inversion to decrease in frequency and height, as well as in total intensity.

For the same time period a decrease in precipitation was observed. Intuitively with warming one would have expected the opposite.

However, at levels at which moisture was advected little or no warming occurred. Several atmospheric indices were tested. The North Pacific Index correlated positively to the precipitation at Barrow at significant confidence levels. This index decreased over the last 4 decades. Further, the Pacific Decadal Oscillation, which has increased for the time period, was positively correlated to easterly winds in the lower troposphere. With easterly winds precipitation is least likely. Both indices support the observed decreased precipitation.

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