Strong Temperature Increase and Shrinking Sea Ice in Arctic Alaska

Gerd Wendler*, Blake Moore and Kevin Galloway

Alaska Climate Research Center, Geophysical Institute, University of Alaska, USA

Abstract: Barrow, the most northerly community in Alaska, observed a warming of 1.51°C for the time period of 1921-2012. This represents about twice the global value, and is in agreement with the well-known polar amplification. For the time period of 1979-2012, high quality sea ice data are available, showing a strong decrease in sea ice concentrations of 14% and 16% for the Beaufort and Chukchi Seas, respectively, the two marginal seas bordering Northern Alaska. For the same time period a mean annual temperature increase of 2.7°C is found, an accelerated increase of warming over the prior decades. Looking at the annual course of change in sea ice concentrations, there is little change observed in winter and spring, but in summer and especially autumn large changes were observed. October displayed the greatest change; the amount of open water increased by 44% and 46% for the Beaufort and Chukchi Seas, respectively. The large amount of open water off the northern coast of Alaska in autumn was accompanied by an increase of the October temperature at Barrow by a very substantial 7.2°C over the 34 year time period. Over the same time period, Barrow's precipitation increased, the frequency of the surface inversion decreased, the wind speed increased slightly and the atmospheric pressure decreased somewhat.

Keywords: Alaska, Arctic Ocean, climate change.

INTRODUCTION

Arctic Alaska is situated North of the Brooks Range, frequently called the North Slope of Alaska. Barrow is not only the northernmost community of this area, but also of the USA, situated at 71°17'N 156°14W. Due to its high latitude, the sun remains below the horizon from 19 November to 22 January and continuously above the horizon from 11 May to 1 August. Summers are short and winters are very long with only three months a year with a mean temperature above the freezing point [1]. Due to these cold temperatures, the ground is frozen (permafrost), and thaws in summer only some 40 cm, the so-called "active layer". Due to these conditions, trees cannot grow in this climate zone, only grass and small brush.

Barrow is situated on the Arctic Ocean; to the northwest is the Chukchi Sea and to the northeast the Beaufort Sea (Fig. **1**). By Alaskan standards, it has a relatively long observed climatological record, with the first observations going back to the beginning of the last century. Originally, Barrow was an Eskimo village, but outside influences arrived early due to exploration, especially the North-East and North-West Passages as well as to whaling activities.

There are a several other communities with meteorological observations of different lengths (see Fig. **1**); the meteorological station at Barter Island is located in northeastern Alaska, near the Canadian border, along the coast of the Beaufort Sea. It was established as part of the DEW (Distant Early Warning System) Line in 1953 and ceased operating in 1989. Now a weather station is operated in the nearby village of Kaktovic. Despite the remote location of the North Slope, a great number of scientific studies have been carried out in the area, originally with frequent support of NARL (Naval Arctic Research Laboratory) and more recently due to oil and gas discoveries at Prudhoe Bay [2-6]. Further, the ARM (Atmospheric Radiation Measurements) site for Polar Regions is located at Barrow (www.arm.gov).

CLIMATE

The climate of the North Slope is quite uniform, as the area is fairly flat, bordered to the south by the Brooks Range and to the north by the Arctic Ocean. The 5 stations, which have a long enough observational period for establishing a 30 year climatology, are all within a 1°C deviation from Barrows (-11.2°C) mean annual temperature with the exception of Wainwright. This latter station is situated at the Chukchi Sea coast, which is having a slightly lower ice concentration than the Beaufort Sea, and is somewhat warmer with a deviation of +1.2°C from Barrow. Only 3 months a year have a mean monthly temperature above the freezing point and snow covers the ground for about 9 months [7]. Precipitation is low due to the very cold temperatures with a long-term annual mean of 115 mm. Cloudiness is high with a mean annual value of 68% [1]. There is a strong annual course in the amount of cloudiness. The minimum is found in March (45%), when the atmosphere is relatively dry after being rewarmed from the very cold winter, while the maximum at 91% is observed in September, frequently consisting of so-called semi-permanent Arctic Stratus. Wind speeds are relative high with a mean annual value of around 5 m/s, blowing normally easterly directions. This is the result of a semi-permanent

*Address correspondence to this author at the Alaska Climate Research Center, Geophysical Institute, University of Alaska, USA;
Tel: 907 474 7378; E-mail: gerd@gi.alaska.edu

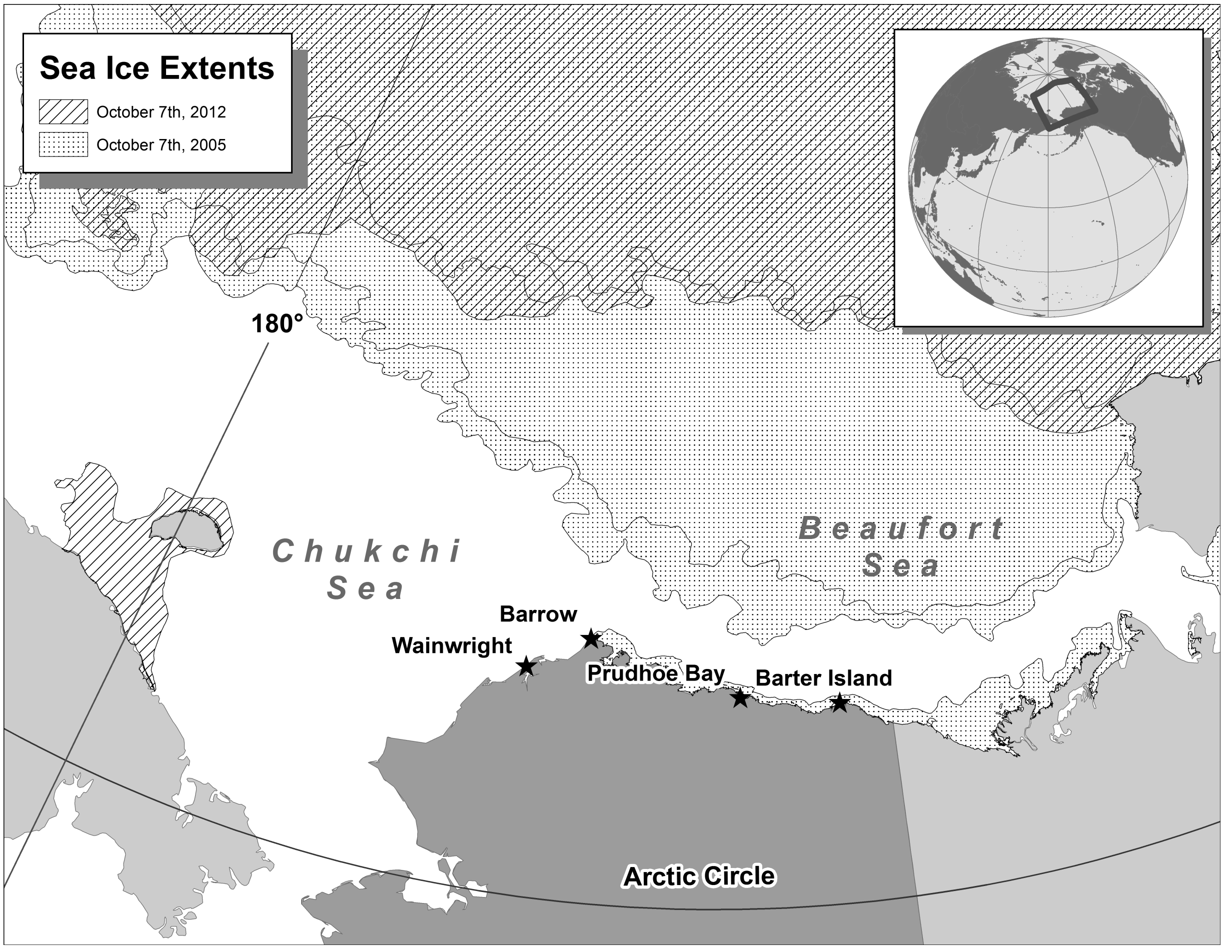

Fig. (1). Alaska's Arctic is the area north of the Arctic Circle, roughly the Brooks Range, and is generally referred to as the North Slope. Further, the extreme amounts of open water for both, the Chukchi and Beaufort Sea is also presented.

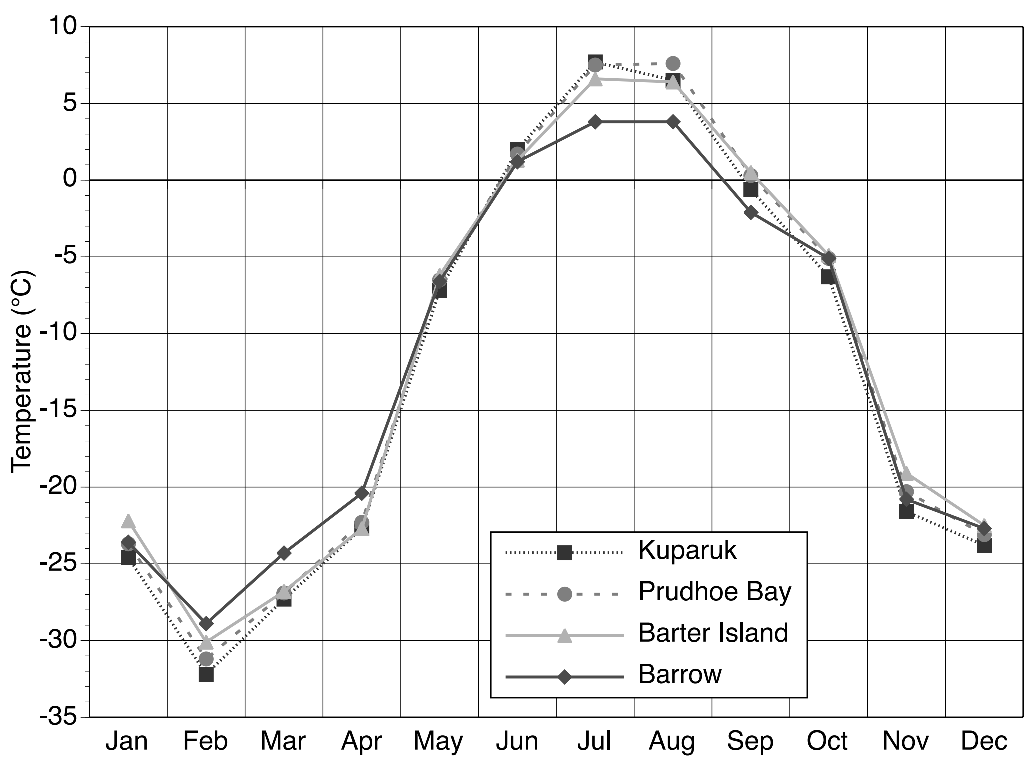

Fig. (2). Annual temperature course for 4 stations on the North Slope, Alaska for the year 1987. Note, that the highest monthly summer temperature stays below 10°, while the minimum occurs in February, with temperatures around -30°C.

anticyclone off the coast of the North Slope. The anticyclone also causes the ice movement to the west (Beaufort Gyre). The climate of the region can be classified after Köppen as ET (tundra climate) [8] which implies it as having an average temperature during the warmest month between 0 and 10°C. The average maximum monthly temperature at Barrow, which is normally observed in July, has a 30 year mean value of 8.3°C.

In Fig. (**2**) the mean monthly temperatures, simultaneously available in 1987 for 4 stations, are shown. This year was chosen, as complete data sets were available for all 4 stations. It can be seen, that the maximum temperatures were observed in July or August, while the minimum occurred in February, a sign of a maritime climate, which delays the extremes when compared to a more continental climate.

Meteorological observations started at Barrow in September 1901, early by Alaskan standards. However, these early observations are not very useful, as long breaks occurred in the dataset. Not only days were missing, but whole months and in some cases, years, are absent. For example, for the time period from 1905-1909, data for not a single month existed. Only starting in 1921 did regular observations became available, hence we analyzed the period from that point to present for trends. Further, data from 1945-48 were missing. In Fig. (**3**) mean annual temperatures as well as the 5-year running mean are presented.

While an overall warming trend has been observed, which is above the global mean and in agreement with the findings of other authors studying the Arctic [9], this warming was anything but linear. The time period for the first 30 years until about 1950 was relatively warm, especially the 1920's. The Washington Post published an article on 2 November 1922 entitled *"Arctic Ocean getting warm, seals vanish and icebergs melt*" indicating that the previous decades had been colder. Further, the Fairbanks meteorological record, which goes back to 1903, also showed the decade of the 1920's as being exceptionally warm. One has to go the 1980's to find a higher decadal temperature. This warm period was followed by a cold period of about 25 years until the mid-1970's. The time period from 1976-2012 observed a strong and fairly consistent warming, which continues to present time for Arctic Alaska. For example, the highest mean annual temperature of the first warm period was recorded in 1929 at -9.3°C and it took nearly 70 years (1997) until a warmer annual temperature occurred. Furthermore, 1997 is the only year with a higher temperature than 1929. Multi-decadal variations in temperatures, which cannot be explained simply by increasing green house gases, are a well-known phenomenon and have been studied widely [10-14].

Looking at the more recent past (1979-2012), the time period for which we have reliable satellite-based sea ice data, a substantial warming of 2.7°C has been observed at Barrow (Fig. **3**). This warming is about an order of magnitude higher than the global value. The observed warming, however, is not evenly distributed over the course of a year. In Fig. (**4**) the temperature change by month for the time period 1979-2012 of Barrow is presented. All months, with the exception of January, display a warming, which is especially strong in autumn (6.3°C), followed by spring (1.8°C), summer (1.5°C) and winter (1.2°C). October displays the maximum temperature increase (7.2°C), a remarkably high value for a time period of only 34 years.

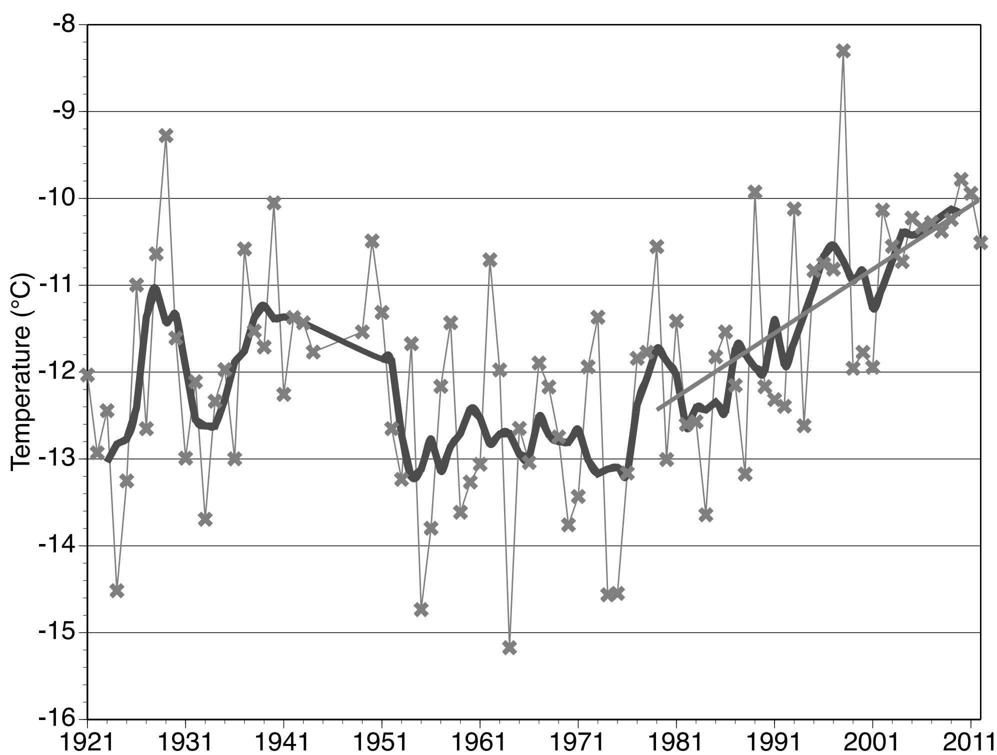

Fig. (3). Time series of the mean annual temperatures for Barrow, 1921-2012. Note, that for the time period since 1979, the best linear fit was added to the graph.

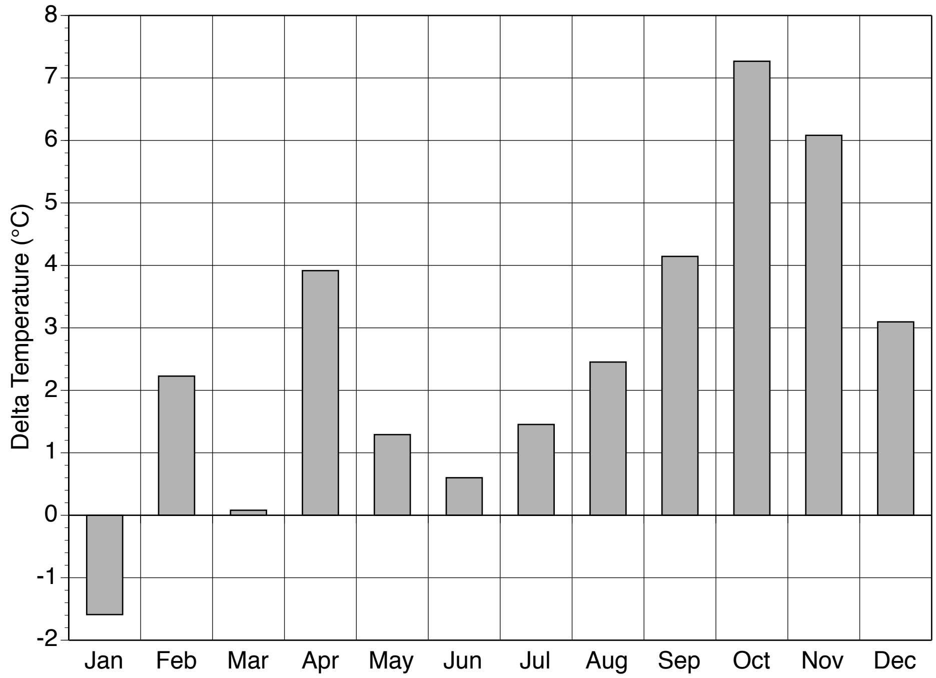

Fig. (4). Temperature change by month for the time-period of 1979 to 2012 at Barrow, Alaska. The data were calculated from the best linear fit of the 34 annual data points for each month.

SEA ICE

While coastal and occasional ship observations of sea ice go back for more than a century, high quality sea ice observations only became possible with the availability of systematic satellite coverage. Such early observations in the visible range were again of limited use [15], as there is considerable darkness in winter, and even when there is light, clouds might obscure the underlying sea ice conditions and Arctic stratus clouds can be semi-permanent. For example, Barrow observes around 90% cloud cover in September [1]. Hence, only after systematic microwave observations began, which are able to look through darkness and clouds, reliable sea ice data exist.

In Fig. (**5**) the annual sea ice concentration in percent is presented for the mean of the observational period 1979-2012 for both, the Beaufort and Chukchi Seas. For the first 4

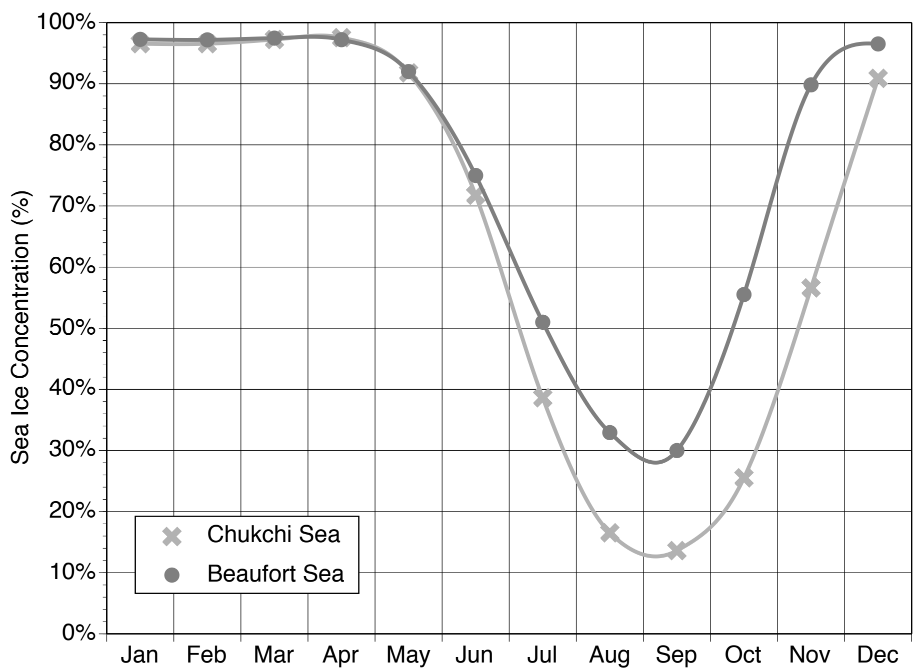

Fig. (5). Mean annual course (1979-2012) of the sea ice concentration for the Chukchi- and Beaufort Seas. While the winter values are very high with value in excess of 95%, basically unbroken pack, mostly open water is experienced especially in August and September, making ocean ship traffic possible.

months of the year, the sea ice concentration is always in excess of 95% for both seas.

Open water occurs seldom, normally in connection with an intense storm, which can break up the ice pack, and form leads and polynyas at any time of the year. In May the first decrease in sea ice concentration is observed. Solar radiation is strong, and measurements of Barrow [6] have shown, that frequently the maximum monthly value in global radiation occurs in May, as in June, with higher solar elevations, the cloudiness has increased. The presence of open water increases, and reaches normally its maximum in late August/early September with 72% (Beaufort Sea) and 87% (Chukchi Sea), respectively. Thereafter, the formation of new ice, which is more rapid than the decay, occurs and by December, values above 90% are again observed. While in winter, both the Beaufort and Chukchi Seas, have similar values, in summer and especially in autumn, large differences can occur, with the melting of sea ice being more intense in the Chukchi Sea. There are two reasons for this: (1) the Chukchi Sea extends further South when compared with the Beaufort Sea, where warmer temperatures are prevailing, and (2) the Chukchi Sea is open to the South through the Bering Strait and storms with northerly wind directions can export large amounts of sea ice into the Bering Sea [16], which is ice free during the summer months, and has less ice density for the rest of the year. Hence, besides ice melt, dynamical processes are of importance.

In Fig. (**6**), the time series of the mean annual sea ice concentration is presented for both, the Beaufort- and Chukchi Seas. A fairly linear, strong decrease in sea ice with time can be observed. The best linear fit is also given which shows that the ice concentration decreased from 83% in 1979 to 69% in 2012 for the Beaufort Sea and from 74% to 58% for the same time period in the Chukchi Sea. From these values a decrease per decade in sea ice of 4.1% for the Beaufort Sea and 4.7% for the Chukchi Sea can be calculated. A previous study [17], analyzing data from the Prudhoe Bay area until 2007, gave a similar trend. Assuming that the observed trend continues, the Chukchi and Beaufort Seas will become totally ice free in late August, early September in some 10 and 20 years, respectively. However, a year-round open Arctic Ocean cannot be expected – even if this strong warming trend observed during the last decades continues linearly, which is a highly unlikely scenario – for at least a century, as there is only a decrease of about 2% per decade over the last decades.

Looking at the correlation coefficients between the sea ice decrease with time, values of r of 0.58 and 0.70 were found for the Beaufort and Chukchi Seas, respectively, which are significant at the 95% confidence level.

The observed decrease in sea ice for the above time period of 34 years is not evenly distributed throughout the year. The first 4 months of the year actually show a very small increase in the concentration of sea ice for both the Beaufort and Chukchi Sea. This correlates with the sea ice increase of the Bering Sea, making it more understandable [18], where the sea ice is only a winter phenomenon. Starting in May the decrease is fairly linear until it reaches its maximum in October at about 45%. Thereafter, the loss in sea ice decreases strongly, and by the end of the year, little change in sea ice concentration over the time period of more than 3 decades can be observed, as can be seen from Fig. (**7**).

SEA ICE - TEMPERATURE INTERACTION

Naturally, there is a relationship between air temperature and sea ice. Cold temperatures will form more ice as long as the temperature is below the freezing point of seawater, on the other hand, open water will warm the air as long as the

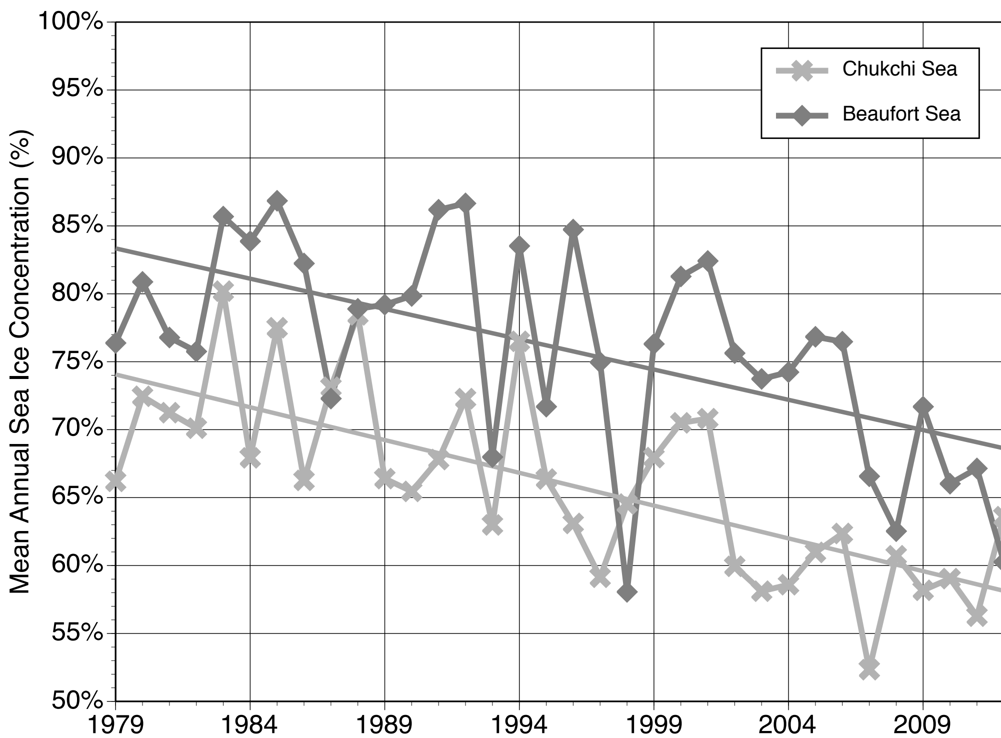

Fig. (6). Trend of the mean annual sea ice concentration of the Beaufort and Chukchi Sea, 1979-2012.

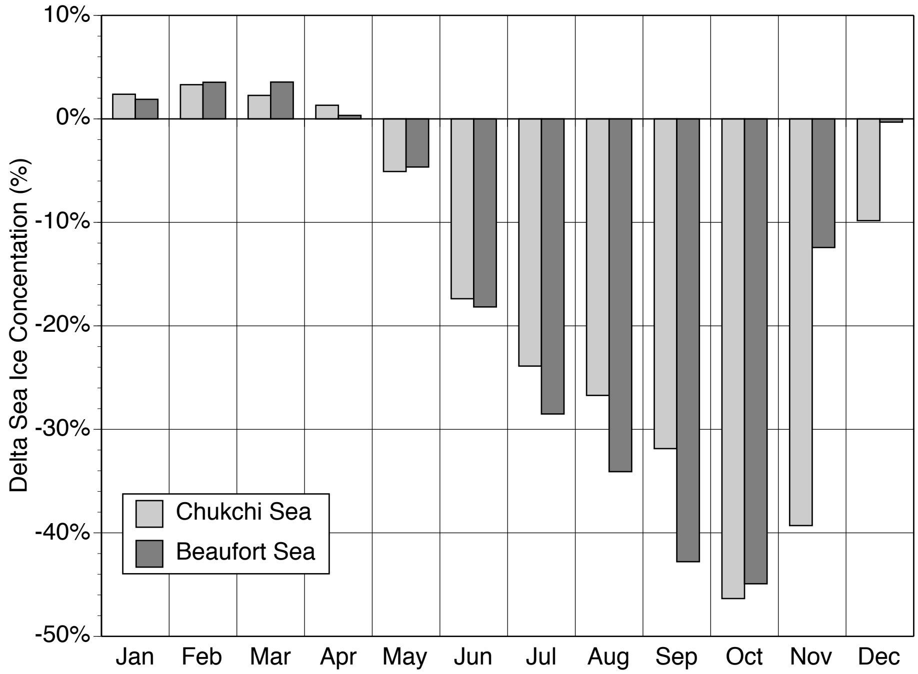

Fig. (7). Change in sea ice extent by month for the 34-year time-period (1979-2012). Note, that there was hardly a change in late winter/early spring, while the loss was especially strong in autumn.

air temperature is below the freezing point. These fairly straight forwards principles of thermodynamics are complicated by the ice dynamics [19]. Sea ice is not stationary, and moves with the atmospheric circulation and ocean currents, which are, of course, related with each other again. Nevertheless, a fairly good relationship between the annual sea ice coverage and the mean annual temperatures was found. In Fig. (**8**) the temperature of Barrow is plotted against the amount of sea ice for both the Beaufort and Chukchi Sea. As expected, with colder temperatures, a greater concentration of sea ice can be found.

Correlation coefficients between the two parameters were -0.76 and -0.73 for the Chukchi and Beaufort Sea, respectively, being significant at the 99% confidence level for both cases. However, these relationships are not constant over the year. In winter there is hardly any open water,

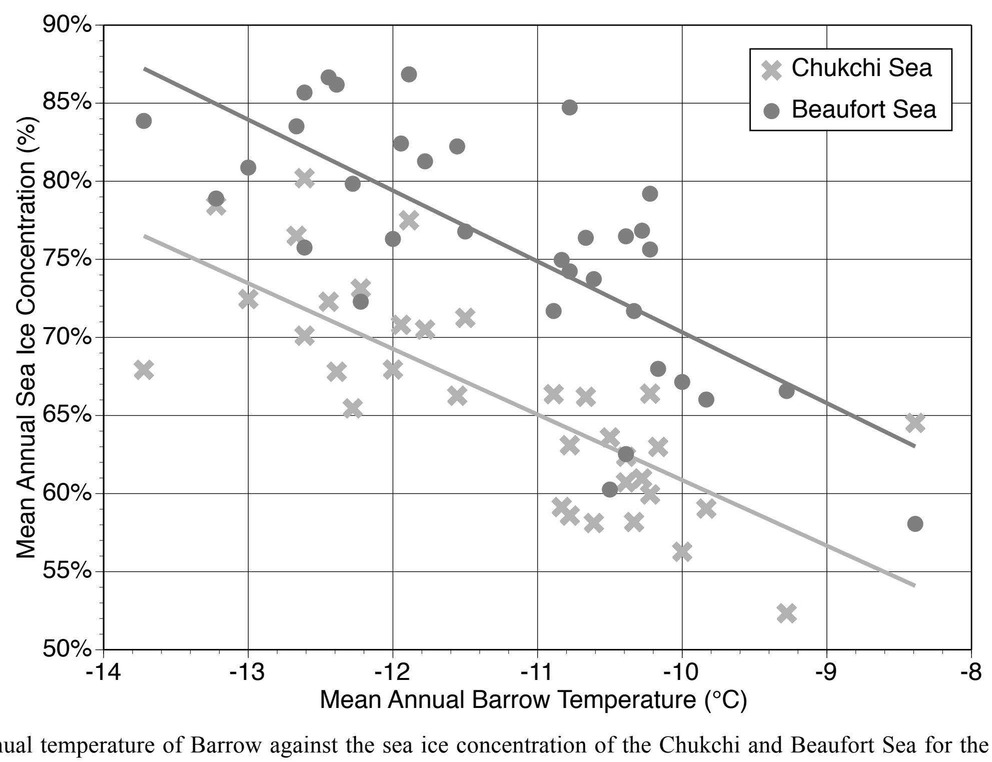

Fig. (8). Mean annual temperature of Barrow against the sea ice concentration of the Chukchi and Beaufort Sea for the time period 1979 - 2012.

which could warm the air, hence no, or a weak relationship exists. In January the temperature of Barrow actually decreased by 1.6°C over the 34 year time period, and indeed the sea ice concentration increased slightly for January and the following 2 months (see Fig. **8**). In general, only small changes are observed in the winter. The relationship improves in spring, and is somewhat weaker in summer, as Barrow's temperatures are above the freezing point and there is little temperature difference between melting sea ice and water. Finally, the maximum correlation is reached in autumn. The temperature increase during this season contributed more than half of the annual temperature increase observed in Barrow and the sea ice decrease of autumn contributed also about half of the annual amount. From the 3 autumn months, October displayed the highest correlation between sea ice concentration and temperature (Fig. **9**). The October mean monthly temperature of Barrow increased by 7.2°C, an extremely large warming for a 34 year period. Furthermore, during the warmest years, the sea ice shrank to under 10% in the Chukchi Sea for 9 occasions and under 30% in the Beaufort Sea for 4 instances. The strong relationship between the amount of open water and temperature is understandable, as the mean October temperature for the last normal in Barrow is -10.3°C, far below the freezing point of sea water of about -1.8°C, the exact value depending on the salt content. Wind speed is fairly strong year-around, but has its maximum in October with 6.9 m/s and a dominant wind direction from a NNE, advecting a large amount relatively warm air to the coastal area of the North Slope. This is in contrast to summer, when the land area is warmer than the adjacent ocean, and a southerly wind direction advects heat to the ocean, helping the decay of sea ice, even though the solar radiation is at that time of higher importance [20].

OTHER METEOROLOGICAL PARAMETERS

The frequency of the temperature inversions is also affected by the expanse of open water. We used the rawinsonde data for Barrow, which are launched twice daily, at 00.00 UTC and 12.00 UTC, to investigate their frequency. We calculated the frequencies on monthly basis by comparing the temperatures of 1000 hPa with the 850 hPa level, and counted it as an inversion, when the 1000 hPa level was at least 1°C colder than the upper level. Normally, one would expect winter to have the greatest frequency, because the sun is continuously below the horizon and lowest frequency around midsummer, as the sun is at its highest elevations and is continuously above the horizon. In Fig. (**10**), the frequency for all ascents, and for the day (00.00 UTC) and night (12.00 UTC) is presented individually. Looking first at the difference of day and night observations, there are no significant differences. This might be caused by the substantial altitude difference of some 1500 m of the 2 levels on which our calculations were based. Only in summer the surface warming is strong enough to make a sizable difference.

More interesting is the annual course, which shows the maximum inversion frequency during the coldest months with values of up to 80%. These are reasonable values, as previous studies have shown [21]. More surprising is the fact that the summer minimum, which might be expected during or close to the maximum in global radiation, does not occur until September with a value of 12%. The summer cloudiness is high with a long-term mean of 82%, mostly consisting of Arctic stratus clouds. In September the cloudiness value increases further to an average value of over 90%. Now, the upper vertical extent of the clouds loses more energy due to long wave outgoing radiation than the

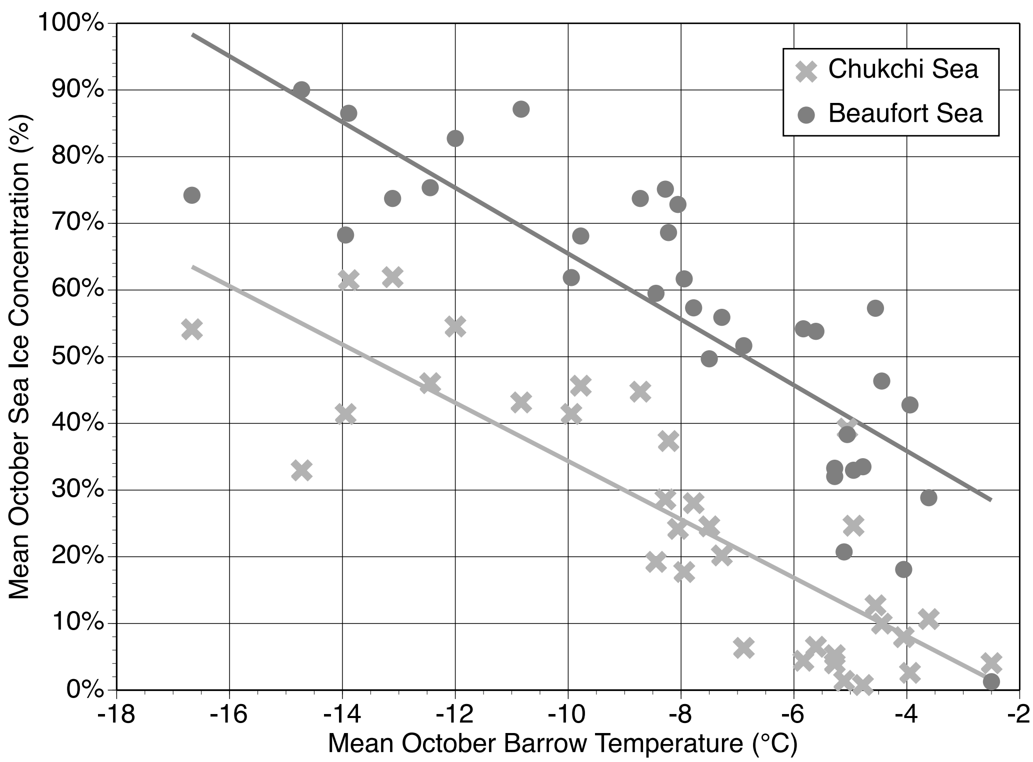

Fig. (9). Barrow's mean October temperature against aerial concentration of sea ice for the time period 1979-2012.

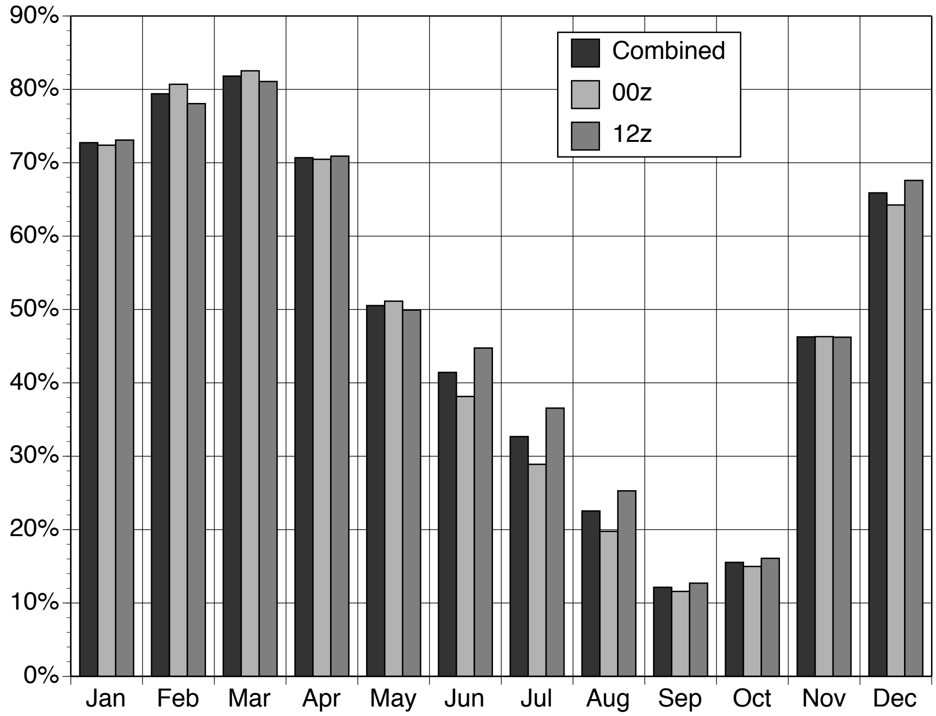

Fig. (10). Frequency of surface inversions at Barrow for the mean of 1979-2012.

surface. This, together with the advection of warm air from the ocean, causes the minimum in surface inversions in autumn, as September is the time of the most open water along the northern coast of Alaska. Further, there is a decrease in the frequency of the surface inversions over the last 3 decades (not shown), which is to be expected with surface warming and increased open water. More details have been discussed previously [22].

The decrease of sea ice resulted in a warmer atmosphere, and a slight decrease in the atmospheric pressure. The mean annual value of the surface pressure at Barrow decreased by 1.1 hPa over the 34 years of this study and is now at 1015.5 hPa. Further, the decrease in the frequency of inversions will enhance the energy transfer of the wind aloft to the surface. Therefore, we expected an increase in the surface wind, and indeed the mean annual wind speed of Barrow increase slightly from 5.3 to 5.5 m/s.

Warmer air can hold more water vapor and additionally, the more frequent open water off the coast of the North Slope is an abundant water vapor source. An increase of precipitation of 48 mm was observed for Barrow over the 34-year period. While this amount would not be a large value for mid-latitudes areas, it is substantial for Barrow, where precipitation is low and the normal value is 115mm.

There are two additional effects of the temperature increase in Northern Alaska. Forest fires are a common experience in Alaska during the summer months, and on average, some 4,000 km^2 are burned annually. While about 90% of the burned area occurs in interior Alaska, the area between the Brooks Range to the North and the coastal Range to the South, a substantial increase of “tundra fires” has been observed in the North over the last decades. This increase was, percentage wise, the highest of all climatic zones of Alaska.

Further, due to the warming, the biological activity has increased on the North Slope, as can be seen from satellite coverage in specific wavelength [23], sometimes referred to as the greening of the tundra. Surface observations showed further an increase in brush, mostly willows and dwarf birch.

We looked at several indices and their influence on the sea ice concentration. The best relationships were found for the NAO and PDO (see Table **1**). They are defined as the following:

1. The **North Atlantic Oscillation (NAO)** is a climatic phenomenon in the North Atlantic Ocean of fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. Through east-west oscillation motions of the Icelandic low and the Azores high, it controls the strength and direction of westerly winds and storm tracks across the North Atlantic. It is part of the Arctic oscillation, and varies over time with no particular periodicity.
2. The **Pacific Decadal Oscillation** (PDO) is detected as warm or cool surface waters in the Pacific Ocean, north of 20° N. During a "warm", or "positive", phase, the west Pacific becomes cool and part of the eastern ocean warms; during a "cool" or "negative" phase, the opposite pattern occurs. It shifts phases on at least inter-decadal time scale, usually about 20 to 30 years.

The relatively good relationship with the PDO [13] is not surprising, as previous investigations [24, 25] have shown its influence on the climate of Alaska. The PDO went from negative values to dominantly positive values in the mid-1970’s, bringing warmer temperatures to the state. Positive values are related to a stronger Aleutian Low, which advects relatively warm air to Alaska. This is of special importance during the winter months, when solar radiation is weak or non-existing. During the last decade the index has become more negative again [26], and the rate of increase of the temperature has decreased when compared with the two prior decades (see Fig. **3**). It can further explain the temperature decrease in January (Fig. **4**), as there is no solar radiation in northern Alaska, and the surface heat budget is strongly dependent on the energy transport towards the region by the atmosphere or ocean.

Table 1. Correlation coefficients (r2) between atmospheric indices and mean annual sea ice concentration.

Index	Chukchi Sea	Beaufort Sea	Arctic Ocean
NAO	0.226	0.485	0.413
PDO	0.300	0.314	0.530

CONCLUSION

Arctic Alaska has seen a recent strong temperature increase of 2.7°C in the last 34 years, a temperature change much larger than during any other time period with meteorological observations in Alaska as well as what is observed in other climate zones. During the same time period the sea ice concentration decreased substantially in the Chukchi and Beaufort Sea. The minimum in ice coverage was observed in September at 13% and 30%, respectively, making marine traffic a reality now, as well as in the future. Annual decreases in sea ice coverage by 16% for the Chukchi Sea, and 14% in the Beaufort Sea were observed over the 34 year time span. If this observed trend continues for the coming decades, the Beaufort and Chukchi Sea will resemble the Bering Sea, where sea ice is a winter phenomenon and disappears totally in late summer, early autumn.

On the negative side, the combination of more open water and increased wind speeds increases coastal erosion, as sea ice, which suppresses the wave action, is more frequently absent. Coastal erosion is of high practical importance for Barrow and other settlements along the northern and western coasts of Alaska.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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