ABSTRACT
Temperature and sea ice concentration measurements indicate a significant climate change in recent decades in the Western Arctic. Western Arctic temperatures have increased; the temperature rise varies significantly from one season to another and over multi-year time scales. At the same time the sea ice concentration has decreased in our investigation area extending over a major portion of the southern Beaufort Sea. We investigated changes during the 23 years period from 1972 to 1994. During this time period the temperature increased by 1.1 °C, while the mean sea ice concentration in our area of interest decreased from 88 % to 82 %. The coefficient of variation between mean annual values of temperature and sea ice concentration was 0.48. Variation coefficients between winter temperatures and the sea break-up in summer gave lower values. Strong deviations from the relationship between temperature and sea ice concentration were experienced when the atmospheric circulation was unusual, as expressed through atmospheric indices as the Pacific Decadal Oscillation, NINO 3.4 and the Western Pacific Oscillation.

INTRODUCTION
The climate on planet Earth is not constant and changes with time have occurred long before human beings had an influence on the climate. However, during the last century, a substantial warming has been experienced to which human activity on Earth has contributed (IPCC 2001). There have been a great number of studies, both observations and modeling efforts and the vast majority of these show that this change is especially pronounced in polar and sub-polar regions (e.g. Walsh and Chapman 1990, Weller et al. 1995, Tao et al. 1996). Changes are not limited to temperature as other climatological parameters such as snow cover (e.g. Brown 2000, Warren et al. 1999), precipitation (e.g. Dai et al. 1997), atmospheric dynamics (e.g. Latif et al. 1996, Overland et al.1999) and sea ice concentration (e.g. Chapman and Walsh 1993) have seen change.

In the present study we investigate temperature changes on the North Slope of Alaska and relate these to sea ice concentration changes in the adjacent Southern Beaufort Sea. We chose the ocean area between 70 and 72°N, and 142 to 152°W, about an area of
200 km by 340 km in extent (Fig. 1). The time period is 1972-1994; we tried to extend the time series to 2001, however, the algorithms used to obtain ice concentrations were changed, and hence such an extension was statistically not warranted.

**TEMPERATURE CHANGE**

The western Arctic experienced a temperature increase during the 20th century (Wallace et al. 1996, Osterkamp and Romanovsky 1999), a result in agreement with most GCM studies. In general, this increase was most pronounced during the winter season, again a result which is correctly modeled. The amount of temperature increase is dependent on the time period chosen (Curtis et al 1998), and is by no means uniform during the 20th century, an indication that such an 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 and cloud-radiative and dynamical interactions associated with changes in circulation also contribute to the temperature variation (Wendler et al. 1981, Zhang et al. 1996, Stone 1997). When considering Alaska, the temperature increase was especially strong on the North Slope of Alaska (Stafford et al. 2000).

![Figure 1: Map of the western Arctic. The study area in the southern Beaufort Sea off the coast of Northern Alaska is framed. Note also the location of Barrow and Barter Island.](image)

Figure 2 shows the mean annual temperatures of Barrow and Barter Island for the 23 year time period, for which we have detailed sea ice observations. The first class weather station was discontinued at Barter Island at the end of 1988, hence, this time series is shorter. It can be seen that both stations show a temperature increase, and in general, the two stations follow each other quite well; the correlation coefficient of 0.89 is calculated for the annual temperature values of the two stations. The best linear fit was applied to the data points of Barrow; from this a temperature increase of 1.1 °C can be found for the 23 year time period. Data from Barter Island would have resulted in slightly higher temperature increase. The Alaskan values were compared to high latitude stations in Canada (Curtis et al 1998), and a similar trend was observed for these stations, indicating that such a temperature increase with time is not a local effect of the North Slope of Alaska.
SEA ICE CHANGE
We were able to analyze systematically the area in the southern Beaufort Sea using a portion of the international Sea Ice Grid (SIGRID) produced by National Ice Center. Weekly sea ice concentration consisting of 0.25° latitude by 0.50° longitude grids derived from satellites for the period 1972-1994. We limited our study to the coastal Beaufort Sea, which was outlined in Fig.1. We chose an area somewhat East of Barrow, as Barrow is located at the most northerly point of Alaska, where the Beaufort and Chukchi Seas meet. Not only the climatic conditions at Barrow, but also 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.

![Temperature Graph](Image)

Figure 2: Mean annual temperatures for Barrow and Barter Island.

In Figure 3 the mean ice concentration is presented as function of season and year. It can be seen that the ice concentration is high for most of the year. From week 44 (beginning November) to week 24 (end of June) ice concentrations below 95 % are rare. However, below normal ice concentration can be found during any time of the year. Only in July, August, September and October are low ice concentrations observed.

![Isopleth Map](Image)

Figure 3: 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 the previous one.

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Table 1. Monthly sea ice concentration (\(^{0}\%\)) and its change (\(^{0}\%\) per year) from 1972 to 1994 assuming the best linear fit for the Southern Beaufort Sea.

<table>
<thead>
<tr>
<th></th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
<th>YEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{0}%)</td>
<td>97.2</td>
<td>98.0</td>
<td>98.4</td>
<td>98.2</td>
<td>97.4</td>
<td>95.1</td>
<td>81.3</td>
<td>55.4</td>
<td>34.8</td>
<td>70.1</td>
<td>94.9</td>
<td>96.6</td>
<td>84.8</td>
</tr>
<tr>
<td>(^{0}%) per year</td>
<td>0.01</td>
<td>-0.11</td>
<td>-0.14</td>
<td>-0.13</td>
<td>-0.10</td>
<td>-0.17</td>
<td>-0.83</td>
<td>-0.86</td>
<td>-0.14</td>
<td>-0.97</td>
<td>-0.25</td>
<td>-0.01</td>
<td>-0.32</td>
</tr>
</tbody>
</table>

The mean annual course for the whole area is presented in Table 1. It can be seen that the “winter” last about 8 months, with mean ice concentrations around 95% or above. The summer is short. Only in July does the ice pack starts to disintegrate, reaching the lowest ice concentration in September with 34.8%, increasing in October to 70.1% and reaching winter values again in November. In the last line of the table the changes in per mill per year are presented on a monthly basis. To obtain these values the best linear fit was applied to the data. All monthly values with the exception of January showed a decline in ice concentration, and even the small increase in January is due to a singular event in 1974. The change in the ice concentration for the winter months is much more modest when compared to the summer. In winter decreases of around 1 per mill per year are observed, which results in a total change of less than 3% for the 23 year study period. In July, August and October, large changes have occurred with values of close to 20% for the 23 year time period. Interesting to note is the relatively small change in September. This month displays the lowest ice concentration, hence, large absolute changes are more difficult to occur; this fact alone is hardly sufficient an explanation. Stone et al. (2001) 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. There are, of course, large variations from year to year. The earlier snowmelt should not only occur on land, but also on the adjacent sea. However, the sea ice concentration in the Southern Beaufort Sea has not changed much in May or June, but a strong decrease in ice concentration occurred in July. This could be a delayed reaction to the earlier snowmelt; after the snow had melted, it will take some time until the sea ice disintegrates.

Variations from year to year are large. In general it can be seen from Table 1 that the amount of low ice concentration and/or open water has increased in the investigated area in the Southern Beaufort Sea over the years. This is pronounced for the summer and fall months, but less change has occurred during the rest of the year. In Figure 4 the mean annual values, which were obtained by integrating values shown in Figure 3, are presented. A large amount of inter-annual variation can be seen. The highest ice concentration was observed in 1975 with 94%, the lowest in 1993 with 70%. In general, a decrease in ice concentration can be observed which has a confidence level of just below 90%. The best linear fit to the data points indicates a decrease from 88% to 82% mean ice cover for the 23 year time period of observations. This is a substantial decrease for the relative short time period. Changes in the near coastal area were very similar to those of the whole area, indicating that the decrease in sea ice was fairly uniform. However, the near coastal area has a lower ice concentration in the summer season (July, August, September) and slightly higher concentrations for the winter months (November through May). In general, the observed sea ice concentration decrease in the Western Arctic is in agreement with observations in other arctic and subarctic regions (Chapman and Walsh 1993, Walsh et al. 1996, Maslanik et al. 1999).
Figure 4: Mean annual ice concentration in the southern Beaufort Sea. The line represents the best linear fit of the annual data points.

CLIMATE – SEA ICE INTERACTIONS.
In Figure 5 the mean annual sea ice concentration of our study area in the Southern Beaufort Sea is plotted against the mean annual temperature of Barrow and Barter Island. 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 coefficient of variation ($r^2$) of 0.48 results for the whole test area, and a slightly improved coefficient of variation of $r^2 = 0.55$ (not shown) is obtained for the ice concentrations closest to the coastline of our test area.

Figure 5: The mean annual temperature of Barrow and Barter Island is plotted against the mean annual sea ice concentration in the Southern Beaufort Sea. Note, that in general warm years have below normal ice concentrations. The circle shows the normal mean annual temperature of Barrow versus the mean annual sea ice concentration (1972-1994).
Statistical measures, of course, do not give 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 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. The relationship between ice concentration and temperature on a seasonal basis was analyzed (not shown). Though it can be assumed that during cold winters thicker ice forms, and hence the decay in summer might be delayed, no improved correlation coefficients were found (Table 2). 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.

Table 2: Correlation coefficients ($r$) between winter temperatures (January to May) and ice concentration during the summer months (June to September) for the Southern Beaufort Sea.

<table>
<thead>
<tr>
<th></th>
<th>Total Area</th>
<th>Coastal Area</th>
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</thead>
<tbody>
<tr>
<td>June</td>
<td>0.23</td>
<td>0.04</td>
</tr>
<tr>
<td>July</td>
<td>0.28</td>
<td>0.40</td>
</tr>
<tr>
<td>August</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>September</td>
<td>0.33</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Low correlation coefficients were found; the reason might be due to:

- The growths 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. The highest correlation coefficient was found between winter temperature and the sea ice decay in the near coastal region in July. In the near coastal region more landfast ice is found, which is less affected by ice dynamics.

Further, we correlated the annual values of the sea ice concentration with different annual mean values of atmospheric indices; the findings are presented in Table 3. 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 95% confidence level with NINO 3.4, and only slightly lower confidence levels were obtained for the Pacific Decadal Oscillation and the Southern Oscillation Index; all other indices did not give significant correlation.

In Fig.5 there are two data points, which deviated far from the expected relationship with temperature, both showing sea ice concentrations far below the expected values with a mean annual value of 70% (1993) and 71% (1987). Looking at these two years
specifically, it should be noted that in 1987 the Pacific Decadal Oscillation (PDO), the NINO 3.4 and the Western Pacific Oscillation (WP) have all their maxima for the 23 years time period. Further, for 1993 the PDO and the WP have very high positive values.

Table 3: Correlation coefficients between the sea ice concentration in the Southern Beaufort Sea and different atmospheric indices.

<table>
<thead>
<tr>
<th>Atmospheric Index</th>
<th>Correlation coefficient (r)</th>
</tr>
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<tbody>
<tr>
<td>Pacific Decadal Oscillation</td>
<td>0.37</td>
</tr>
<tr>
<td>NINO 3.4</td>
<td>0.42</td>
</tr>
<tr>
<td>Southern Oscillation Index</td>
<td>0.40</td>
</tr>
<tr>
<td>Quasi-Biennial Oscillation</td>
<td>0.04</td>
</tr>
<tr>
<td>Western Pacific Oscillation</td>
<td>0.30</td>
</tr>
<tr>
<td>North Atlantic Oscillation</td>
<td>0.07</td>
</tr>
<tr>
<td>Arctic Oscillation</td>
<td>0.05</td>
</tr>
</tbody>
</table>

We analyzed the frequency of storms in the area, a storm being here defined as wind speeds in excess of 30 knots at Barrow. A total of 54 storms were observed during the 23 year time period. It can be clearly shown, that the frequency of such storms increased substantially towards the end of the observational period. These storms occur most frequently in fall when Northern Alaska already has cooled, but the Beaufort Sea is still partly ice free or covered with thin ice. A secondary less pronounced maximum has been observed in February, which is the coldest month at Barrow.

These storms can form coastal polynyas, if the wind direction is offshore. However, with one exception, these polynyas were not very wide, typically in the 10 km range. Such width agrees with model calculations after Pease (1987).

CONCLUSION
Temperature has increased along the shore of Northern Alaska during the last decades, and the sea ice concentration in the adjacent Beaufort Sea decreased. This decrease in sea ice concentration was specifically pronounced in summer. Annual mean values of atmospheric indices such as the NINO 3.4, SOI or PDO correlated significantly with the mean annual sea ice concentration in the Southern Beaufort Sea during our observation period 1972 to 1994; however annual mean values of other atmospheric indices describing the local atmospheric condition of the Beaufort Sea and adjacent geographic regions showed no correlation with the investigated sea ice concentration.

ACKNOWLEDGEMENT
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REFERENCES