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PRECIPITATION DECREASE IN THE WESTERN ARCTIC, WITH SPECIAL EMPHASIS ON BARROW AND BARTER ISLAND, ALASKA

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ABSTRACT

Over the Arctic during the last few decades a decrease in annual precipitation and snow depths have been observed; this decrease is especially pronounced during the winter months. This decrease was not only found over northern Alaska but also over the high latitude Canadian stations and Russian drift stations. Further, satellite monitoring of North America snow cover has revealed a significant decreasing trend in mid-spring cover since 1972.

The temperature increased during the last few decades in the Arctic, hence the simplest explanation—normally increased temperature leads to high precipitation—is not valid. A causal explanation for these trends had been related to the shift of the Aleutian low and Arctic high. This study, with special emphasis on the surface observation data from Barrow and Barter Island, indicates:

(i) not only the frequency, but the mean intensity of precipitation has decreased;
(ii) the amount of total cloud cover, and in particular, low cloudiness, has decreased with time;
(iii) sea-level pressure did not show any significant trends. Variability in atmospheric pressure, however, decreased with time, suggesting that either the intensity and/or frequency of cyclones has decreased;
(iv) a shift in seasonal resultant winds at Barrow has been observed.

KEY WORDS: Alaska; western Arctic; climatic trend analyses; cloud cover; temperature; precipitation

1. INTRODUCTION

Over the last few decades, climate change has been observed in the western Arctic (Chapman and Walsh, 1993; Osterkamp, 1994; Wallace *et al.*, 1996; Walsh *et al.*, 1996; Stone, 1997). Two climate variables in particular show this quite clearly: temperature and precipitation.

Western Arctic temperatures have increased, but the observed mean increase varies strongly from month-to-month making it difficult to explain the annual trend solely on the basis of an anthropogenic effect resulting from the increase in greenhouse gases in the atmosphere. Climate models predict that warming due to this effect should be greatest during the Arctic winter which we observed. More complicated feedback mechanisms involving surface albedo changes and cloud-radiative and dynamical interactions associated with changes in circulation also contribute to temperature variations (Wendler *et al.*, 1981; Zhang *et al.*, 1996; Stone, 1997).

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Precipitation has decreased in the western Arctic and the Arctic Ocean. Such decreasing trends were found in (i) the amount of precipitation at meteorological stations in the Arctic, (ii) in the depth of the snow cover, and (iii) in the aerial extent of the snow cover. Precipitation measurements are not easy, especially if precipitation falls in solid form for about 9 months of the year in areas where strong winds are frequently observed. However, the above three points together give convincing evidence that this trend is real. In this paper, we will try to explain the decreasing trend in precipitation with other climatological parameters, putting special emphasis on the data from Barrow and Barter Island. Both stations operated concurrently for a 40-year time period (1949–1988) as first order weather stations.

We intentionally used seasonal (December, January and February are considered as winter, etc.) instead of monthly means in our analysis to lessen the influence of extreme daily weather events. By averaging over longer time intervals, we lose some temporal resolution, but obtain a data set less influenced by the rare, extreme events which can strongly affect averages especially in winter when precipitation is light. For example, snowfall in January 1962 for Barter Island was more than 700% of normal, strongly influencing trend analyses for this particular month.

The decreased amount of snow cover in arctic North America together with the increased temperature has led to an earlier date of snow melt which has substantial influence on the regional surface energy budget. A decreasing trend of sea ice amount in the Beaufort Sea and increased bore hole temperatures in the permafrost are in agreement with this finding (e.g. Weller *et al.*, 1995).

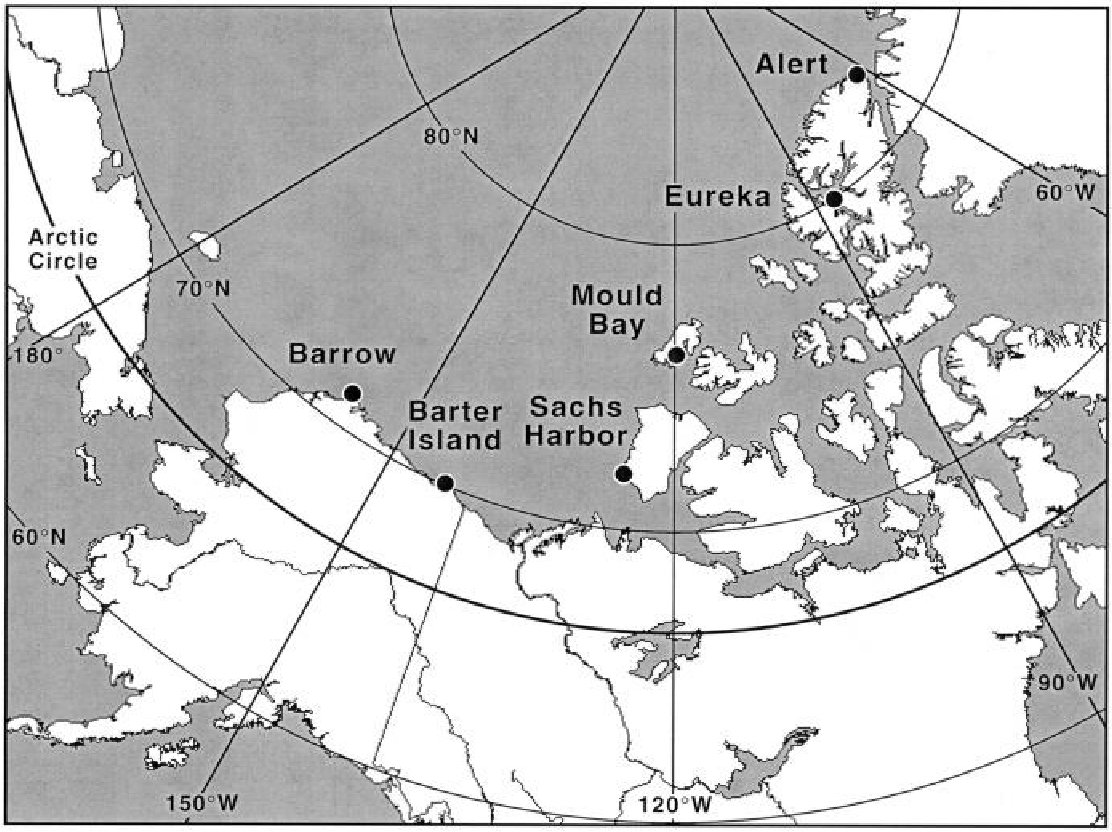


Figure 1. Map of the western Arctic. The locations of the stations are mentioned in the text

2. PRECIPITATION

In general, the recorded precipitation is very light in the western Arctic (Figure 1). Barrow has a long-term (1949–1988) annual mean of 118 mm water-equivalent, and Barter Island a mean of 153 mm. Actual precipitation is higher than these values, as precipitation and especially snowfall are parameters which are not easy to determine accurately. This is especially true for areas with moderate to strong winds as observed in northern Alaska. Precipitation gauges normally underestimate snowfall, and for the North Slope, this can be substantial (Black, 1954; Benson, 1982; Zhang *et al.*, 1996). Clagett (1988), making measurements with the large wind shielded Wyoming gauges, made the most detailed comparison. The Wyoming gauge comes much closer to 'actual' values. However, the ratio in precipitation to standard rain gauges depends strongly on the wind speed. This ratio is also different for solid and liquid precipitation. Hence, an easy correction mechanism is not available. For both Barrow and Barter Island, standard rain gauges were used.

For the observation sites, several local moves occurred for the period of record. The Barrow recording site moved from the Weather Bureau quarters # 1 on 2 April 1955 to a position about 48 m to the southeast and moved again another 106 m to the southeast from there on 7 November 1966. The Barter Island station moved from a location 850 m west of the airstrip on 9 December 1956 to a location 1.6 km further west. The coastal area of the North Slope is flat and displays very little local topography.

Looking at the annual cycle for both stations, August is normally the month with the maximum precipitation, while March displays the minimum. For 9 months (September through May), the mean monthly temperature is below the freezing point and most of the precipitation falls as snow. Only in June through August does the mean monthly temperatures raise above the freezing point, and the precipitation occurs predominantly as rain. Snow, however, can still occur any time of the year.

In Figure 2 the time series for the annual total of precipitation are presented for both stations. We analyzed the measured precipitation values keeping in mind that the measured values were too small. We preferred to use the actual measurements for trend analyses over some 'corrected' values. The analysis with 'corrected' data revealed a similar decreasing trend line (not shown). The best linear fit shows a substantial decrease for both stations (which are 550 km apart), despite a large scatter from year to year (Figure 2). The decrease in precipitation was significant at the 95% level for Barrow for both the 1949–1988 and 1949–1996 time periods. For Barter Island, the statistical significance was even higher and surpassed the 99% confidence level. While the general trend is similar for both stations, individual years do not follow each other for all cases. For example, at Barrow, the extremes were found in 1963 (maximum) and 1970 (minimum), while at Barter Island they occurred in 1954 and 1974, respectively. The absolute maximum was observed at Barter Island in 1954. If this extreme value is omitted from the trend analyses, the trend stays significant at the 99% level.

The best agreement in precipitation between the two stations on seasonal basis was found in winter, when the Beaufort Sea is ice covered; the worst in autumn, when there exists large difference in open water areas close to shore. These differences affect local water vapor sources.

In Figure 3 the precipitation trend lines for both stations are presented again for the different seasons. The actual data points were omitted to make the graph easier to read, but there is a substantial amount of scatter, similar to the scatter which could be seen in Figure 2. For both stations, and all seasons, a decrease in precipitation can be observed; the decrease was the strongest in winter, followed by spring. Furthermore, Barter Island shows a stronger decrease than Barrow. Since Barrow is much more affected by urbanization—at Barter Island the meteorological station was located at the airfield of the old DEW line site which has experienced no growth—this indicates that decreasing precipitation is not caused by urbanization. For Barrow, where we have more recent data, the declining trend in precipitation continued nearly unchanged through 1996. Only the winter and spring values of both stations are statistically significant, surpassing the 95% confidence level.

The number of days annually with measurable precipitation has decreased for both stations. Additionally, the decrease in the annual number of days with precipitation was less than the decrease in annual precipitation, resulting in a decrease in intensity (Figure 4). On the seasonal basis, the data are presented in Table I.

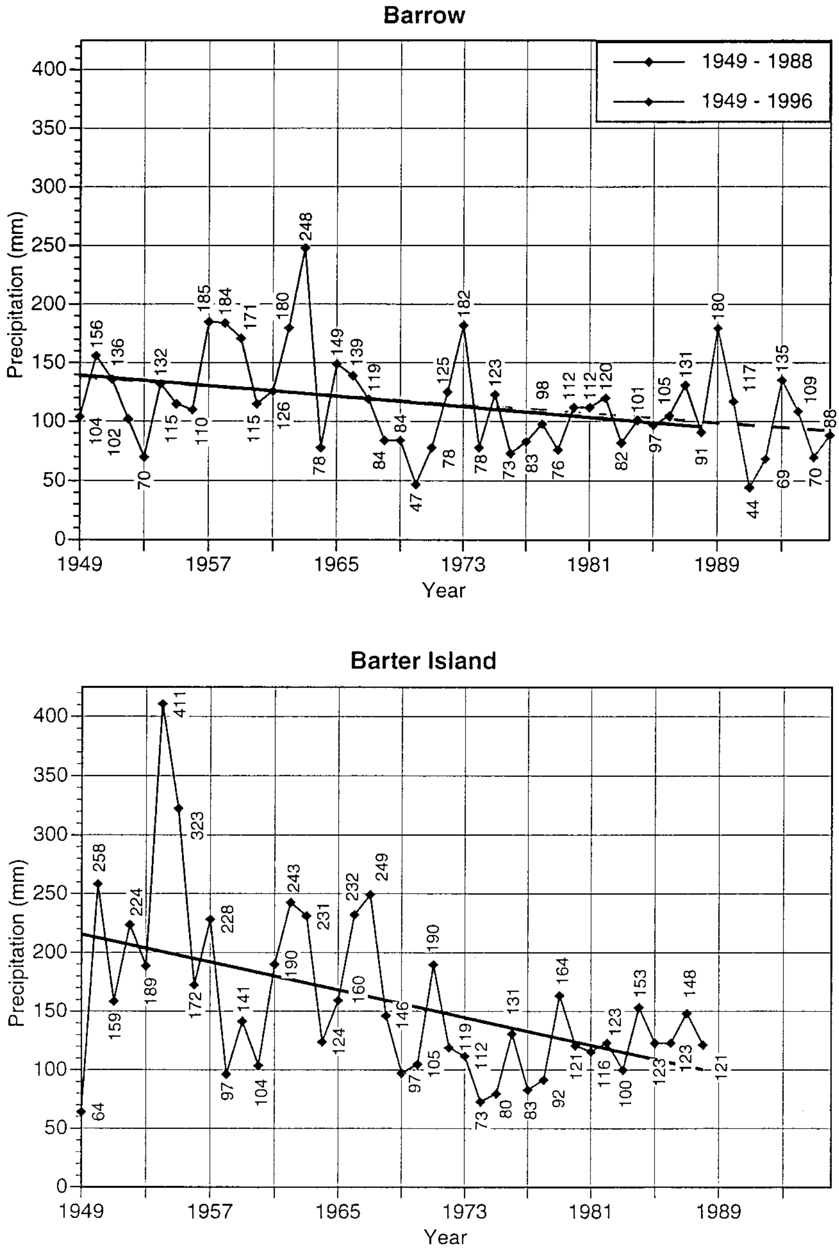


Figure 2. Time series (1949 through 1988) of the annual precipitation totals for Barrow and Barter Island. A second lighter shaded broken trend line for Barrow extends the data through 1996

The observed decreased precipitation, both in frequency and amount is especially large in winter. This is contrary to most predictions from GCM's (Tao *et al.*, 1996).

3. SNOWFALL AND SNOW COVER

The amount of snowfall was analyzed by season for Barrow and Barter Island. It would have displayed the identical course to the precipitation data if all precipitation had fallen in solid form with unchanging density. However, since most of the summer precipitation as well as part of the autumn (September) precipitation can fall as rain, these two seasons showed the poorest agreement between precipitation and snowfall amounts.

Comparing Tables I and II, spring and winter displayed the largest decreases in liquid water content as well as in the amount of snowfall for both stations. The agreement for autumn is less perfect. September, displaying a mean monthly temperature just below freezing, has on the average a larger amount of precipitation than October or November. Due to the observed warming (see detailed discussion later in the text), more precipitation will fall as rain than snow in the later years. Our observations verify this: the decrease in total precipitation is larger than the one for snowfall. Looking at the number of days with

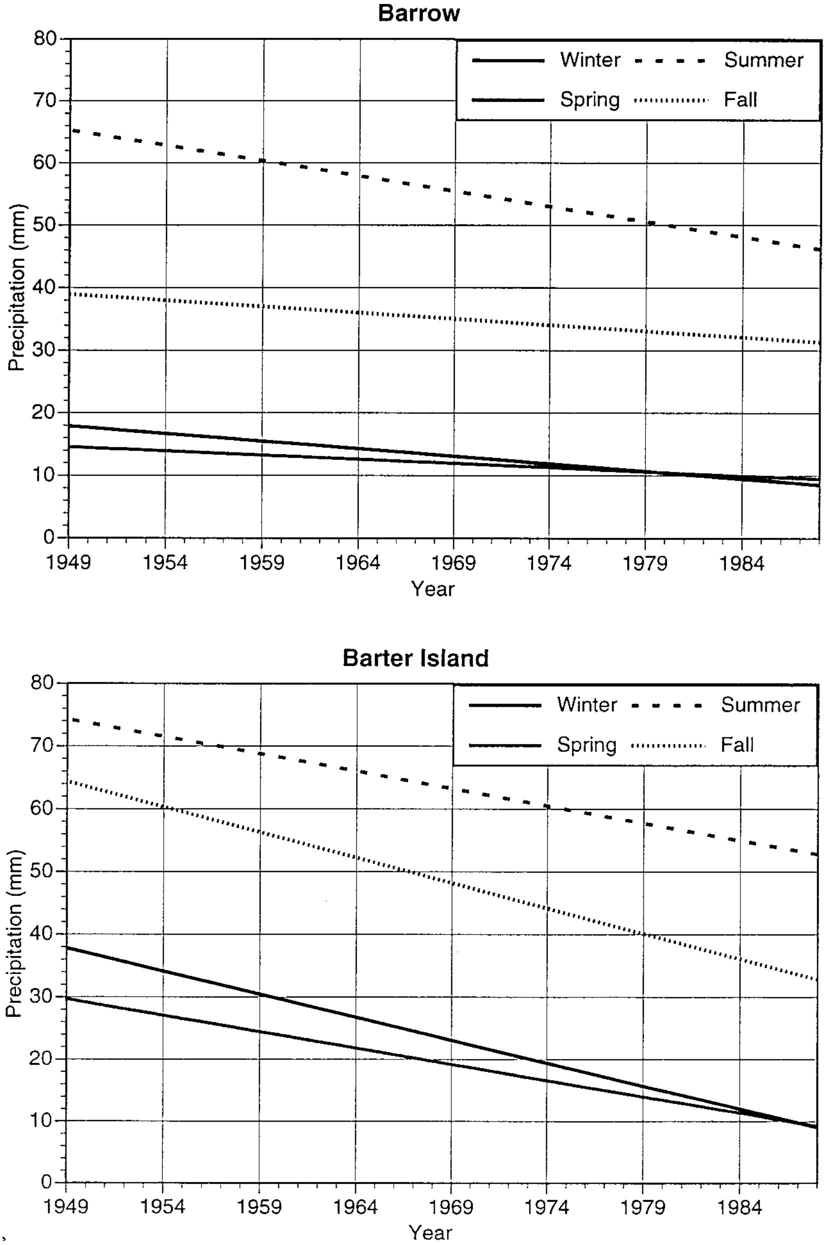


Figure 3. Trend lines (1949 through 1988) of the precipitation for Barrow and Barter Island for different seasons

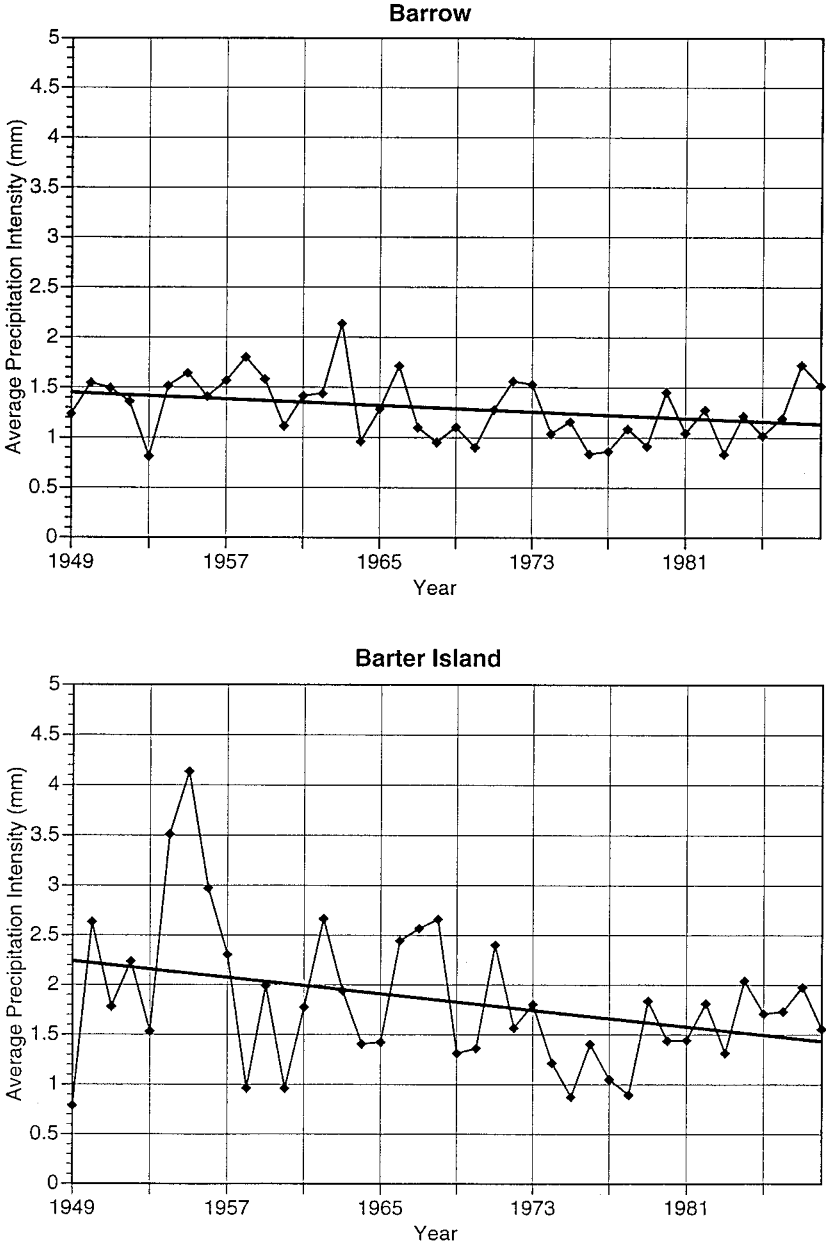


Figure 4. Time series (1949 through 1988) of the annual precipitation intensity for Barrow and Barter Island

measurable snowfall, we observed a decrease in the annual number of days from 75 to 53 at Barter Island, with no decrease at Barrow; additionally, the decrease in the amount measured was much greater at Barter Island than Barrow.

Snow can be measured on the ground (accumulation). It is carried out once daily at a permanently-mounted snow stake. Drifting and blowing snow will modify the amount measured at any specific location, and sublimation, which can be substantial in spring, will reduce the amount present. Therefore, snow depth is a parameter which is not expected to be in total agreement with the measured precipitation. Looking at the amount of snow on the ground for Barrow and Barter Island, a substantial decrease in the amount of snow cover could be observed during the 40-year observational period. Such a decrease is

Table I. Mean number of days with measurable precipitation and change of this frequency of occurrence (%) and the amount (%) by season for the time period 1949–1988 for Barrow and Barter Island

Stations	Spring	Summer	Autumn	Winter	Year
Barrow, days	15	27	32	16	90
Change in days (%)	−11	−10	−17	−20	−14
Change in amount (mm) (%)	−36	−30	−20	−53	−30
Barter Island, days	17	25	29	15	86
Change in number (%)	−54	+7	−18	−42	−25
Change in amount (mm) (%)	−69	−20	−48	−74	−47

in agreement with the observed decrease in precipitation. In Figure 5 the snow depth at the end of each month is plotted for the mean, first and the last 5 years of the observational period (40 years). In general, at the beginning of the snow season the amount of snow cover has not changed, while the amount of snow cover has been declining for the rest of the season for the later observational time period. This finding is in disagreement with the mean for all of Alaska which reported an increase of 11% in snowfall for the time period 1950–1990 (IPCC, 1996).

Foster (1989) looked at the date of snow cover disappearance on the Arctic Tundra in Alaska. He found that this date had become earlier for Barrow and Barter Island over the last four to five decades. Earlier melting of the snowpack each spring may result from: (i) less than normal accumulation of snow throughout the winter months, (ii) a warmer and earlier spring which accelerates ablation, or (iii) a combination of (i) and (ii). He speculated on the importance of his findings for climatic change. However, Dutton and Endres (1991) showed for Barrow that the earlier melt was in part due to the effect of local urbanization. The North Slope of Alaska, and especially Barrow, has seen rapid growth during the last two decades due to oil field related activities.

The disappearance of snow is frequently not well defined, as a broken snow cover can last for days and the date of snow melt depends on an exact location. Consequently, to evaluate the amount of accumulation, we analyzed the long-term records of the thickness of the snow cover on 30 April, a date prior to the onset of spring melt. Time series up to 1996 with linear regression analyses for six sites located in the Alaskan and selected Canadian Arctic are shown in Figure 6. A general decrease in snow depth for that date can be observed. While some stations (e.g. Barrow) may have been affected by urbanization, others were definitely not (e.g. Barter Island). Results shown suggest that there has been a decrease in winter precipitation over the entire western Arctic. The decrease was above the 95% confidence level for all stations except Eureka and Alert. Since 1972, this could be independently verified through satellite imagery (Robinson *et al*., 1993). The amount of snow covered area over North America was derived for April (Figure 7). A linear regression line was fitted through the data to identify a possible trend; this trend was not statistically significant due, in part, to the few data points, and high variance in the data.

Table II. Mean amount and observed changes of snowfall by season and year for Barrow and Barter Island, 1949–1988

Stations	Spring	Summer	Autumn	Winter	Year
Barrow, amount (mm)	154	45	342	164	705
Change (%)	−39	+56	−1	−35	−16
Barter Island, amount (mm)	199	91	513	269	1072
Change (%)	−31	+22	−18	−54	−29

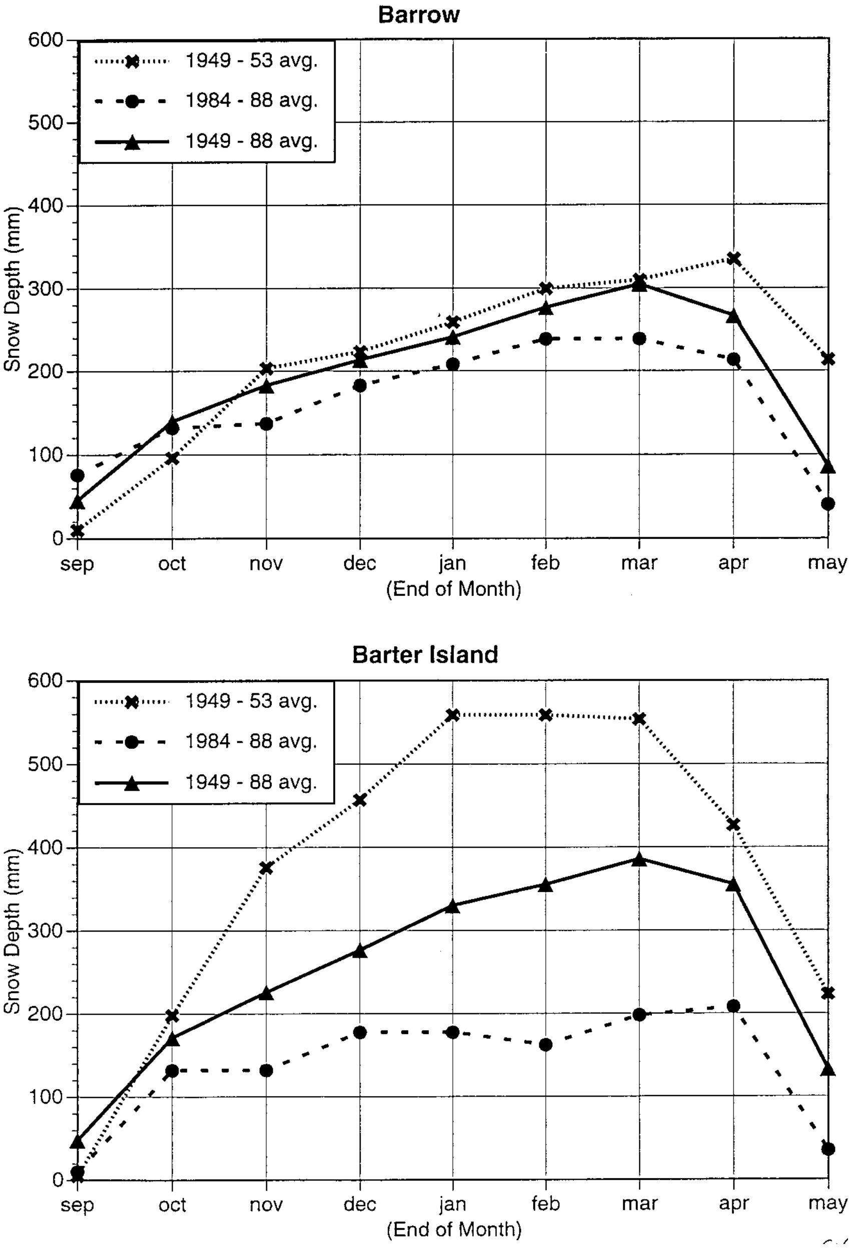


Figure 5. Snow depth of the snow cover on the ground as measured at the end of each month. The 40-year mean (1949–1988), and the first and last 5 years of the observational period are presented. Notice the decrease in the snow cover in winter and spring for both, Barrow and Barter Island

The two data sets are not directly comparable. The first is based on surface observations representing snow depth at a specific location and the second showing aerial extent of the annual snowpack. Nevertheless, both indicate an apparent downward trend. This is in agreement with other studies in the Arctic. Radionov *et al.* (1997) using Russian Arctic Basin drifting stations for the period 1954–1991, shows a 53% decrease in May snow cover depth and a snow cover melting date occurring 15 days earlier by the end of the study period.

4. PRECIPITATION AND CLOUDINESS

Normally clouds are present when precipitation occurs. However, in polar regions during winter, clear sky precipitation can be observed. This occurs when a relatively warm air mass is radiatively cooled and ice crystals are formed, which fall out during times of otherwise clear skies. Optical phenomena (haloes, sun dogs, etc.) can be frequently observed during such occasions. The amount of precipitation is small and often not recorded. Low-level clouds are normally the most important as far as precipitation is concerned. For both Barrow and Barter Island, the highest amount of low-level cloudiness is observed in autumn and summer with the smallest amount occurring in winter and spring. Annually, 10/10 cloud cover is the most frequent category (about 15%) with stratocumulus the most frequently observed cloud type. Totally clear conditions are infrequent with less than 2% (see Table III). The decrease in frequency from total overcast

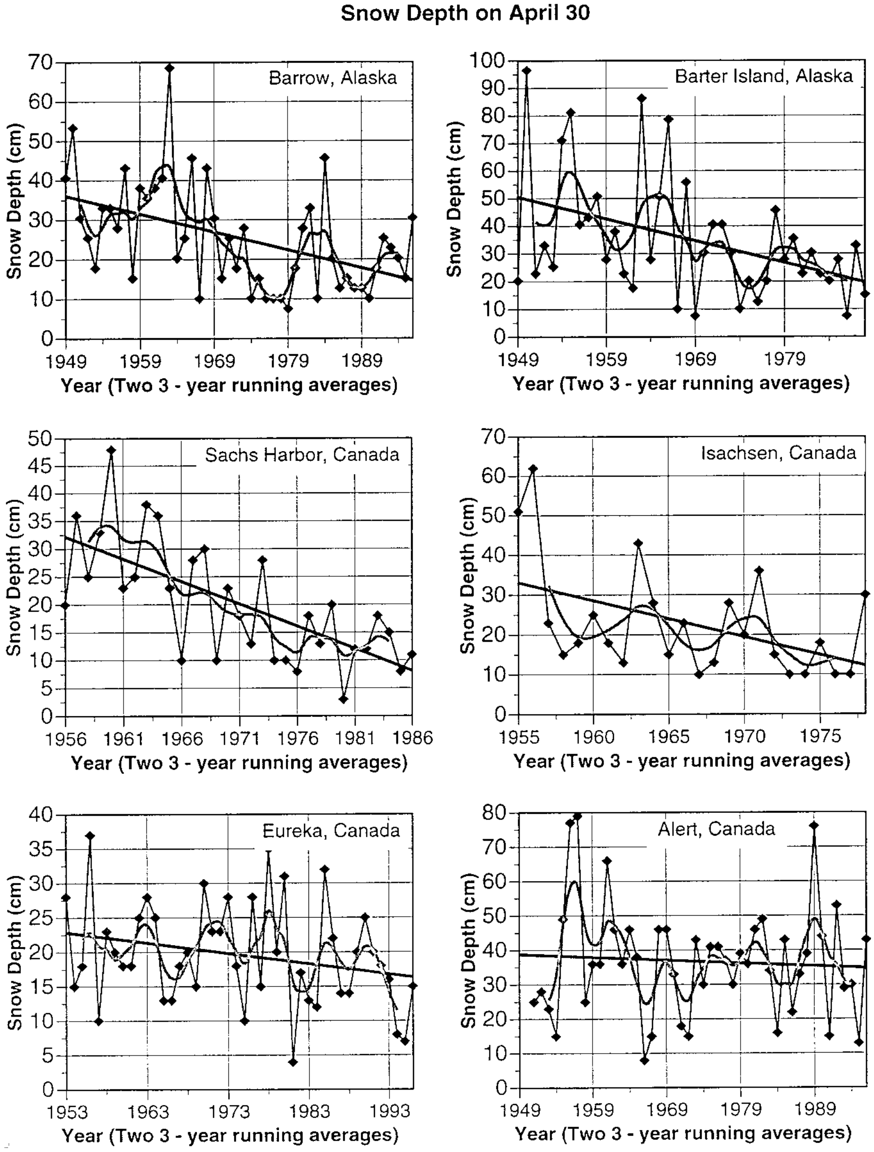


Figure 6. Snow depth on 30 April for arctic stations in Alaska (Barrow and Barter Island) and selected high latitude Canadian stations (Sachs Harbour, Isachsen, Eureka and Alert). Yearly depth are averaged twice using a 3-year running average. The linear trend line shows a decrease in snow depth for all stations

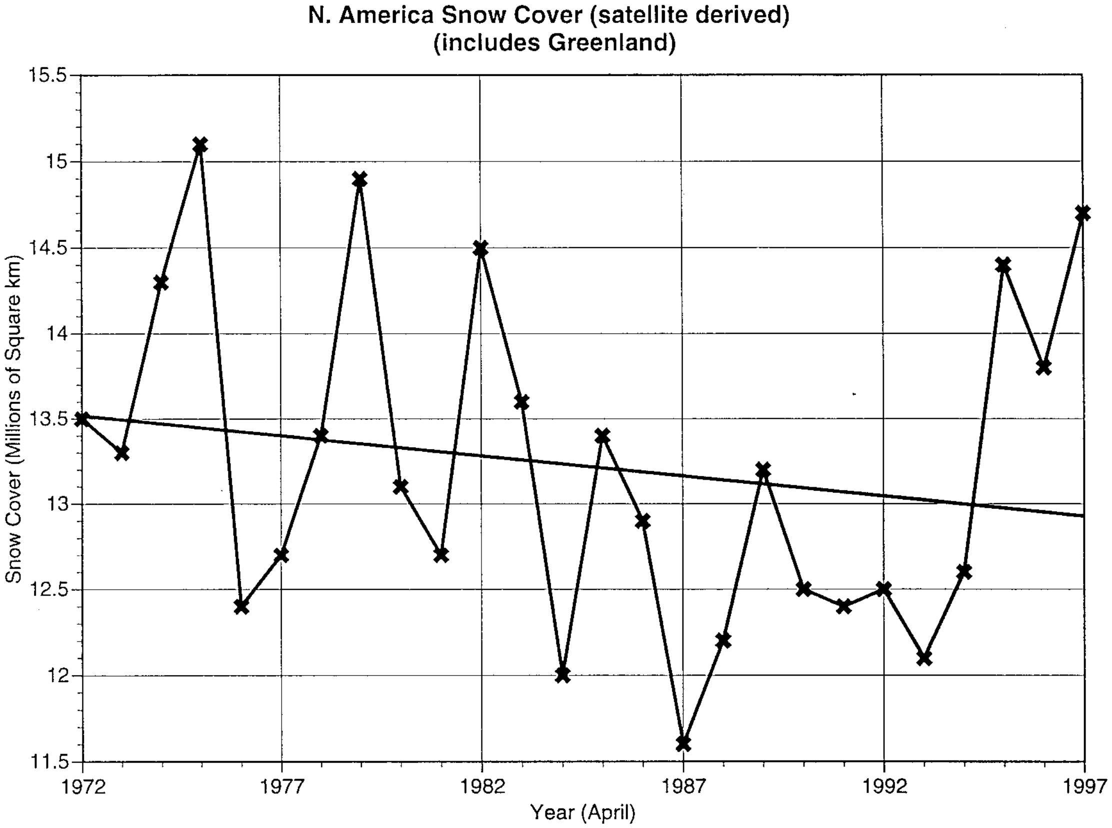


Figure 7. Area of snow cover (million square-km) in North America, including Greenland, for April, as derived from satellite (Robinson *et al.*, 1993). The linear trend line shows a decrease. Note, that the time series is shorter than the one in Figure 6

conditions to clear sky conditions is not linear; a secondary maximum occurs at 7/10 at Barrow and at 6/10 at Barter Island. The probability of precipitation as a function of low-level cloudiness is presented in Figure 8. For both stations, the increase in the probability is quite similar. The curve is fairly flat in the beginning (e.g., 2% probability of precipitation at 1/10) and towards the end with the steepest increase occurring in the mid-range (2–8/10 cloudiness). The increase in precipitation with increasing low-level cloudiness is statistically significant at the 99% confidence level (linear fit) for the annual and all seasonal (not shown) values.

Figure 9 shows the time series for Barrow and Barter Island of the low-level cloudiness during the 40-year period. Observations are carried out in 3-h intervals by a human observer; these can be difficult during times of darkness. The stations display a decrease in cloudiness with time which is in the order of 20%. For both stations, this decrease is significant at the 99% confidence level. This strong decrease in low-level cloud cover on the North Slope is in agreement with the decrease in precipitation which was observed for the same time period (Figure 2).

Table III. Frequency by percentage of low clouds for Barrow and Barter Island, 1949–1988

Clouds (1/10)	0	1	2	3	4	5	6	7	8	9	10
Barrow	1.7	3.1	5.2	6.6	8.3	9.8	11.8	12.7	12.5	12.1	16.2
Barter Island	1.3	2.8	5.1	7.6	9.9	12.0	13.0	12.7	12.0	10.2	13.7

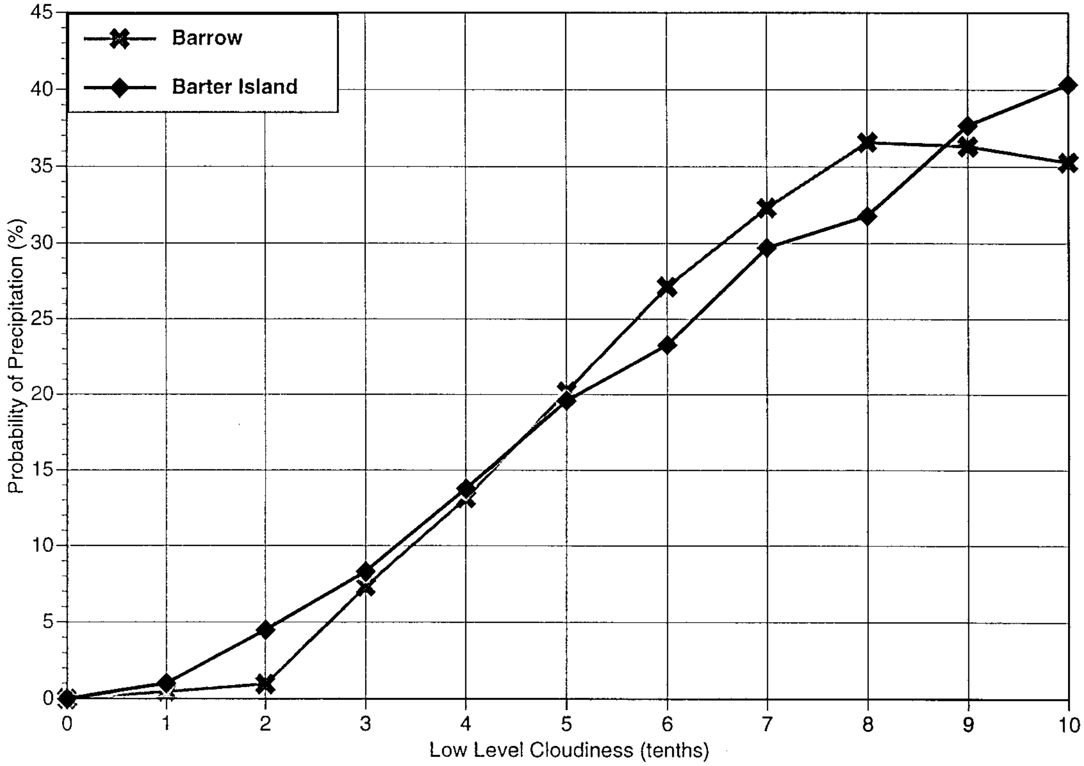


Figure 8. Probability of precipitation as function of low-level cloudiness for Barrow and Barter Island, 1949 through 1988

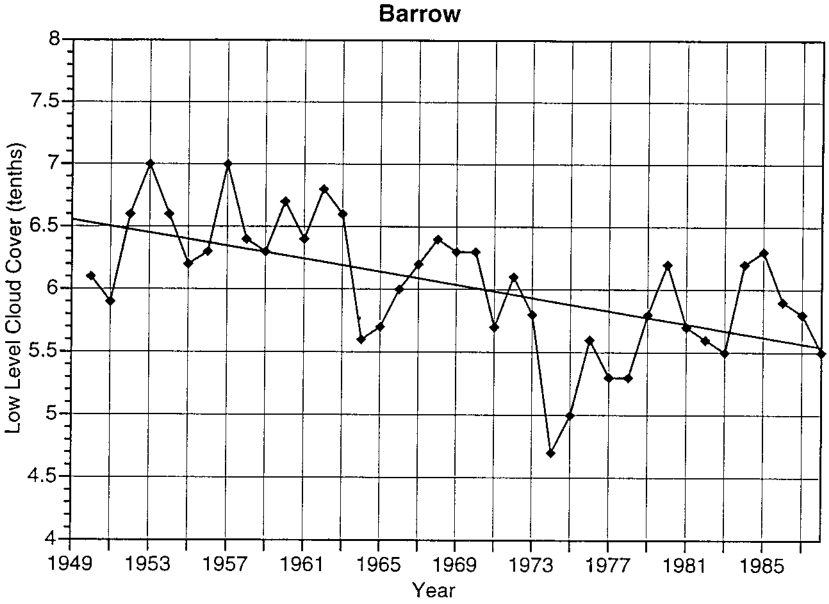
The seasonal trends are summarized in Table IV. The change in cloudiness was obtained by forcing the best linear fit through all points of observations for each season and station. All seasons for both stations displayed a decrease in cloudiness. Further, for both stations the decrease in low cloudiness is strongest in autumn, followed by summer, winter and spring.

We also analyzed the total amount of cloud cover, independent of the heights of the clouds (not shown). While the direction of the trends was for all cases identical to the low cloud cover scenario, the magnitude varied somewhat. Further, for Barrow since 1988, a reversal of the trend is being observed which reduces the steepness of the observed decrease in low-level cloudiness for the period 1949–1996. In summary, the observed decrease of low cloudiness is in agreement with the observed decrease in precipitation.

5. PRECIPITATION AND TEMPERATURE

The mean annual temperature has increased at many western Arctic locations (Stone *et al.*, 1992). According to Stone (1997), Barrow and Barter Island displayed a warming of 1.4°C and 1.0°C, respectively, during the last 30 years (1965–1995). For the longer time period (1949–1996), we calculated a mean warming of 1.5°C for Barrow. The warming is not evenly distributed over the year; the maximum is found in winter (2.1°C for 1949–1996) which is in agreement with model calculations. For the 40-year time period (1949–1988), the mean warming was less pronounced. The winter value was high, but in autumn, a strong temperature decrease was observed which is in agreement with Chapman and Walsh (1993). They analyzed the temperature trends of the Arctic for the 1961–1990 time period. For northern Alaska, they found a strong warming in winter, a cooling in autumn and a slight warming in summer, all in agreement with our observations. Only the trend in spring (they found warming) is in disagreement with our findings which is due to the different time period used. Further, Wallace *et al.* (1996), looking at the total northern hemisphere, observed a strong warming for the cold season since about 1980.

We estimated the total change in precipitation to be expected from the observed in low-level cloudiness. The data were averaged for Barrow and Barter Island for the 40-year period. We took the beginning and end-points of the linear trend in low-level clouds and found a decrease in cloud amount for all seasons with summer and autumn showing the greatest decline (> 20%) (see Table V(a)). Winter showed the least change followed by spring. Next we took low-level cloud cover in one-tenth sky cover bins and averaged daily precipitation for all cloud categories whether precipitation occurred or not. A second order regression least square fit with a forced intercept at zero was derived. The coefficients for the different seasons and year are given in Table V(b). Now, we looked and the actual observed decrease in



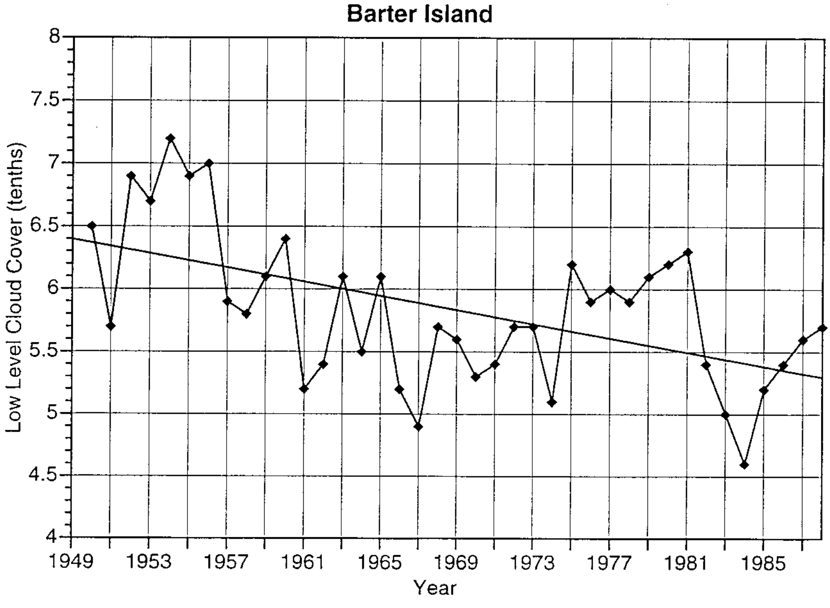


Figure 9. Time series of low-level cloudiness for Barrow and Barter Island. The lines represent the best linear fit

Table IV. Amount of low-level cloudiness (in tenths), observed change (%) and level of significance for Barrow and Barter Island, 1949–1988

Stations, Seasons	Start	End	Change	Significance
Barrow				
Spring	6.10	5.45	−11	>0.95
Summer	7.17	5.80	−24	>0.999
Autumn	7.78	6.01	−29	>0.999
Winter	5.30	5.06	−18	>0.999
Year	6.55	5.53	−18	>0.999
Barter Island				
Spring	5.91	5.62	−5	<0.90
Summer	6.41	4.93	−30	>0.999
Autumn	7.48	5.62	−33	>0.999
Winter	5.80	5.06	−15	>0.95
Year	6.43	5.32	−21	>0.99

precipitation on a seasonal and annual basis (Table V(c)) applying linear regression trend lines. As the final step, the percentage of the precipitation decrease, which could be expected solely by the observed decrease in cloud amount is presented in the last line of Table V(c). By comparing the measured precipitation decrease over the 40 years with the amount calculated from the decrease in low cloud cover amount, 60% of the observed annual decrease could be explained by the decrease in cloudiness. By seasons, the agreement is better for summer and autumn than in winter and spring. This might be due to the small amount of precipitation during these two seasons and its large variability from year to year. Besides cloudiness, other climate parameters, such as changes in large scale circulation patterns, wind direction, moisture advection and frequency of cyclones will all affect precipitation.

In Table VI, the probability of precipitation (days with precipitation as function of the total number of days) is presented as a function of temperature for both Barrow and Barter Island. One can see that the probability increases on average from about 10% at temperatures below −30°C to above 35% for temperatures above −15°C; thereafter the course is fairly flat and irregular. In winter, the temperature

Table V. Trend in low-level cloud amount (a), cloudiness versus precipitation (b) and the observed decrease in precipitation (c) averaged for Barrow and Barter Island, 1949–1988.

		Winter	Spring	Summer	Autumn	Year
(a) Low-level cloudiness						
Trend line	Start	5.4	6.0	6.8	7.6	6.5
	End	5.1	5.4	5.4	5.8	5.4
	Δ (%)	−5.2	−9.1	−21.1	−23.6	−15.9
(b) Cloudiness vs. precipitation						
2nd order fit coefficients	A (X^2)	0.00105	0.00063	0.00060	0.00320	0.00073
	B (X)	0.00039	0.00166	0.02079	−0.00543	0.00186
	r^2	0.955	0.949	0.912	0.983	0.969
(c) Precipitation amount						
Trend line	Start	38.9	24.2	44.8	65.5	173.9
	End	20.2	8.9	31.1	39.5	99.5
	Δ (%)	−48.0	−63.2	−30.5	−39.7	−42.8
Explained decrease (%)[a]		20.6	29.4	78.0	118	59.8

[a] The percentage of the precipitation decrease, which could be expected solely by the observed decrease in cloud amount.

Table VI. Probability of precipitation as function of temperature (°C) for Barrow and Barter Island, 1949–1988

Temperature Bin	Barrow (%)	Barter Island (%)
> −40 to −36	2.8	2.8
> −35 to −31	5.4	7.7
> −30 to −26	9.4	12.7
> −25 to −21	15.8	17.9
> −20 to −16	27.3	25.3
> −15 to −11	36.4	34.1
> −10 to −6	33.6	32.5
> −5 to −1	32.4	29.7
>0 to 4	29.7	27.9
>5 to 9	41.4	31.3

is normally warmer when there is a large amount of low cloud cover. This is also the time when it is most likely for precipitation to occur. This causes the precipitation amount to increase with increasing temperatures. However, in summer the opposite holds true; clear days are the warmest, and cloudy ones are the coolest. This reversal is caused by the radiation balance which in winter is dominated by the long wave radiation but in summer by the solar radiation (Weller and Holmgren, 1974; Wendler *et al.*, 1981; Dutton *et al.*, 1985; Wendler, 1991; Stone *et al.*, 1996). For that reason, at warmer temperatures the strong relationship between temperature and probability of precipitation breaks down. Isaac and Stuart (1996) carrying out a study in northern Canada came to the same conclusions.

Figure 10 shows the average amount of precipitation plotted against temperature. The base for the calculations were all days at a specific temperature, independent of whether it rained, snowed, or was dry on this specific day. The observed precipitation amounts where, therefore, small. Because cases below − 40°C and above 9°C are infrequent, the frequency distribution was terminated at these points. For both cases, a non-linear increase in the amount of precipitation was observed with increasing temperature. This non-linear increase is expected from the Clausius–Clapyeron curve (saturation vapor pressure as a function of temperature) which is also non-linear. The variance (r^2) between water vapor saturation pressure as derived from the measured temperature and the average amount of precipitation is 0.85 for Barrow and 0.72 for Barter Island. This means that for the long-term average, 85% and 72%, respectively, of the average daily precipitation on a day with a specific temperature could be explained solely by the saturation vapor pressure over water at that temperature. In summary, only in autumn when we observed a decrease in temperature can the decrease in precipitation be explained by a temperature change.

6. PRECIPITATION AND ATMOSPHERIC PRESSURE

In Table VII, the probability and averaged amount of precipitation is presented as a function of atmospheric pressure for Barrow and Barter Island. The expected increased likelihood of rain or snow with decreasing pressure was observed. At a surface pressures between 990 hPa and 994 hPa, the likelihood of precipitation is about 50% for Barrow and 37% for Barter Island. At higher pressures such as between 1030 hPa and 1034 hPa, it is 7% for Barrow and 14% for Barter Island. Pressure affects not only the probability of occurrence but also the amount of precipitation. Expectedly, on an average day with low pressure, more rain or snow is falling than on a day with high pressure. However, the rate of decrease is strongly dependent on the season, as can be seen from Figure 11 in which the seasonal results are presented for Barrow. The rate of decrease of precipitation is large in summer and to a lesser extent in autumn (confidence level exceeds 99%). For winter and spring little if any relationships exist between atmospheric pressure and precipitation intensity. No statistical significance was observed.

The atmospheric pressure displays a strong annual cycle (not shown). The maxima are found early in the year (January through March) with values of about 1020 hPa; February is normally the coldest month. The minima occur in late summer and early autumn (August through October) with mean values of about 1010 hPa. This was observed for both North Slope stations.

We analyzed the data for long-term atmospheric pressure changes. The mean annual values varied between 1014 and 1018 hPa. However, no trend for the 40 years could be observed. If a linear regression line is put through the data points, Barrow showed a insignificant increase, while Barter Island displayed

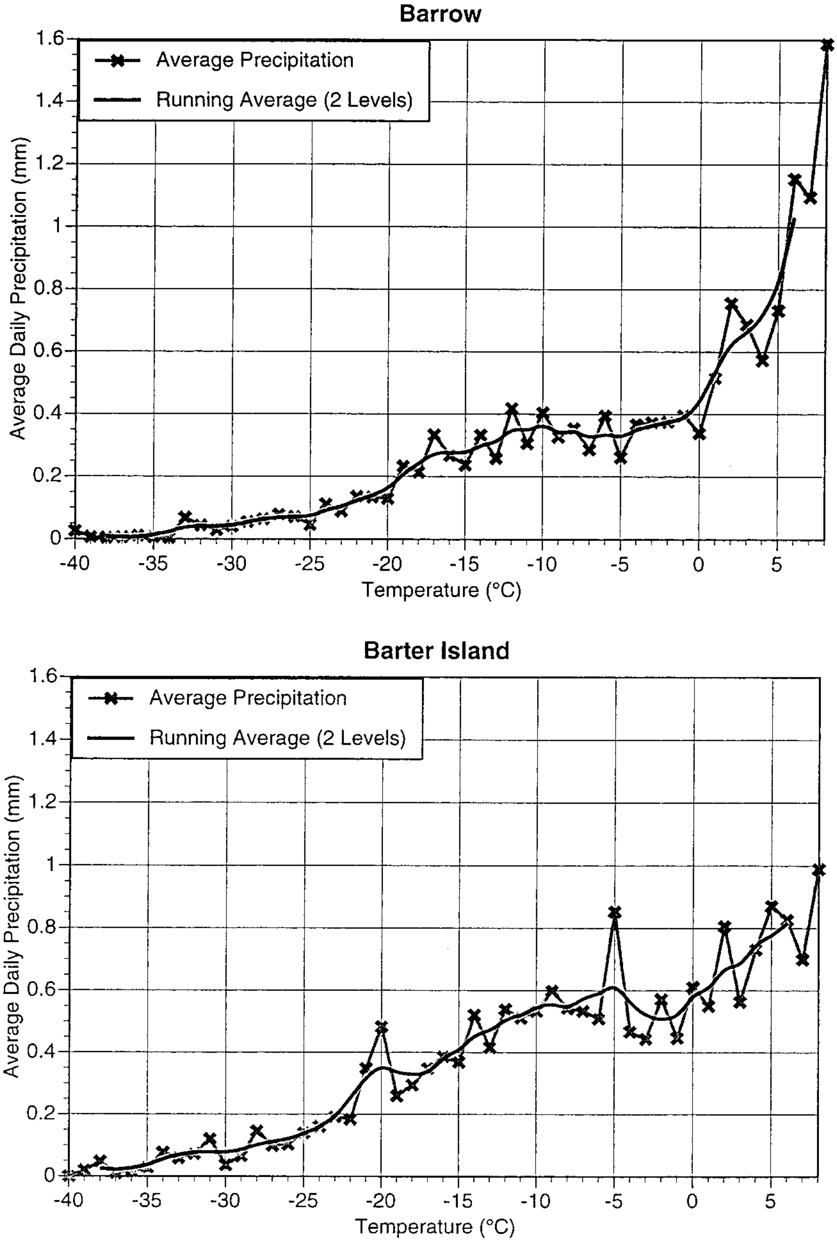


Figure 10. Mean amount of precipitation as function of temperature (all days, with or without precipitation included). Note, the increased amount in precipitation with increasing temperature

Table VII. Averaged amount and probability of precipitation as function of surface pressure for Barrow and Barter Island, 1949–1988

Pressure	Barrow		Barter Island	
Bin (hPa)	Average precipitation (mm)	Probability (%)	Average precipitation (mm)	Probability (%)
>986 to 990	0.59	46.8	0.53	31.3
>990 to 994	1.03	50.4	0.62	36.8
>994 to 998	0.98	51.8	0.84	35.6
>998 to 1002	0.84	47.3	0.63	32.7
>1002 to 1006	0.70	42.8	0.61	32.3
>1006 to 1010	0.50	35.3	0.62	28.5
>1010 to 1014	0.34	28.7	0.46	24.8
>1014 to 1018	0.25	21.7	0.32	21.5
>1018 to 1022	0.15	17.3	0.31	20.5
>1022 to 1026	0.11	13.3	0.27	15.6
>1026 to 1030	0.08	11.0	0.20	15.3
>1030 to 1034	0.06	7.2	0.29	14.1
>1034 to 1038	0.04	6.4	0.13	11.7

a small decrease in atmospheric pressure. For both cases, the change over the 40 years was less than 1 hPa. Further, the seasonal trends are weak and statistically insignificant.

We attempted to correlate the decrease in precipitation with the number of transiting synoptic lows. For the data base we used a 28 year record (1966–1993) of twice-daily extra-tropical cyclone statistics for the northern hemisphere (Serreze, 1995). The data set includes the position and central pressure of each cyclone. In our analysis, low pressure centers were counted if they passed within 5° latitude and 10° longitude and within + 24 h of Barrow and Barter Island.

Slow moving lows, therefore, could count as more than one occurrence. Neither for Barrow nor for Barter Island was there any relevant correlation between the number of cyclones and precipitation amounts found. Perhaps our area was too large or the counting of lows several times during their transit influenced the results. Furthermore, the smaller scale polar cyclones (not in the database) might have more of an influence than extra-tropical systems for producing precipitation. It is interesting to note that the El Niño year of 1982 showed the lowest number of low pressure events for the 23 years (1966–1988) for Barter Island; for Barrow's 28 years, it was the third lowest.

We also looked at the variability of the atmospheric pressure, using the difference between the daily maximum and minimum and averaging these values for each year. A decrease in diurnal variability would suggest that either the intensity and/or frequency of synoptic systems has decreased. Hence, we suggest that a decrease in variability is connected with fewer or less intense cyclones and, therefore, less precipitation. In Figure 12 the annual trend lines are presented both for Barrow and Barter Island. It can be seen that for both stations the variability in pressure decreased by more than 10%. These decreases were statistically significant (for Barrow above 95%, and for Barter Island above 99% confidence level). For the seasons, the decrease in variability in surface pressure was the strongest in winter and spring (not shown), the two seasons in which the greatest decrease in precipitation was observed.

In summary, by using statistical means we were able to establish meaningful relationships between atmospheric pressure variability and precipitation which can explain the decreasing trend in precipitation observed in northern Alaska. This is in agreement with changes in teleconnection, circulation and upper air patterns which have been observed in recent decades. Hurrell (1996) showed that atmospheric pressure over the North Pacific was 2.2 hPa lower during the winter months between 1977 and 1988 when compared to the long-term mean of 60 years. This resulted in a change involving the Pacific–North American teleconnection pattern and corresponded to a deeper and eastward shift of the Aleutian low pressure system which advects warmer and moister air along the west coast of North America. Harris and Kahl (1994) studying transport patterns to Barrow during 1985–1992 revealed that during an anomalous warm year of 1989, there was an increase number of trajectories from the Aleutian region. Furthermore, Serreze *et al.* (1997) studying cyclone frequency for the period 1966–1993 noted that a more positive North Atlantic Oscillation index in recent years corresponds to a significant local increase in cyclone activity north of 60°N during both cold and warm seasons.

7. PRECIPITATION AND WIND

Precipitation probability is dependent on wind direction. Normally, on the North Slope, westerly and southerly winds advecting relatively warm and moist air are most likely to result in precipitation. In Table VIII, the probability is presented for the different seasons and year for Barrow (no detailed wind data for Barter Island could be obtained). As base for the statistics, 24-h time periods were used, for which the resultant wind direction was calculated and related to the precipitation during the same time period.

The last number of the first line of the Table VIII (0.26) means that on the yearly average, there is a 26% probability of precipitation if the wind blows from a northerly direction (> 315–45°). In general, the table shows that precipitation is much more likely to occur in autumn and summer than in spring and winter. With winds from an easterly direction, blowing from the continental Canadian Arctic, it is most unlikely for precipitation to occur, while for three seasons, westerly winds advect the

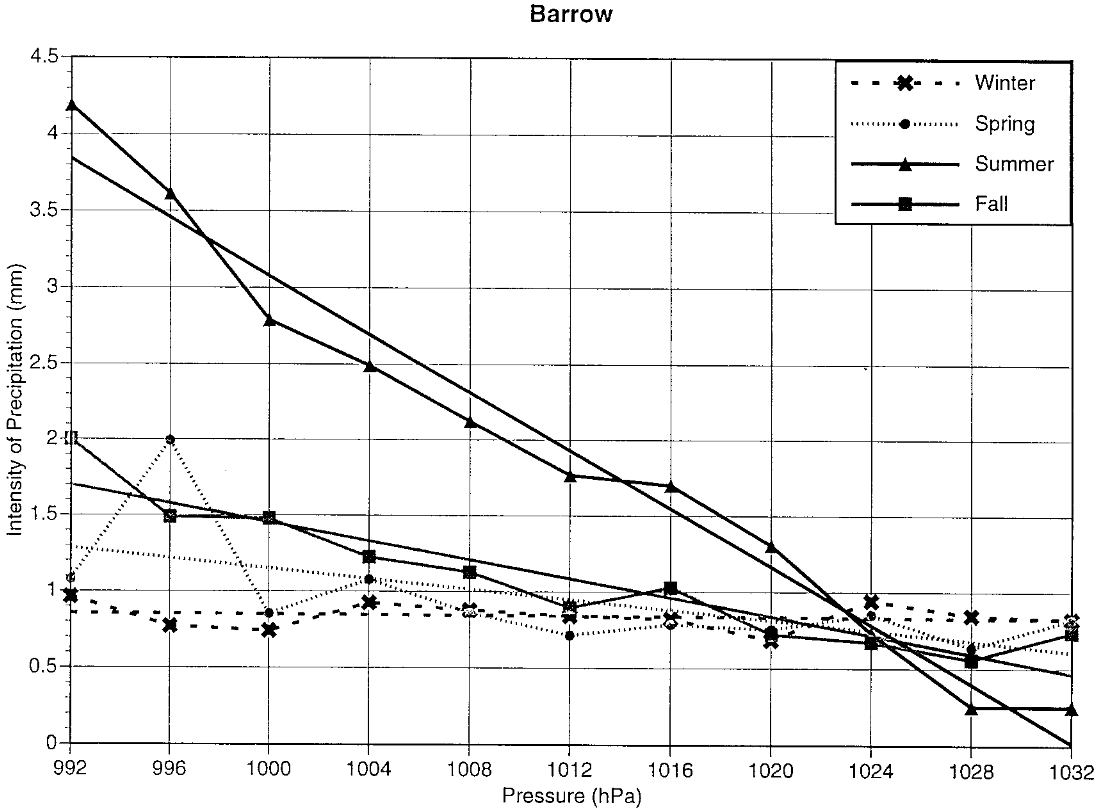


Figure 11. Intensity of precipitation with trend lines as a function of surface pressure by season for Barrow. Note, that the increase in precipitation is most pronounced in summer, the least in winter, and the two intermediate seasons are somewhere between winter and summer

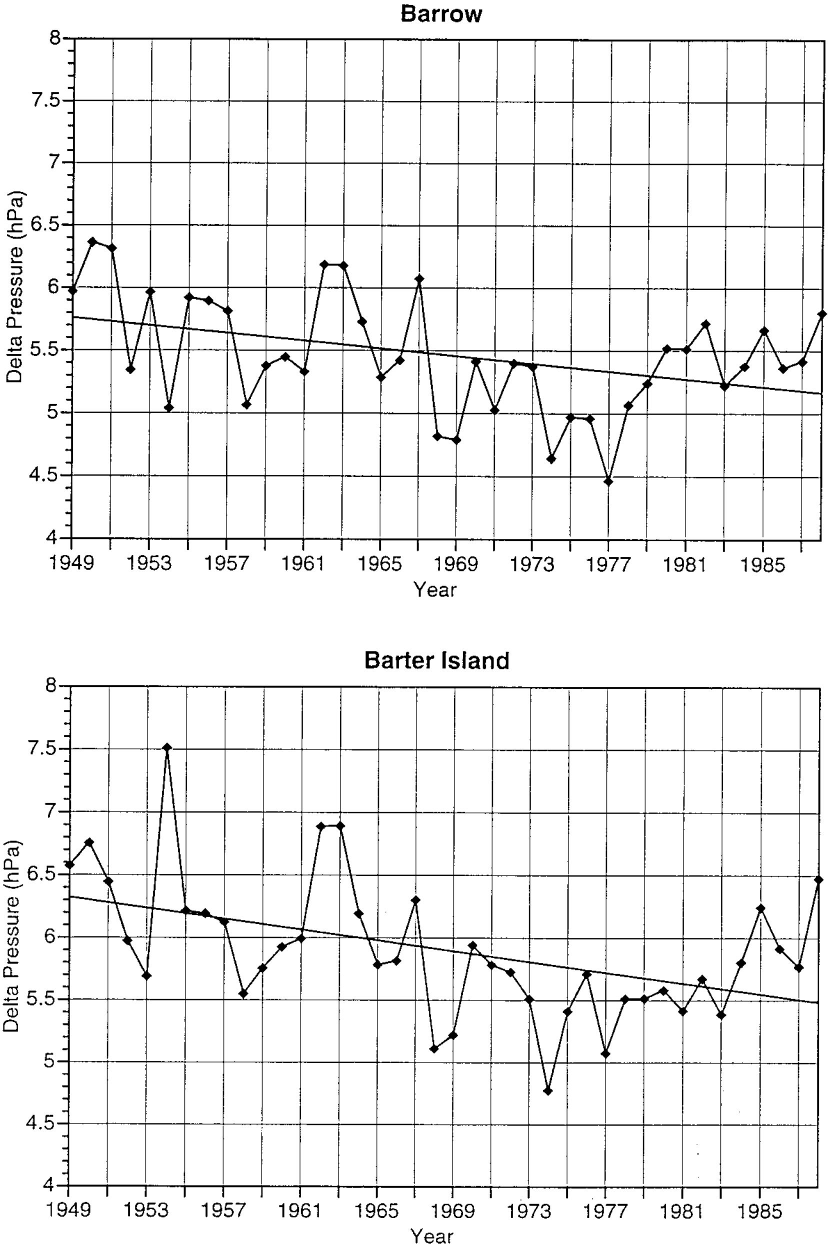


Figure 12. Variability (annually averaged values of daily maximum minus daily minimum) of atmospheric pressure, Barrow and Barter Island, 1949 through 1988. Note the decrease in variability with time for both stations

most moisture. It is interesting to note that the probability of precipitation is high in autumn with a northerly wind. The smallest decrease in precipitation as observed in autumn might be caused by a relative increase in open water for this season, as observed in the Beaufort Sea.

In Table IX, the frequency of occurrence of different wind directions is presented for Barrow. The most frequent wind direction (easterly is observed about half the time) is also the one with the lowest probability of precipitation. Westerly winds which have the highest probability of precipitation occur only 18% of the time while northerly and southerly winds are even less common.

Table VIII. Probability of precipitation by season as function of wind direction for Barrow, 1949–1988

	Spring	Summer	Autumn	Winter	Year
North	0.16	0.27	0.42	0.18	0.26
East	0.15	0.19	0.29	0.15	0.20
South	0.17	0.50	0.37	0.24	0.32
West	0.22	0.41	0.48	0.21	0.33

Table IX. Frequency of directional wind distribution by season and year for Barrow, 1949–1988

	Spring	Summer	Autumn	Winter	Year
North	0.18	0.18	0.16	0.16	0.17
East	0.56	0.48	0.52	0.47	0.51
South	0.12	0.12	0.17	0.15	0.14
West	0.14	0.22	0.15	0.22	0.18

Table X. Average amount of precipitation (mm) as function of wind direction by season and year at Barrow, 1949–1988

	Spring	Summer	Autumn	Winter	Year
North	0.12	0.45	0.39	0.11	0.27
East	0.12	0.38	0.30	0.12	0.23
South	0.17	1.20	0.44	0.26	0.50
West	0.19	0.91	0.58	0.18	0.49

In Table X, the average amount of precipitation (mm) as a function of wind direction is presented independent whether raining, snowing, or dry on a specific day. In general there is a fair agreement between Table VIII and Table X. If the probability of precipitation is high, the amount of precipitation for this wind direction is also high and vice versa. The lowest amount of precipitation can be expected with easterly winds, followed by winds from the north. The highest amount is found with westerlies, followed by winds from the south. Because annually more than twice the average precipitation is found with westerly winds compared to easterly winds, the sensitivity to changes in the circulation systems is clearly demonstrated.

We compared the frequency distribution of the wind direction for the first and last 5 years of the observational period for Barrow. In winter, the season with the strongest decrease in precipitation, a relative increase in northerly wind of 42% was observed. Northerly winds are the ones that advect the least amount of moisture at this time of the year (Table X). On the other hand, the frequency of westerly winds which advect the most moisture decreased 36%. In spring there was also a less pronounced increase with winds from a northerly direction, the direction of the lowest amount of moisture. In summer, the frequency of southerly winds decreased, and the frequency of northerly winds increased, also leading to a decrease in precipitation. Autumn is the only season during which no systematic shifts in the frequency distribution of the wind directions could be observed. This is also the season during which the lowest decrease in precipitation was observed. In general, it can be stated that the observed shifts in the frequency of surface wind directions is, for all seasons, in good agreement with the observed decrease in precipitation.

8. CONCLUSION

A strong decrease in precipitation has been observed on the North Slope of Alaska over the last half century. Canadian observations and Russian drift stations show that this decrease is widespread over the western Arctic. The decrease was especially pronounced in winter and spring. Using 40 years of fairly consistent observations from two stations on the North Slope, we tried to explain these changes. The temperature has increased for all seasons except autumn and cannot explain the decrease in precipitation. However, plausible explanations could be obtained from wind direction changes, decreasing variability in surface pressure, and decreasing cloudiness. Since surface winds are coupled with the upper level winds for most of the year; future work should include a thorough investigation of the synoptic-scale upper-level wind patterns over time and how these relate quantitatively to precipitation amounts.

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