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ORIGINAL PAPER

# Changes in the climate of the Alaskan North Slope and the ice concentration of the adjacent Beaufort Sea

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**Abstract** A reliable data set of Arctic sea ice concentration based on satellite observations exists since 1972. Over this time period of 36 years western arctic temperatures have increased; the temperature rise varies significantly from one season to another and over multi-year time scales. In contrast to most of Alaska, however, on the North Slope the warming continued after 1976, when a circulation change occurred, as expressed in the PDO index. The mean temperature increase for Barrow over the 36-year period was 2.9°C, a very substantial change. Wind speeds increased by 18% over this time period, however, the increase were non-linear and showed a peak in the early 1990s. The sea ice extent of the Arctic Ocean has decreased strongly in recent years, and in September 2007 a new record in the amount of open water was recorded in the Western Arctic. We observed for the Southern Beaufort Sea a fairly steady increase in the mean annual amount of open water from 14% in 1972 to 39% in 2007, as deduced from the best linear fit. In late summer the decrease is much larger, and September has, on average, the least ice concentration (22%), followed by August (35%) and October (54%). The correlation coefficient between mean annual values of temperature and sea ice concentration was 0.84. On a monthly basis, the best correlation coefficient was found in October with 0.88. However, the relationship between winter temperatures and the sea ice break-up in summer was weak. While the temperature correlated well with the $CO_2$ concentration ($r$=0.86), the correlation coefficient between $CO_2$ and sea ice was lower ($r$=−0.68). After comparing the ice concentration with 17 circulation indices, the best relation was found with the Pacific Circulation Index ($r$=−0.59).

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## 1 Introduction

The climate on planet Earth is in constant flux, and changes with time have occurred long before human beings had influence on the climate. However, during the last few decades a substantial warming has been experienced to which human activity on Earth most likely has contributed (IPCC 2007). There have been a great number of studies, including both observations and modeling efforts, and the vast majority of these show that this change is especially pronounced in polar and sub-polar regions (Serreze and Barry 2006; Wendler 2006). Changes are not limited to just temperature, as other climatological parameters such as snow cover (Warren et al. 1999; Brown 2000; Stone et al. 2002), precipitation (Curtis et al. 1998), atmospheric dynamics (Overland et al. 1999), and sea ice concentration (Chapman and Walsh 1993; Kay et al. 2008) have all demonstrated changes.

In the present study, we investigate the climate change of the North Slope of Alaska and the sea ice concentration changes in the adjacent Southern Beaufort Sea. The Alaskan North Slope is the area north of the Brooks Range, and has in the western part a width of about 200 km, decreasing to some 100 km close to the Canadian border. The climate is polar (ET after Köppen), with all months having mean temperatures below 10°C. Only 3 months, June to August, have average temperatures above the freezing point, and for about 9 months a year snow covers the tundra. Permafrost underlies the surface, and the active layer (the layer which thaws in summer), has a thickness of about 300 to 400 mm. The annual mean temperature is below −10°C. The precipitation is light with some 150 mm in the coastal regions, increasing somewhat towards the foothills. Further, over the last few decades there has been a decrease in precipitation observed in the western Arctic (Curtis et al. 1998). Wind speeds are fairly strong with a mean annual value of about 6 m/s, as the coastal stations are freely exposed to the Arctic Ocean. Mostly easterlies are observed, which drive also the Beaufort Gyre, a current flowing towards the west in the coastal area.

Given the substantial temperature changes on the North Slope of Alaska it is natural to relate these to changes in the sea ice concentration of the adjacent Beaufort Sea. The analysis was carried out for the time period is 1972–2007, for which reliable satellite-derived sea ice concentrations are available. We chose the ocean area between 70 and 72°N, and 142 to 152°W, about an area of 220 km by 380 km in extent (Fig. 1). We chose an area somewhat to the East of Barrow, as we wanted to avoid additional complications due to the ice dynamics in the Chukchi Sea, which is located to the west of Barrow.

## 2 Temperature

The western Arctic experienced a temperature increase during the twentieth century (Wallace et al. 1996; Osterkamp and Romanovski 1999; Stafford et al. 2000), a result in agreement with most GCM studies. In general, this increase was most pronounced during the winter season. The amount of temperature increase is dependent on the time period chosen (Curtis et al. 1998; Walsh and Chapman 1990), and is by no means uniform during the twentieth century; an indication that this annual trend cannot be solely explained on the basis of an anthropogenic effect resulting from the increase of the greenhouse gases in the atmosphere. More complicated feedback mechanisms involving surface albedo changes, cloud-radiative processes and dynamical interactions associated with changes in circulation also contribute to the temperature variation (Wendler et al. 1981; Zhang et al. 1996; Stone 1997). Investigating the different climatic zones of Alaska, the temperature increase was especially strong on the North Slope (Shulski and Wendler 2007), while the temperature was fairly constant for the rest of Alaska after an atmospheric circulation shift which occurred in 1976 (Hartmann and Wendler 2005).

Figure 2 shows a time series of the temperature for stations located in the coastal area of the North Slope of Alaska. Barrow is the most northerly point of the North American continent; Prudhoe Bay and Deadhorse (airport for Prudhoe Bay area) are centrally located on the North Slope, while Barter Island is located to the East close to the Canadian border. Barrow (solid black line) is the only first-order weather station that was operation for the whole time period. The first-order weather station at Barter Island was

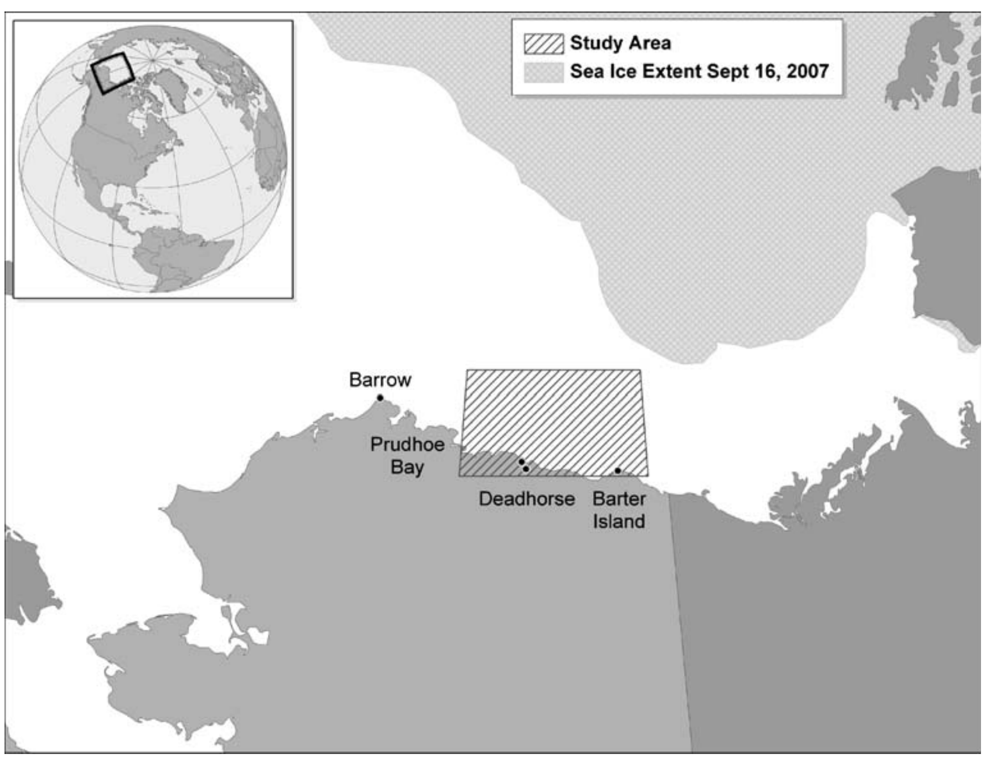


**Fig. 1** Map of the western Arctic. The study area in the southern Beaufort Sea off the coast of Northern Alaska is outlined

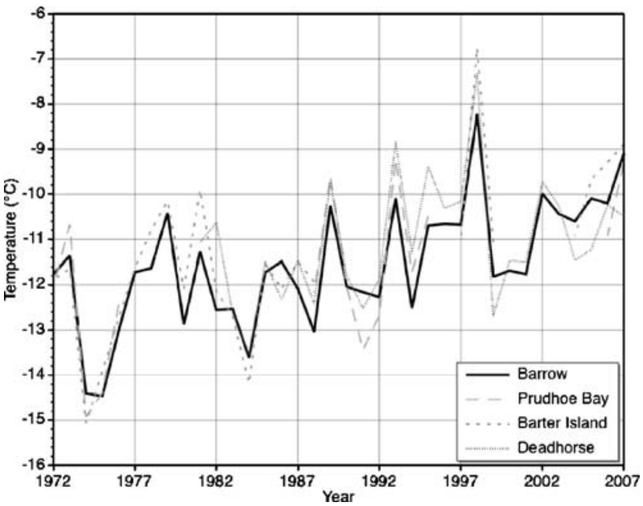


**Fig. 2** Mean annual temperatures for Barrow, Prudhoe Bay, Deadhorse, and Barter Island

discontinued at the end of 1988, and the automatic station was established at the nearby native village of Kaktovik. Deadhorse has now an automatic weather station; data from 1981 are available. The record of Prudhoe Bay, close to Deadhorse, starting in 1988, is broken. However, it can be noted from Fig. 2 that the stations agree well which each other, a sign that the climate of the coastal zone of the North Slope is fairly uniform (Shulski and Wendler 2007). We correlated the mean annual temperatures of Barrow and Barter Island, the most westerly and most easterly station of the Alaskan North Slope, with each other for the time period at which both stations were first class weather stations (1972 to 1988) and a correlation coefficient of 0.89 was found, confirming the visual impressions of Fig. 2. The best linear fit at Barrow results in a warming of 2.9°C for the 36-year time period, a very substantial value. Distribution of the change over the year is not even. Winter is the season with the greatest observed temperature increase contributing 38% to the annual warming. This cannot be caused by the frequently quoted snow-albedo feedback mechanism, as there is no or negligible solar radiation during this time of the year. Hence, this change is the result of either increased advection of warm air from more southern latitudes (circulation changes) or increased infrared back radiation from the atmosphere due to increased cloudiness, water vapor or $CO_2$. Most likely it is result of a combination of these two processes. Spring is the season with the second highest value (26%), followed by summer and autumn, which contribute nearly identical values with 18% each to the annual warming. The Arctic Alaskan temperature trends were compared to high latitude stations in Canada (Curtis et al. 1998), and similar values were observed for these stations, indicating that such a temperature increase with time is not a local effect of the North Slope of Alaska.

## 3 Wind

The mean wind speed is high on the North Slope of Alaska, as the coastal area is flat and open to the Arctic Ocean. The mean annual value for the whole time period is 5.6 m $s^{-1}$. There is hardly any annual course, but September/October show somewhat elevated values. An explanation might be that in early fall there is still open water at or close to the coast, while the land area has cooled substantially, increasing the thermal instability. About 10% higher values were observed for these 2 months. Figure 3 gives the time series of the mean annual values for Barrow.

Annual mean values vary substantially, the lowest value (4.5 m $s^{-1}$) observed both in 1974 and 1975, the highest one in 1993 (6.3 m $s^{-1}$). The best linear fit (black thick line) does not represent the data well. A maximum in the wind speed was observed in the early 1990s, while lower values occurred earlier as well as later. The resulting wind direction is easterly, but reversals in the wind direction do occur. The dominantly easterly winds also drive the Beaufort Gyre, the general ice and water movement to the west along the Alaskan coast. For the formation of leads and polynyas, as well as for erosion of the coastline, not the mean wind speed, but the frequency of storms is of greater importance, which is presented in Fig. 4. Here a "storm" is defined with a wind speed >15 m $s^{-1}$. Winds of 15 m $s^{-1}$ are somewhat in the middle of Beaufort Scale 7, defined as "moderate gale" with 4 m waves and foam beginning to streak. At least one hourly value has to exceed this threshold to count as a stormy day. The graph is somewhat similar to Fig. 3, but the variations are much larger from year to year.

Again, the best linear fit does not represent the data well. A maximum occurs in 1992 and 1993, and less frequent storms

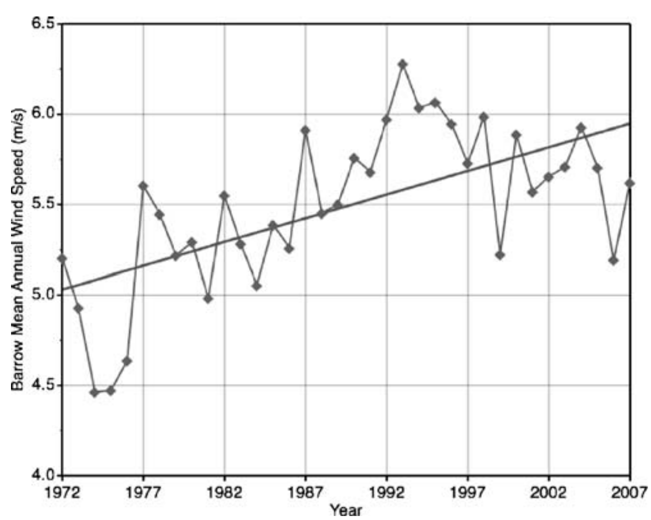


**Fig. 3** Time series of the mean annual wind speed of Barrow, 1972–2007

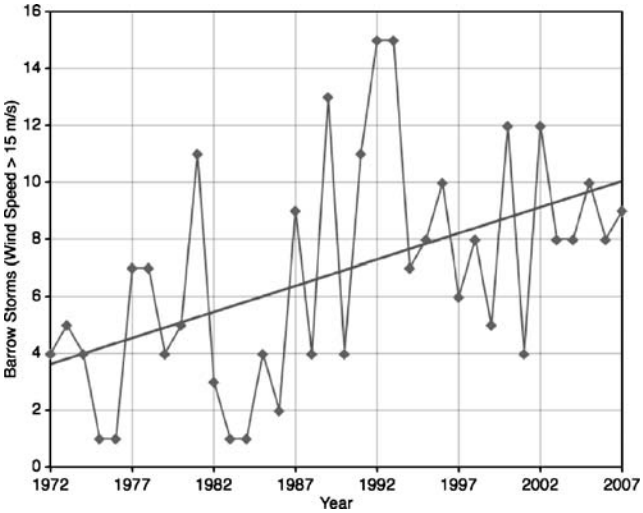


**Fig. 4** Time series of frequency of storms for Barrow, 1972–2007

were observed before and after this maximum. Nevertheless, the best linear fit gives a substantial increase in the number of days, from four in 1972 to ten in 2007. Furthermore, years with less than four storms a year have not been observed since 1987, while there have been six such occurrences observed in the time period from 1972–1986.

## 4 Sea ice

We were able to systematically analyze the area in the southern Beaufort Sea using a portion of the *NIC Arctic and Antarctic Sea Ice Data* (Benner 1996) and *Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I Passive Microwave Data* (Cavalieri et al. 2006). Weekly sea ice data consisting of 0.25° latitude by 0.50° longitude grids derived from satellites started in January 1972. Beginning in October 1978, NIMBUS-7 bi-daily data became available. Followed by products from the Defense Meteorological Satellites with their Special Sensor Microwave/Imager (SSM/I). Programs F8 starting in July 1987 with daily data, then F11 in December of 1991 and finally F13 in May 1995.

This study was limited to the coastal Beaufort Sea, which was outlined in Fig. 1. An area somewhat east of Barrow was chosen, as Barrow is located at the most northerly point of Alaska, where the Beaufort and Chukchi Seas meet. Both the climatic conditions at Barrow and the sea ice dynamics in either ocean will influence the ice conditions off Barrow, making the situation here more complex. There are a total of 164 sea ice data grid points in our area of interest.

In Fig. 5 the annual course of ice concentration is presented for the average of the 36-year time span (1972–2007). It can be seen that for 6 months (December though May), the concentration is high with values above 95%. A weak maximum with 97% occurs in April, when on average the maximum ice concentration is recorded. Melting does not occur during the whole time period, and often times open water is caused by dynamic processes, frequently in connection with storms, which can form leads and polynyas at any time of the year (Fig. 6). In June, the melting starts to occur; however, as the sea ice is still thick, the ice concentration decreases only slightly (90%). Thereafter, the disintegration of sea ice accelerates, and in September the minimum is reached with a value of 21%. In October, with temperatures steadily below freezing, new

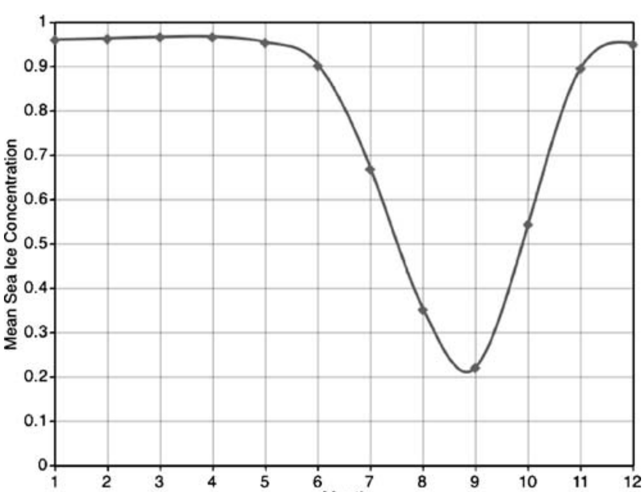


**Fig. 5** Mean annual course of the sea ice concentration for the time period 1972–2007, Southern Beaufort Sea

**Fig. 6** Early spring photograph taken from 9 km height, Southern Beaufort Sea. Notice the two leads and a great number of ice ridges. Coastal wind-driven polynyas are, however, relatively seldom, but can occur at any time of the year

sea ice is formed and by November the ice concentration reaches again 90%.

In Fig. 7, the time series of the mean annual sea ice concentration is presented. A fairly linear decrease in ice concentration with time can be observed. The best linear fit is also given which shows that the ice concentration decreased from 88% in 1972 to 68% in 2007, which is a decrease of 5.6% per decade. If the decrease should continue linearly—a highly unlikely scenario—the Southern Beaufort Sea would be year-round ice free in 120 years. Interesting to note is the fact that 1998 had the lowest sea ice concentration (59%) followed by 2007 (61%). 2007 was the year when in September the ice had receded to a new recorded maximum retreat in the Western Arctic Ocean as well as for the Arctic Ocean as a whole, (shown in Fig. 1). Since 1993, 7 years had mean annual ice concentrations below 70%, while in the previous 21-year time period there is only one year (1987), which has such a low value.

In Fig. 8, the sea ice concentration is presented as a function of season and year. Note that the ice concentration is very high for more than half a year. Even though from week 44 (beginning November) to week 24 (end of June) ice concentrations rarely fall below 90%, below normal ice concentration can be found during any time of the year. In July, the ice pack starts to disintegrate, reaching the lowest ice concentration in September, increasing in October and reaching close to winter maximum values again in November. Further, the figure shows that the length of the season with open water has extended fairly evenly in late spring/early summer and in late autumn.

We calculated the percentage change also on monthly basis for the time period 1972 to 2007, applying the best linear fit to the data points (not shown). In general, the changes were large in late summer/early fall, but the late winter values were mostly unchanged. January and March showed even a slight increase in ice concentration, but the changes are too small (+0.3 and +0.1%, respectively) to be meaningful. If we look at the seasons, the greatest change is observed when the most open water was present. As September was the month with the most open water (see Fig. 5), we centered the seasons around this month. The values are given in Table 1.

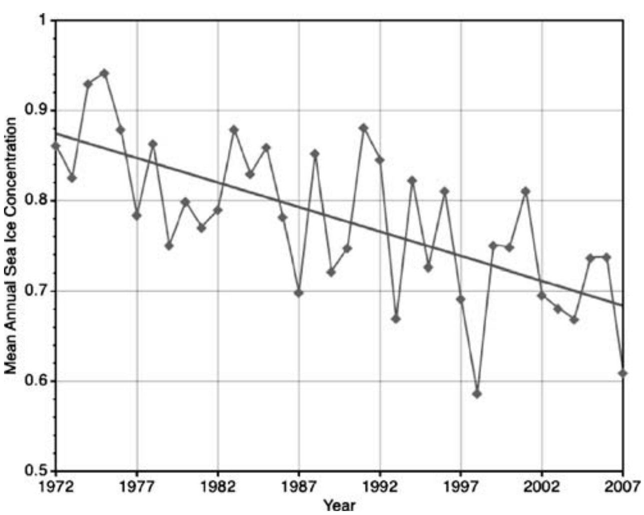


**Fig. 7** Trend of the mean annual ice concentration in the southern Beaufort Sea. The *line* represents the best linear fit of the annual data points

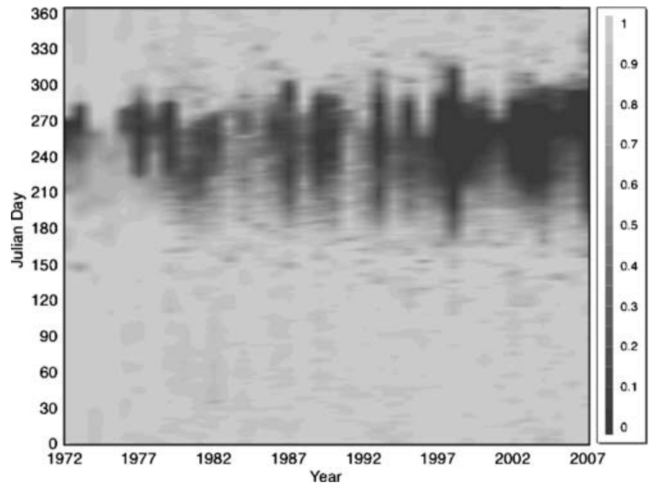


**Fig. 8** Temporal isoplete presentation of the mean ice concentration of the study area. In the last decade of the observational period more open water has occurred than in any previous ones

Ten months of the year showed a decline in ice concentration. The change in the ice concentration for the winter months is much more modest when compared to the rest of the year. The first month of the year with a substantial reduction in ice concentration is June with 11.7% for the 36-year time period. Stone et al. (2002) showed that the snowmelt season does occur earlier at Barrow. Half a century ago, it occurred most frequently around middle June, while now it happens very late May or very early June, with, of course, large variations from year to year. The earlier snowmelt should not only occur on land, but also on the adjacent sea ice pack. For the following month, July, a reduction in sea ice of 37.6% is observed. Solar radiation is strong during this time of the year (Wendler et al. 1981), and as the albedo has been lowered due to melting of the previous month, decay of the ice cover accelerates. The following 3 months lose as mean slightly more than 50% of the ice cover, and even in November a decrease in ice concentration of 15.8% is found. In general, the observed sea ice concentration decrease in our study area in the Western Arctic is in agreement with observations in other arctic and sub-arctic regions (Chapman and Walsh 1993; Walsh et al. 1996; Maslanik et al. 1999; Kay et al. 2008).

**Table 1** Seasonal sea ice concentration and the observed changes from 1972 to 2007 for the Southern Beaufort Sea based on the best linear fit of the trends

| Season | Minimum | Intermediate | Maximum | Intermediate |
|---|---|---|---|---|
| Months | ASO | NDJ | FMA | MJJ |
| Sea ice concentration 1972 | 63.3% | 96.6% | 96.9% | 93.0% |
| Sea ice concentration 2007 | 12.0% | 90.8% | 96.4% | 75.6% |
| Difference | −51.3% | −5.8% | −0.5% | −17.4% |

## 5 Temperature—sea ice interactions

In Fig. 9, the mean annual sea ice concentration of our study area in the Southern Beaufort Sea is plotted against the mean annual temperature of Barrow. It can be seen in general that cold years are those with above normal ice amount, while warm years show on average a below normal amount of sea ice. A variance ($r^2$) of 0.71 can be observed between the mean annual values of sea ice concentration and Barrow temperatures.

We also correlated the mean annual sea ice concentration with the $CO_2$ concentration (not shown); however, the relationship is weaker than with the temperature. A variance ($r^2$) of 0.46 was found; with other words nearly half of the observed sea ice change might be contributed to the increased $CO_2$ concentration.

Statistical measures, of course, do not define a causal relationship. Above normal temperature in summer will lead to accelerated ice decay, but, on the other hand, open water or thin ice in winter will increase the heat flux from the ocean to the atmosphere, which should result in a warming of the coastal area. The situation is further complicated by weather situations, sea ice dynamics and the position of the coastline. In general, southerly winds will not only advect air with above normal temperatures, but also tend to push the ice away from the coastline, as long as these winds are of certain strength and duration. Northerly winds will result in the opposite effect. Looking at the relationship between ice concentration and temperature on a seasonal basis (not shown), no improved correlation coefficient was found. Indeed, for all seasons with the exception of fall, the relationship was less well established. In fall, especially in September and October, similar values as those for the whole year were found.

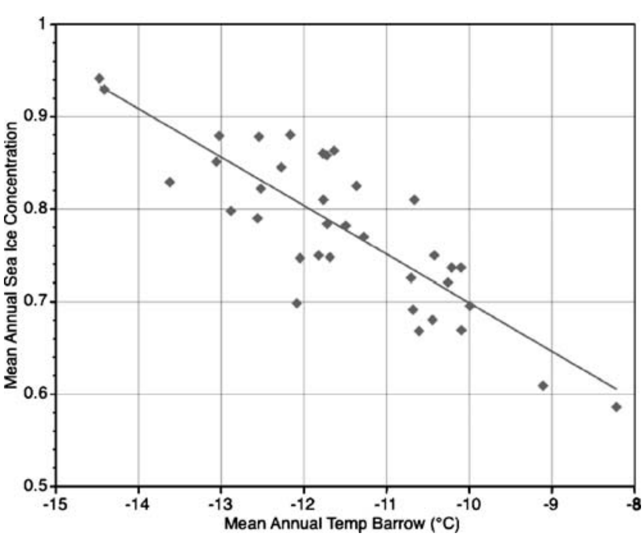


**Fig. 9** Mean annual temperature is plotted against the mean annual sea ice concentration in the Southern Beaufort Sea

We looked also on the relationship between the “winter” temperature and the ice concentration during the following “summer”. It can be assumed that during cold winters, thicker ice forms, and hence the amount of open water in summer might be reduced. The correlation between winter temperature (January through April) and the season with the minimum in sea ice (August, September, and October) is weak; a variance ($r^2$) of 0.21 was calculated (not graphically shown). We extended these calculations also to the onset of the melting season (June), as well as for individual summer months; however, the correlation coefficients stayed low; the reason might be due to:

- The growth of the sea ice in winter will not only be a function of the temperature, but will also depend on the snowfall. A substantial snowfall early in the season will tend to insulate the atmosphere from the ocean and hinders the growth of the sea ice, and vice versa.
- Ice dynamics play a major role. The ice formed in the near coastal region of the Beaufort Sea in winter will have moved by summer and ice formed under different climatic conditions will have been advected.

**Table 2** Correlation coefficients between the sea ice concentration in the Southern Beaufort Sea and different atmospheric indices

| Atmospheric index | Correlation coefficient ($r$) |
|---|---|
| Pacific Circulation Index | −0.59 |
| East Atlantic Pattern | −0.47 |
| Pacific/ North American Pattern | −0.36 |
| Scandinavian Pattern | 0.34 |
| Polar/ Eurasia Pattern | 0.33 |
| Pacific Decadal Oscillation | −0.27 |
| NINO 3.4 | −0.25 |
| East Atlantic/West Russia Pattern | 0.25 |

Further, we correlated the annual values of the sea ice concentration with different atmospheric indices; the findings are presented in Table 2. There have been a great number of publications on this subject, and we present here only a selected number of references (Trenberth and Hurrell 1994; Latif and Barnett 1996; Mantua et al. 1997; Zhang et al. 1997; Brown 2000). The correlation coefficients were significant at the 99% confidence level solely with the Pacific Circulation Index (PCI) and East Atlantic (EA) pattern. The PCI is the cumulative summation of negative northwesterly atmospheric circulation frequency anomalies, while the EA is the second prominent mode of low-frequency variability over the North Atlantic. Lower significant pattern of 95% confidence level were found for the Pacific/North American (PNA) pattern and the Scandinavia Pattern (SCAND) index. The PNA is one of the most prominent modes of low-frequency variability in the Northern Hemisphere. The SCAND, sometimes also referred to as Eurasia-1 pattern, has two phases. The positive is associated with positive height anomalies, sometimes reflecting major blocking anticyclones, over Scandinavia and western Russia, while the negative phase of the pattern is associated with negative height anomalies in these regions. All other indices had correlation coefficients below the 95% confidence level.

From Fig. 7, we could see that 1998 had the lowest mean annual ice concentration with 58%. Furthermore, the highest mean annual temperature was observed during this year (see Fig. 2). Looking at atmospheric indexes for this year specifically, it should be noted that in 1998 the North Pacific Oscillation and Scandinavian Pattern had their respected minima in 1998 for the 36-year time series.

## 6 Conclusion

Temperature has substantially increased along the shore of Northern Alaska during the last decades, much more than the rest of Alaska. Further, the sea ice concentration in the adjacent Beaufort Sea decreased. This decrease in sea ice concentration was specifically pronounced in late summer and early autumn and more than doubled the amount of open water when averaged over the year. This is, besides the scientific interest, of special importance for the following reasons:

- Coastal erosion has taken place along the northern coast of Alaska for many centuries. This clearly demonstrated by the sub-sea permafrost, which stretches in some areas more than 10 km from the coastline (this is significant since permafrost cannot be formed below water). Decreasing sea ice will enhance erosion rate due to wave action, even if the overall storminess of the ocean stays unchanged. This has tremendous economical and social consequences for coastal communities in the Arctic such as Barrow.
- The North Slope of Alaska is mostly inhabited by indigenous people (Inuit), whose lifestyle, even today, is based to a great extent on subsistence hunting. Changing sea ice will change the abundance and the access to seals, walrus, polar bears and whales, and changing climate of the North Slope might affect the abundance of caribou.
- This area is of high interest for its energy reserves and for their further development, i.e., Prudhoe Bay.

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