Anomalies and Trends of Sea-Ice Extent and Atmospheric Circulation in the Nordic Seas during the Period 1864–1998

TORGNY VINJE

Norwegian Polar Institute, Oslo, Norway

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ABSTRACT

The extent of ice in the Nordic Seas measured in April has decreased by ~33% over the past 135 yr. Retrospective comparison indicates that the recent decrease in the ice extent is within the range of variability observed since the eighteenth century. Temporal, monotonically reduced extreme events occur with intervals of 12–14 yr, suggesting that series longer than ~30 yr should be considered to obtain statistical significance regarding temporal changes. Otherwise, decadal temperature variation is also found in the northbound warmer ocean currents. The temperature in the upper layers of these currents seems moreover to have increased by the order of 1°C since the cooling during the Little Ice Age. This temperature increase accounts for most of the ice extent reduction since ~1860. A strong negative correlation is found between the larger North Atlantic oscillation (NAO) winter index and the Nordic Seas April ice extent, and a corresponding positive correlation is observed for the Newfoundland–Labrador Sea. It is not until the warming of the Arctic, 1905–30, that the NAO winter index shows *repeated* positive values over a number of sequential years, corresponding to repeated northward fluxes of warmer air over the Nordic Seas during the winter. An analog repetition of southward fluxes of colder air during wintertime occurs during the cooling period in the 1960s. Concurrently, the temperature in the ocean surface layers was lower than normal during the warming event and higher than normal during the cooling event. Northward atmospheric winter fluxes are observed after the enhanced global warming after ~1970, and, for the first time over the period considered, a positive correlation is observed between atmospheric and oceanic reducing effects on the ice extent. The enhanced global warming over the past two decades seems also to be manifest in an intensified winter circulation at higher latitudes, rather than a contemporary change in the Arctic Ocean surface temperature.

1. Introduction

The area here referred to as the Nordic Seas comprises the Greenland, Iceland, Norwegian, Barents, and Western Kara Seas, bounded by 30°W, 70°E, and 80°N (Fig. 1). The area is divided at 10°E. The area west of this longitude is here referred to as the western area, while the area to the east is referred to as the eastern area. It is noted that by this division the northbound ice stream along the western coast of Spitsbergen is included in the Eastern area. This ice stream actually emerges from the Barents Sea. The period 1864–1998 will be considered for a scaling of the ice extent change with the North Atlantic oscillation (NAO) winter index (Hurrell 1995).

To obtain the assumed best homogeneity in an ice edge observation series collected from ship and satellite observations, the outer ice edge has been used as the limit for the ice extent. The difference in the definition of the outer ice edge during the ship observation period, as compared with the satellite observation period indicates that the April and August ice extents before the advent of satellites, should be, on average, increased by ~6 and ~18%, respectively. This would eventually increase the temporal trend in the ice series discussed below (see appendix).

2. April ice extent

a. Nordic Seas

Significant heat of fusion is released in the margins during freezing with brine release and change of the stability structure in the upper ocean layers. The extent of the spring ice cover reflects the net effect of winter dynamics and the northbound warmer currents. Southerly warmer winds cause compaction and reduced freezing in the ice margin, while colder northerly winds cause a relatively rapid expansion of the ice extent and increased freezing during the polar night.

The time series of the April ice extent in the Nordic Seas (Fig. 2) indicates a highly variable, but substantial reduction in the April ice extent over the period considered. The regression equation reads:

Corresponding author address: Torgny Vinje, Norsk Polarinstitutt, Post Office Box 8100 DEP, N-0032 Oslo, Norway.
E-mail: Torgny.Vinje@online.no

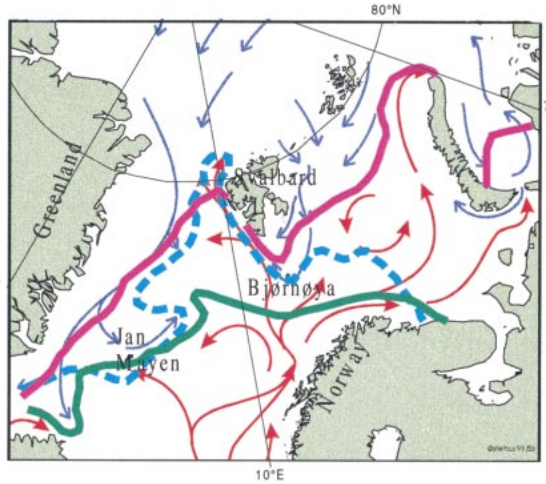

FIG. 1. Study area with some ice edge observations and outlined ocean current pattern. Extreme southern and northern Apr ice edge locations during the twentieth century were observed in 1966 (blue dashed line) and in 1995 (magenta). The extreme southern Apr extension during the nineteenth century was observed in 1866 (green line). The red and blue arrows indicate the respective movement of warm and cold water masses during the cold season (courtesy S. Østerhus).

$$y = 0.0266x^2 - 9.46x + 2377 \quad (10^3\ km^2) \quad (1)$$

where y = Nordic Sea April ice extent and x = year − 1860. The explained variance is $R^2 = 0.42$.

The regression line indicates an overall April ice extent reduction of 0.79×10^6 km², or ~33%, over the 135-yr period. Nearly half of this reduction, 0.32×10^6 km², took place before 1900, that is, before the warming of the Arctic, which took place during the first three decades of the twentieth century (Vinnikov 1986). The time series indicates that we are in a state of continued recovery from the cooling effects of the Little Ice Age, during which a maximum sea-ice expansion was observed around 1800, both in the Iceland Sea (Ogilvie 1992) and in the Barents Sea (Vinje 1999). This sea-ice expansion occurred contemporarily with a noticeable fall in the temperatures in central England [Fig. 30 in Lamb (1995)].

Trends in the Northern Hemisphere *annual mean ice extent* have been reported by a number of investigators for the last three to five decades, for example, Walsh and Johnson (1979), Mysak and Manak (1989), Johannessen et al. (1995), Zakharov (1996), and Parkinson et al. (1999). An overall decrease in the annual mean ice extent is generally observed, also in the Nordic Seas, in accordance with the present observation of a decrease in the winter ice extent.

Returning to the above regression line for the Nordic Seas, it is seen that the temporal reduction rate for the April ice extent decreases from 8×10^3 km² yr⁻¹ in 1880 to 3×10^3 km² yr⁻¹ in 1980. The global warming (Nicholls et al. 1996) is accordingly concurrent with a decelerating seasonal freezing rate over the past 100 yr.

The temporal, monotonically reduced extreme events illustrated in (Fig. 2) seem to occur with a periodicity of 12–14 yr over the 135-yr period. The decadal periodicity in sea-ice extent that has been observed during recent decades by, for example, Mysak and Manak (1989), Slonosky et al. (1997), and Mysak and Venegas

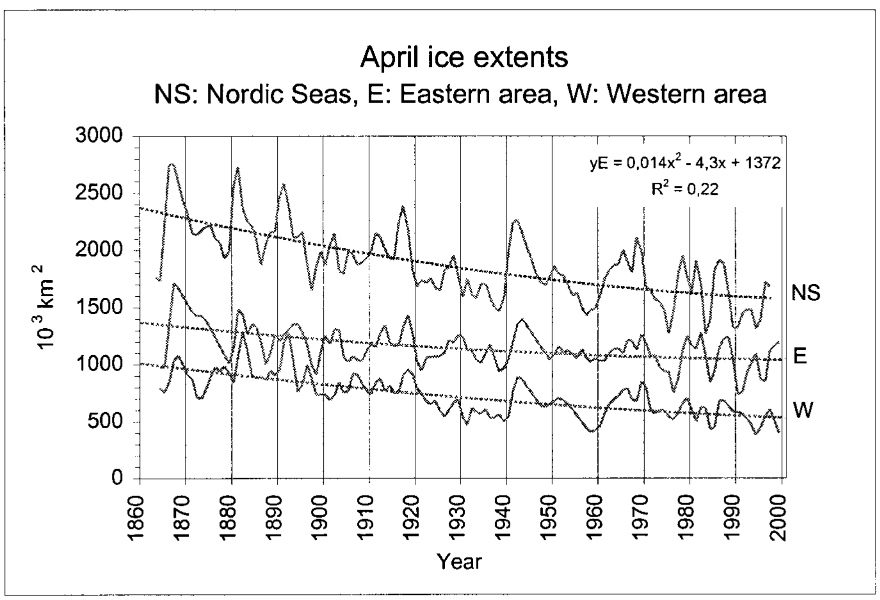

FIG. 2. Time series of the Apr ice extent in the Nordic Seas (NS), eastern area (E), and western area (W) given by 2-yr running mean and regression lines. Linear year-to-year interpolations of the ice extent have been made for the western area for 1940 and 1944–46, and for the eastern area for 1868–70, 1874–78, 1880, 1892, 1894, 1940–41, 1943–48, and 1961. Observations for Apr 1942 were kindly provided by V. Abramov.

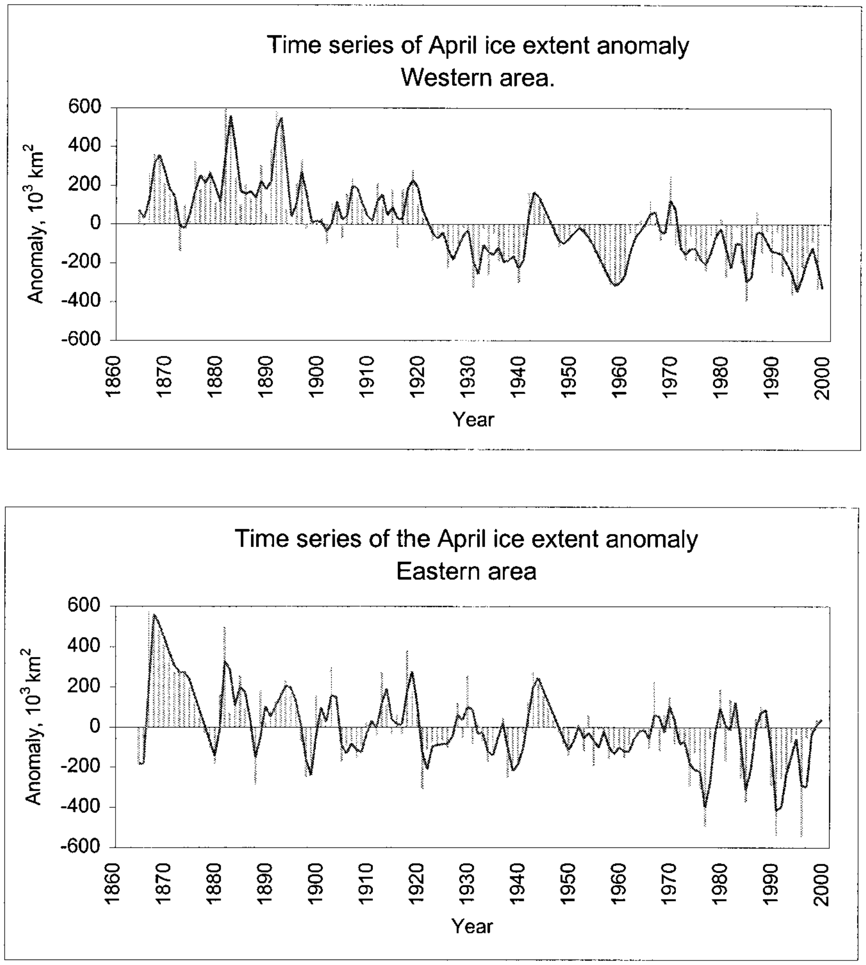

FIG. 3. Gray columns: time series of the Apr ice extent anomaly for the (upper) Eastern and (lower) western areas of the Nordic Seas. Black line: 2-yr running mean curve.

(1998), therefore seems to be a feature characteristic also for the extended period considered here.

The above regression line suggests that about 42% of the variance of the annual time series for the Nordic Seas can be statistically explained. This percentage drops below 18% for a time series shorter than 90 yr, and below 3% for a series shorter than 30 yr. The observed variability in the Nordic Seas is accordingly so high that series longer than a multiple of decadal periods should be considered in order to obtain a substantial statistical significance regarding temporal changes of the ice extent.

b. Western and eastern areas

The decadal periodicity in the ice extent observed for the Nordic Seas is more systematic than for the individual western and eastern areas (Fig. 3), especially for the period before 1920. Also, for the 1920–40 period the two series are out of phase. It is assumed that the variable correspondence between extremes in the two areas is caused, to some extent, by a variable track of low pressures into the Nordic Seas, and that the total effect of the variability is captured when considering the western and eastern area together.

The regression lines for the annual series of ice extent in eastern and western areas (Fig. 2) indicate that the percentage of April ice extent reduction over the period 1864–98 has been greater by 46% in the western area, as compared with 24% in the eastern area. It is assumed that this mainly reflects a reduced occurrence and extension of local ice formation in the Odden ice feature in the Greenland Sea (Vinje 1976) as well as the reduced frequency in ice sightings from Iceland over the same period (Ogilvie 1999).

The overall correlation between the western and eastern April ice extents is 0.52. However, the correlation varies significantly from period to period, being 0.41 during 1864–1900 with a small rise in the circumpolar mean temperature as reported by Vinnikov (1986), decreasing to a minimum of 0.26 during the warming of the Arctic during 1905–35, increasing again to a maximum of 0.62 during the cooling of the Arctic (Zakharov 1976; Vinnikov 1986) from 1935 to 1970, with a subsequent fall to 0.34 during 1970–98. The variable correlation indicates accordingly a far better physical connection between the two ice bodies during cooling periods than during warming periods. This is to be expected considering the difference in current patterns, ice composition (Fig. 1), and atmospheric effects in particular. The higher correlation observed during cooling periods may reflect the preponderance of northerly winds over the whole area, in contrast to warming periods when the eastern area may be affected by Southwest winds and the western area by recurring northeast winds (Hilmer et al. 1998).

The maximum correlation of 0.62 during cooling periods illustrates the correspondence between increased ice extents in the Iceland Sea (Ogilvie 1992) and in the Barents Sea (Vinje 1999) during the extreme expansion around 1800. To put the present series in a longer historic perspective, it is of interest to note that Ogilvie (1992) found that the iciest period around Iceland since 1600 and possibly even from 1500, is observed during 1780–1800, when a rapid deterioration took place over only a couple of decades (see Fig. 5.4 in Ogilvie 1992).

3. Annual melt-back

Taking the period 1920–98, for which we have almost continuous April *and* August ice edge observations for the Nordic Seas, we observe an overall ice extent shrinkage for April and August of ~12% and ~40%, respectively (Fig. 4, upper). The large percentage difference in seasonal changes of ice extent is reflected in the contemporary net increase in the Spitsbergen seasonal temperatures: being considerably larger during spring (3°) than during winter (1°), summer (0.5°), and autumn (0.0°) (Hanssen-Bauer and Førland 1998). The large percentage difference in seasonal shrinkage indicates also that the global warming (Nicholls et al. 1996) has a far higher impact on the disintegration rate of ice than on the seasonal freezing rate, which moreover seems to have decelerated over the past 100 yr according to the above April ice extent time series.

A comparison between the western and eastern areas (Fig. 4), indicates April ice extent reductions of ~16% and ~10%, and August ice extent reductions of ~22% and ~62%, respectively. It is assumed that the significant August difference between the two areas is due to the fact that the thicker, multiyear ice exported from the Arctic Ocean to the western area, is affected to a lesser extent by a global warming than the thinner, first-year ice in the eastern area. Also the mentioned marked rise of about 3°C in the Spitsbergen spring temperature correlates with a significant increase in the annual withdrawal of the ice edge in the eastern area, where the August ice extent has been more than halved over the past 80 yr. The August series for the eastern area (Fig. 4, lower) indicates, moreover, that a complete disappearance of ice from the Barents Sea proper (south of 80°N), has become more frequent since about 1930, with a maximum melt-back into the Arctic Ocean in 1984.

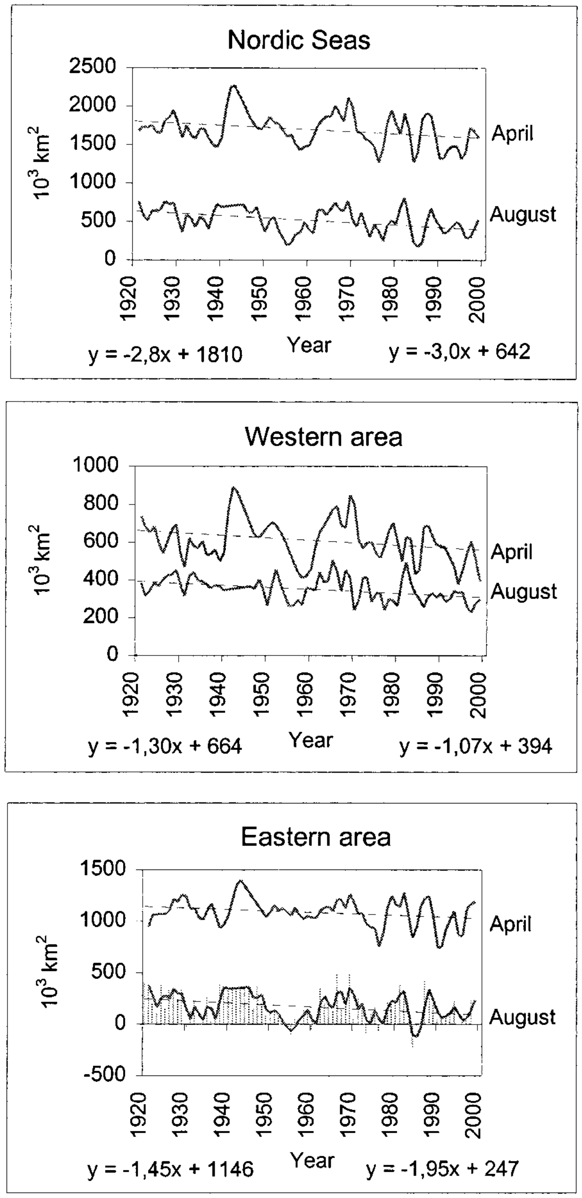

FIG. 4. Time series of Apr and Aug ice extent given by 2-yr running means for (upper) the Nordic Seas, (middle) Western area, and (lower) Eastern area, for the period 1920–98. The linear regression equations used for trend estimations are given below the abscissas [$y = 10^3$ km^2, and $x =$ (year − 1920)]. Linear interpolations of the Aug ice extent have been made for the period 1940–45. The Apr interpolation years are given in the caption of Fig. 2. Negative ice extents in the lower graph, where the ice extent for the individual Aug months is also given, indicate a melt-back into the Arctic Ocean (north of 80°N).

The overall correlation between the April and August ice extents of the Nordic Seas is 0.52. While the western April and August ice extents are poorly correlated ($R = 0.20$), the eastern April and August ice extents show a higher correlation of $R = 0.60$. This difference in temporal correlation for the two areas is in all probability caused by the fact that the Western area is dominated by the highly variable import and residence time of thicker ice from the Arctic Ocean (Vinje et al. 1998; Hilmer et al. 1998). The relatively high correlation between the April and August ice border in the eastern area has long since been of practical use for optional planning of industrial and scientific investigations.

Annual melt-backs of the magnitude observed after about 1930 (Fig. 4, lower) have not been observed in the Barents Sea since the eighteenth century temperature optimum (Vinje 1999). He found a very high negative correlation (−0.87) between the 10-yr mean Barents Sea August ice extent and the Northern Hemisphere mean annual temperature (NHMT) back to ~1860, as well as a close relationship between the 50-yr mean Barents Sea August ice extent and the 50-yr mean summer temperature in central England back to 1700 [Fig. 30 in Lamb (1995)]. This comparison indicates a fall in the NHMT of about 0.6°C over the last few decades of the eighteenth century, contemporary with the rapid expansion of ice around Iceland (Ogilvie 1992) and in the Barents Sea, and a rise of about 0.7°C over the period ~1800–2000. This retrospective comparison indicates accordingly that the recent reduction of the ice extent in the Barents Sea as well as the increase in the NHMT is still within the variation range observed since the eighteenth century.

4. April ice extent and atmospheric winter circulation

The North Atlantic oscillation (NAO) index (Hurrell 1995) characterizes the strength of the westerlies between Iceland and Portugal, which in turn represent a dynamic source for the low pressures subsequently forming the northeast Atlantic trough, which extends from Iceland, over the Norwegian, Barents, and Kara Seas onto the margins of Siberia (Proshutinsky and Johnson 1997). The pressure distribution in this trough and the corresponding wind effects on the ice extent in the Nordic Seas are highly dependent upon the frequency of blocking high pressure events over Iceland, and, accordingly also on the magnitude of the NAO winter index.

The relation between the negative phase of the NAO winter index and the sea ice extent in the Nordic Seas for the past decades has been investigated by Mysak et al. (1996), Rogers (1997), Mysak and Venegas (1998), Dickson et al. (2000), Yi et al. (1999), and Deser et al. (2000). A dipole in ice extent anomalies (+ in the Nordic Seas and − in the Labrador Sea), is well known from investigations by Walsh and Johnson (1979) and Slonosky et al. (1997). Also, a strong positive correlation between NAO and the Labrador Sea ice cover goes back to the early work of Rogers and van Loon (1979). The recently published ice extent series for the period 1810–1998 for the Newfoundland–Labrador Sea (Hill 1998), has made it possible to study the mentioned dipole over a longer time period.

By considering periods over which the NAO winter (December–March, DJFM) index shows maximum changes per year, an optimal correlation is obtained (Fig. 5).

The slope factor of the linear regression lines in Fig. 5 (dy/dx) gives the change in the April ice extent with respect to a change in the NAO winter index. A marked difference in this slope factor (sensitivity) is observed from region to region, the eastern area being 4.5 times more sensitive than the western area, and 2.3 times more sensitive than the Newfoundland–Labrador Sea area. These marked regional differences in sensitivity, in all probability, reflect the effects of the difference in ocean current pattern and preferred tracks and dimension of the atmospheric low pressure systems passing the different areas. It is, for example, only the Nordic Seas that are affected by major northbound warmer ocean currents, and it is mainly the eastern area that is affected in this respect (by the branch moving into the Barents Sea and the branch moving northward along the west coast of Spitsbergen, Fig. 1)

The western area is subject to effects of the variable influx and residing time of thicker ice from the Arctic Ocean and by the cold East-Greenland Current. The western area may also be affected by recurring northeast winds while the eastern area is affected by southwest winds by northeastward-moving low pressures (Hilmer et al. 1998). This may also explain the comparatively lower sensitivity and smaller correlation between the NAO winter index and the ice extent observed for the western area (Fig. 5b).

5. Atmospheric and oceanic effects on the ice extent in the eastern area

a. Atmospheric effects

The regression equations for the NAO-scaled, winter wind effects on the April ice extent in the eastern area (Fig. 5a) read

$$\Delta(E - \mathrm{EA}) = (-58)\mathrm{NAO}, \quad (10^3\ \mathrm{km}^2) \qquad (2)$$

where $\Delta(E - \mathrm{EA})$ is the NAO winter index scaled effect on the April ice extent (E) in the eastern area (EA) of the Nordic Seas. Analog relationships for the less sensible regions, the western area (WA), and the Newfoundland–Labrador Sea (NFL) read: $\Delta(E - \mathrm{WA}) = (-12.8)\mathrm{NAO}$ and $\Delta(E - \mathrm{NFL}) = (25)\mathrm{NAO}$. By implementation of the NAO winter index (Hurrell 1995) in Eq. (2), we obtain an approximate time series of the April ice extent anomalies caused by the mean meridional circulation during the preceding four months, December, January, February, and March (Fig. 6).

Because of the nonsystematic, though large, variations of the NAO winter index observed before 1900,

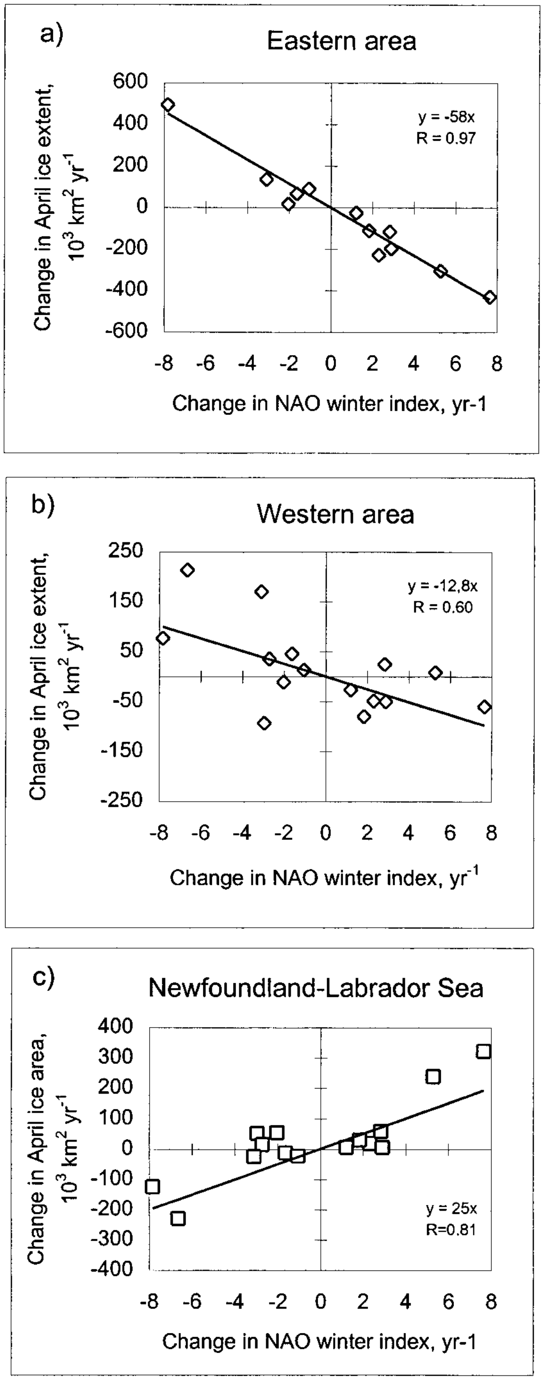

FIG. 5. Change per year in the NAO winter index and the corresponding change per year in the Apr ice extent for major changes in the NAO over the period 1864–96. (a) Eastern area, (b) western area, and (c) Newfoundland–Labrador Sea (south of 55°N). Regression equations and correlation coefficients are given in insets. The years used for the calculations are flagged in Fig. 6. Ice extent data for the Newfoundland–Labrador Sea was kindly provided by Hill (1998).

only a small average net effect is exerted on the April ice extent during the period 1864–1900. It is not until the first decade of the twentieth century, during the warming of the Arctic (Vinnikov 1986), that a sequence of annually repeated occurrence of southerly winds during winter are affecting the April ice extent to a significant degree. Followed by a short-lived increase in the ice extent, 1917–20, corresponding in time with a short-lived cooling (Vinnikov 1986), a series of somewhat smaller, negative anomalies are observed between 1920 and 1930, during the continued warming. Annually repeated maximum positive anomalies are observed during the cooling in the 1960s (Vinnikov 1986), with a preponderance of northerly winds causing an extreme expansion of ice in the Barents Sea, Iceland Sea, and Greenland Sea, then particularly in the Odden area, the latter extending northeastward from Jan Mayen (Fig. 1). Since the mid-1960s, a noticeable change toward negative anomalies is observed, with a maximum between 1989 and 1995 when the Kara Sea for the first time since 1864 is observed to be partly ice free in April (Fig. 1).

The effect of wind patterns on the ice extent, east and west of a trough or a ridge over Greenland is illustrated by the negative correlation between the ice extent variations in the eastern area and the Newfoundland–Labrador Sea (Figs. 5a,c). The above evaluation indicates that significant reductions/increases in the Nordic Seas ice extent correspond with significant increases/reductions in temperature *only* when southerly/northerly winds occur *during some winters in sequence* (Fig. 6). This indicates that changes in ice extent and temperature in the Nordic Seas are highly dependent upon a year-to-year repetition of troughs/ridges over Greenland, a feature that in turn is connected with the positional stability of troughs/ridges in the circumpolar Rossby wave pattern.

A *general* correlation between the NAO winter index and the subsequent April ice extent in the eastern area shows a highly variable, time-dependent explained variance (Fig. 7), and it is only for the periods with a repetition of large NAO winter indexes, 1905–35 and 1966–96 (Figs. 7b,d), that the explained variance and the sensitivity (dy/dx) approach the values observed for the relationship (2) above. A similarly high correlation has also been observed by Yi et al. (1999) for the period 1954–94 and by Deser et al. (2000) for the period 1953–97. Particularly small explained variances and sensitivities are observed for the periods with more unsystematic variations in the NAO winter index, 1864–1900 and 1935–60 (Figs. 7a,c).

b. Oceanic effects

An outline of the branching of the Atlantic water in the Nordic Seas is given in (Fig. 1). This simplified picture, which indicates mean conditions, masks a number of important temporal deviations, which include me-

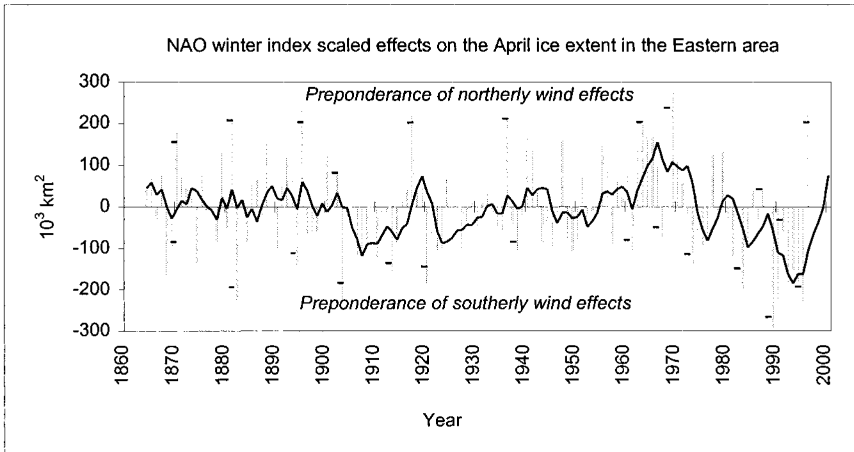

FIG. 6. Gray columns: time series of the NAO winter index scaled effects on the Apr ice extent in the eastern area. Black line: 5-yr running means. Tick-marked gray columns indicate the years for which observations are used as basis for Fig. 5 and Eq. (2).

andering effects correlated with the variable NAO index, and a variable redistribution to the Barents Sea and the Arctic Ocean of the Atlantic water entering the Norwegian Sea (Hansen and Østerhus 2000; Blindheim et al. 2000). This means that the temperature observed at Station Mike in the Norwegian Sea since 1949 (Fig. 8) is not always representative for the temperature of the Atlantic water that subsequently enters the Barents Sea. With this in mind, the long-term temperature series from the Norwegian Sea will be compared with the ice extent

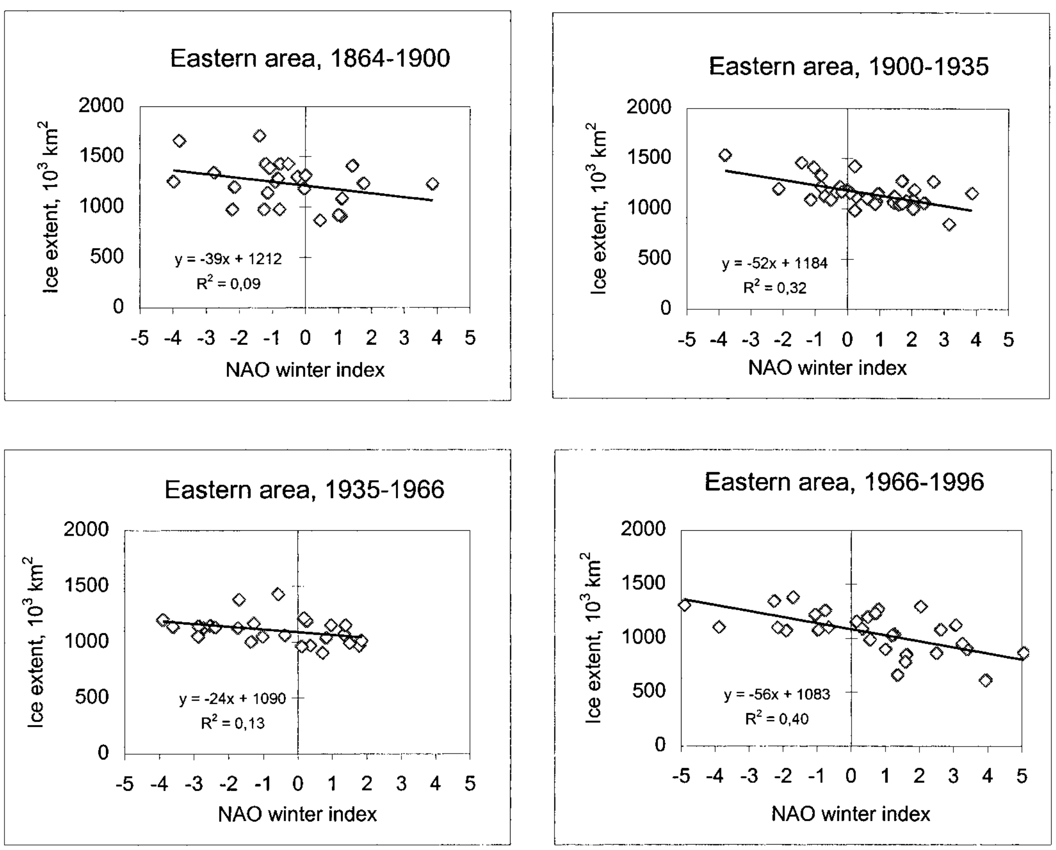

FIG. 7. Correspondence between the NAO winter index and the Apr ice extent in the eastern area for periods with different intensity of the meridional atmospheric circulation as indicated by Fig. 6. The regression equation and explained variance are given as insets.

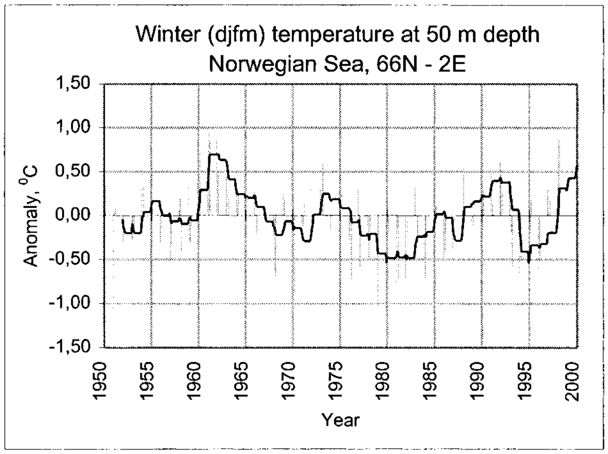

FIG. 8. Time series of the winter (DJFM) temperature anomaly at the depth of 50 m as measured at Station Mike, 66°N–2°E, in the Norwegian Sea. The line represents the 2-yr running mean. The observations were kindly provided by S. Østerhus.

series from the Barents Sea. Observations at Station Mike show temperature variations on a decadal scale (Gammelsrød et al. 1992; Østerhus and Gammelsrød 1999; Fig. 8) with an amplitude in the upper layers of about 1°C.

A time series of the anomaly of the oceanic effect on the April ice extent in the eastern area is obtained by subtracting the anomaly of the (dynamic and thermodynamic) atmospheric effects during winter, (−58)NAO, given in Fig. 6, from the April ice extent anomaly series, given in Fig. 3a. The time series of the oceanic effect anomaly is given in Fig. 9.

The right-hand scale given in Fig. 9 is based on the following evaluation: the temperature of the Atlantic Water in the Norwegian Sea will have a lagged effect on the ice extent in the Barents Sea. This time lag will vary with the velocity of the current and accordingly vary from year to year. A separate analysis of the correlation between the annual series of temperature anomalies at Station Mike (Fig. 8) and oceanic effect on the ice extent, 1950–96, indicates a maximum correlation of −0.42 for a mean delay of 2 yr. The correlation for 1, 3, and 4 yr delay are −0.20, −0.14, and −0.14, respectively. A mean time lag of 2 yr is supported by a number of observations: temperature anomalies in the Atlantic Water in the western part of the Barents Sea are observed one-half year later in the eastern part (Loeng 1991), and ocean temperature anomalies outside Lofoten are negatively correlated with 1-yr lagged anomalies in the Barents Sea ice extent (e.g., Helland-Hansen and Nansen 1909). This suggests a period of 2–3 yr for anomalies from the more southern location of Station Mike to reach the Barents Sea and the west coast of Spitsbergen. Considering periods with a stable anomaly lasting over periods of three or more years (cf. Fig. 8), a strong correlation of −0.80 is observed between temperature anomalies in the upper ocean layers at Station Mike and the lagged oceanic effect on the ice extent in the Barents Sea (Fig. 10). It is possible that the effects of the above-mentioned meandering and variation in current velocity are reduced by using long-lasting anomaly periods, and that this is the reason for the marked increase in correlation, from −0.42 to −0.80.

The decadal periodicity observed in the ice extent

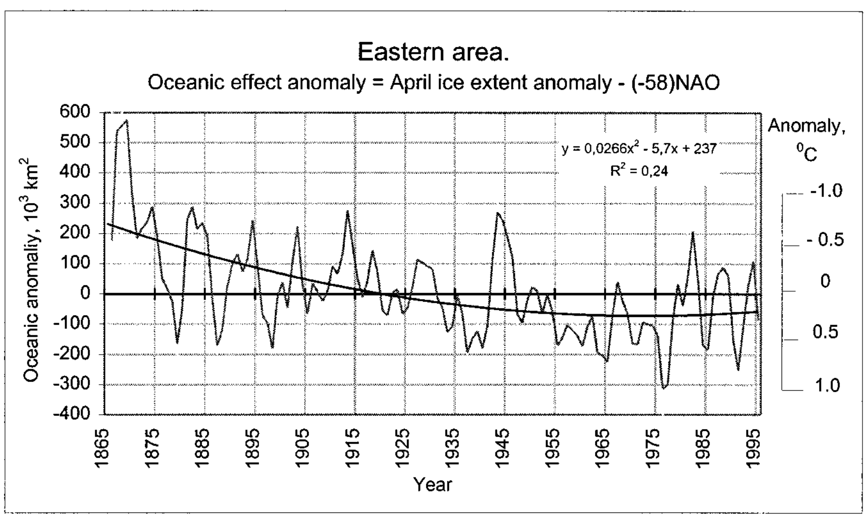

FIG. 9. Time series of the oceanic effect anomalies during winter on the Apr ice extent in the eastern area (left scale). Gray line: 2-yr running mean. Black line: regression line, where y = oceanic effect anomaly and x = year − 1860. The major oceanic effects observed around 1870 and during the Second World War are uncertain because of reduced observations (cf. Fig. 2 caption). The right-hand scale shows the temperature anomaly at Station Mike as obtained from the observed relationship with the oceanic effect anomaly (Fig. 10).

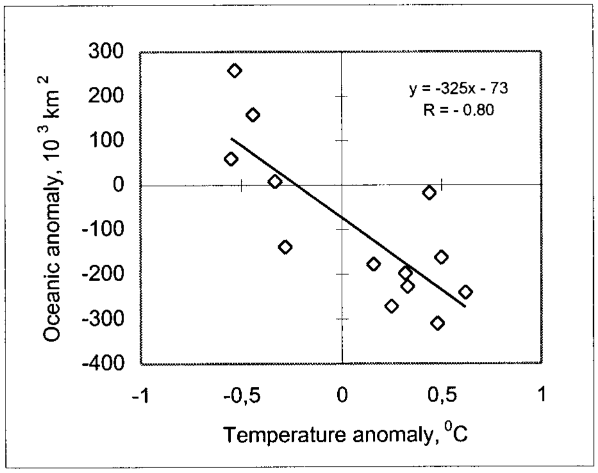

FIG. 10. The relationship between temperature anomalies at the depth of 50 m at Station Mike and time-lagged oceanic effect anomaly on the eastern area ice extent for the periods 1960–65, 1978–82, and 1990–92, when relatively stable temperature anomalies were observed at Station Mike during 3 yr or more in succession (cf. Fig. 8).

variability (Fig. 3a) is retained in the time series of oceanic effects on the ice extent (Fig. 9), indicating that this periodicity in ice extent is caused by decadal temperature variations in the ocean. A comparison between the period 1864–1900, with small net wind effects (Fig. 6), and 1975–95, with relatively strong southerly wind effects, indicates that the periodicity has decreased from 11–12 yr before 1900 to 6–7 yr after 1970 (Fig. 9). This may indicate that the velocity of the northward advected temperature anomalies in the ocean upper layer is positively correlated with the wind speed, or the velocity of the ocean currents.

The amplitude of the decadal variations seems to be of the same order over the 135-yr long period. The regression line (Fig. 9) indicates, however, that the temporal increase in ocean temperatures has decelerated considerably over the last 100 yr. The most rapid increase in ocean temperature took place before 1900 with an increase of ~0.5°C over a period of ~40 yr, ~1860–1900. A subsequent, similar temperature increase took place over the next 100 yr, ~1900–2000. The increase in ocean temperatures since the Little Ice Age seems therefore to be on the order of 1°C. This increase is two-tenths more than observed for the NHMT over the same period of time (Nicholls et al. 1996). The relatively close accordance may illustrate the importance of the conditions in the Nordic Seas for the circumpolar mean temperatures.

6. The balance between atmospheric and oceanic effects in the eastern area

Time series of the atmospheric and oceanic effects as illustrated in Figs. 6 and 9, respectively, are given in Fig. 11, together with a scale for the temperature anomalies in the upper layers of the northbound warmer currents. A relatively rapid increase in the ocean temperature, of the order of 0.5°C, took place before 1900. This increase took place during a period with small net atmospheric effects, or week net meridional atmospheric energy exchange (Fig. 11). This indicates that a change in the ocean temperature of ~0.5°C corresponds to a change in the April ice extent of ~0.15 × 10^6 km^2 (Fig. 2e). The maximum amplitude of the decadal temperature

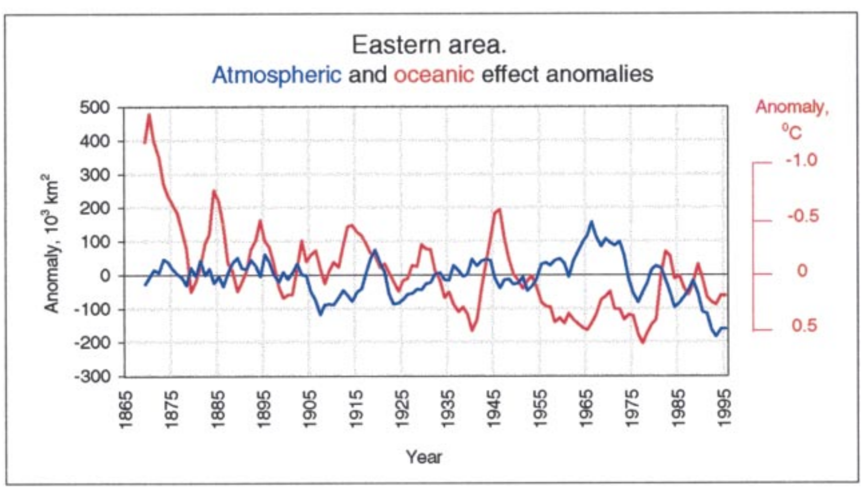

FIG. 11. Time series of 5-yr running mean anomalies (left scale) of the winter atmospheric effects (blue), and the winter oceanic effects (red) on the Apr ice extent in the eastern area. The right-hand (inverted) scale indicates the temperature anomaly in the northbound warmer currents as estimated from derivatives of the regression line in Fig. 10. The major oceanic effects observed around 1870 and during the Second World War are uncertain because of reduced observations (cf. Fig. 2 caption).

variations, which is of the order of 1°C (Fig. 8) corresponds accordingly to a maximum variations of 0.30 × 10^6 km^2 in the oceanic effect on the ice extent. A change of this magnitude is of the same order as the one observed in the eastern area April ice extent over the whole period considered, ~1860–2000, namely 0.33 × 10^6 km^2. This indicates that the net increase in the ocean temperature of about 1° since ~1860 seems to account for the majority of the ice extent reduction since then, and, accordingly, that the contemporary net increase in air temperature plays a minor role over this period of time.

Counteracting effects of the atmospheric and oceanic influences on the ice extent is illustrated by a negative correlation of −0.43 between these effects over the period 1900–70 (Fig. 11). The most pronounced feature in this connection is the colder ocean during the warming at the beginning of the twentieth century, and the warmer ocean during the cooling during the 1960s. A smaller, but positive correlation of 0.12–0.22 is for the first time observed after 1970, indicating a concerted, disintegrating effect on the April ice extent thereafter. This marked change in correlation is concurrent with the onset of the enhanced global warming since 1970 (Nicholls et al. 1996). The variation in the ocean temperature and its positive or negative correlation with wind direction seems therefore to be of crucial importance for the variation in the ice extent. In particular, since the temperature variations in the ocean seem to vary considerably over periods of two decades, a coincidental concerted effect of wind and ocean effects may lead to a considerable retreat or advance of the ice over a period that is very short in a climatic sense.

7. Contemporary variations of different physical parameters

Apart from a noticeable reduction in the ice extent and increase in ocean temperatures, there is a relatively small change in other pending parameters before 1900. The warming event during the first decades of this century is characterized by a significant decrease in the Nordic Seas April ice extent, an increase of ~3°C in the Arctic surface winter temperature, averaged over the circumpolar zone between 72.5° and 87.5°N, and an increase in the Spitsbergen mean winter temperature of as much ~9°C (Table 1). During this warming event the temperature in the ocean was lower than normal. An increasing preponderance of positive ice extent anomalies, with an optimum in the 1960s, is observed during the period 1949–66, concurrent with a cooling in the circumpolar zone of ~1°C, a fall in the Spitsbergen mean winter temperature of ~3°C, and an increase in the mean winter air pressure in the western Barents Sea of ~6 hPa. During this cooling event the temperature in the ocean was higher than normal.

A renewed, substantial reduction of the ice extent took place during the period ~1966–92, concurrent with an increase in winter temperature in the margins of ~2°C and a significant fall of ~12 hPa in the mean winter air pressure in the western Barents Sea (Table 1). For the same period, a high correlation between the frequency of southerly winds and the Spitsbergen mean winter temperature is observed by Hanssen-Bauer and Førland (1998). Concurrently, no trends in the air temperature in the Arctic Ocean proper are observed over the past 40 yr (Kahl et al. 1993; Radionov et al. 1997). Accordingly, the temperature difference between Spitsbergen and the Arctic Ocean is subject to a noticeable increase since 1966. The sharpening of the poleward temperature gradient at higher latitudes is conditioned on and concurs with a marked increase in the atmospheric circulation indicated by the marked fall of 12 hPa in the air pressure in the western Barents Sea during winter. Walsh et al. (1996) also report on a marked increase in the winter and spring circulation since 1988 in the extension of the northeast Atlantic trough in the eastern Arctic. The enhanced global warming since about 1970 (Nicholls et al. 1996) seems accordingly to be manifest in an intensified winter circulation at higher latitudes rather than a contemporary rise in the Arctic Ocean surface temperature.

There is a general agreement in Table 1 between a positive/negative change in the April ice extent and a decrease/increase of the Spitsbergen winter temperature, $\Delta T(\Delta E)^{-1}$, and the circumpolar winter temperature, $\Delta Tz(\Delta E)^{-1}$. The magnitude of the proportionality factors are at a maximum during the warming of the Arctic, and has decreased drastically since 1935. This means, that in spite of a reduction in the April ice extent during the last decades, there is a correspondingly small change in the preceding winter temperature in the Arctic. In all probability, we see here an increasing effect on the surface temperature of the heat sink caused by the melting of ice. The increasing number of pulses of warmer air masses moving onto the ice margins cannot increase the surface temperature above the melting point. This concurs also with the previous findings that the global warming has a significantly smaller effect on the April ice extent reduction, determined by the winter temperature increase of ~1°C in the margins, as compared with

TABLE 1. Temporal variations of 1) the Nordic Sea Apr ice extent from Fig. 2, ΔE (10^3 km^2); 2) the Spitsbergen winter temperature, ΔT (°C); 3) the zonal winter temperature between 72.5° and 87.5°N, ΔTz (°C); 4) the change in Spitbergen winter temperature per unit change in the Apr ice extent, $\Delta T/\Delta E$; 5) $\Delta Tz/\Delta E$; 6) the variation in the mean winter air pressure, ΔP (hPa), in the western Barents Sea.

Period	1) Δ*E*	2) Δ*T*	3) ΔTz	4) Δ*T*/Δ*E*	5) ΔTz/Δ*E*	6) Δ*P*
1880–1909	−396		~0.5		−0.001	
1909–35	−272	8.5	3.4	−0.031	−0.015	
1949–66	202	−3.4	−1.2	−0.017	−0.006	6
1966–92	−578	2.4	0.6*	−0.004	−0.001*	−12

* Period 1966–80; 2) Hanssen-Bauer and Førland (1998); 3) Vinnikov (1986); 6) *Die Grosswetterlagen Europas*.

the increased seasonal disintegration, determined by the increase of $\sim$3° in the spring temperature in Spitsbergen.

8. Conclusions

The extent of ice in the Nordic Seas measured in April has been subject to a reduction of $\sim$33% over the past 135 yr. Nearly half of this reduction is observed over the period $\sim$1860–1900, prior to the warming of the Arctic. Decadal variations with an average period of 12–14 yr are observed for the whole period. The observation series indicates that less than 3% of the variance with respect to time can be explained for a series shorter than 30 yr, less than 18% for a series shorter than 90 yr, and less than 42% for the whole 135-yr long series. While the mean annual reduction of the April ice extent is decelerating by a factor of 3 between 1880 and 1980, the mean annual reduction of the August ice extent is proceeding linearly.

The August ice extent in the Eastern area has been more than halved over the past 80 yr. A similar meltback has not been observed since the temperature optimum during the eighteenth century. This retrospective comparison indicates accordingly that the recent reduction of the ice extent in the Eastern area is still within the variation range observed over the past 300 yr.

Although a strong negative correlation is observed between the NAO scaled winter circulation and the subsequent April ice extent in the Nordic Seas, this correlation becomes positive for the Newfoundland–Labrador Sea. This regional difference in correlation reflects the effect of wind patterns around a trough or a ridge over Iceland–Greenland. A given change in the NAO index causes an ice extent change in the eastern area that is 4.5 times larger than the change in the western area, and, 2.3 times larger than the change in the Newfoundland–Labrador Sea.

A significant reduction in the April ice extent took place before 1900. Due to a contemporary small net atmospheric effect, this reduction is ascribed to a dominant oceanic effect, corresponding to a net rise in the upper layers of the Atlantic Water of about 0.5°C. The atmospheric and oceanic effects are negatively correlated over the long period 1900–70. Accordingly, the atmospheric warming with southerly winds during the first decades after 1900 occurred with a colder ocean, and the cooling during the 1960s with a warmer ocean. After 1970 this correlation becomes positive, indicating that a concerted reducing effect of the ice extent has taken place in conjunction with the enhanced global warming since then.

The variation in the ice extent caused by a 1° change in the ocean temperature since $\sim$1860 compares with about 90% of the concurrent total ice extent variation observed in the eastern area. The net effect of atmospheric temperatures seems accordingly to be relatively small over the same period of time. This concurs with the large difference in the individual heat capacity.

Temperature variations on the order of 1°C occur in the ocean on a decadal scale. Provided there is *positive* correlation between the atmospheric and oceanic effects, a considerable expansion or contraction of the ice extent should be expected to occur over periods of a decade or two only. It is possible that such a *coincident* occurred during the comprehensive advance of ice and fall in temperature during the last decades of the eighteenth century.

During the continued global warming the annual mean air temperature in the Arctic Ocean has been nearly the same. The corresponding sharpening of the meridional temperature gradient is concurrent with the observed increase in the atmospheric circulation in the Nordic Seas.

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APPENDIX

The Database

a. Data history

Annual sealing and hunting in the ice margins of the Nordic Seas was taken up by the Norwegians around 1850. In addition to the collection of ordinary ships' logs, meteorological observations were noted in separate books for use by the Norwegian Meteorological Institute (DNMI). The ice extent series consists of ice maps depicted by Adolf Hoel from 285 ship logs covering the period 1850–1922. For most of this period we have controlled the ice edge positions given in the ships' logs with remarks and positions given in 170 meteorological observation series collected by DNMI.

The ordinary ships' logs were collected by Otto Sverdrup on a round trip in Norway in 1922 in connection with the planning of coal shipping from Longyearbyen, Spitsbergen. Since then, ice information has been collected at the Norwegian Polar Institute from sealers, ship traffic, and retrospectively from trappers wintering on islands in the Svalbard archipelago (Fig. 1) since 1800.

Russian, Norwegian, and American aircraft observations have been collected since 1950, and observations from the meteorological land stations on Bjørnøya and Jan Mayen have been gathered since 1963. Ice maps edited by DNMI, the Met. Office, and the U.S. Navy–NOAA Joint Ice Center have been compared to obtain a modified, consistent series for the period after U.S. satellite information became available in 1966. This quality control was performed by G. Kjærnli, who for many years was responsible for editing ice maps at DNMI.

The absolute variation range of the April ice extent over the past 135 yr is illustrated in Fig. 1. Some of the Norwegian observations from the nineteenth century have been published in *Peterm. Geogr. Mitt.* 1869, 1875; *YMER,* 1884, 1885, 1886, 1889; and *Norsk Geogr. Tidsskr.,* 1926. The list of ships' logs used in this investigation is given in *Meddelser* Nr. 18, 1932, and the meteorological observation series have been lent from DNMI. In about 1900 the Danish Meteorological Institute (DMI) was appointed as the European center for ice data, and most of the Norwegian observations were copied and sent to DMI for presentation in the *DMI Yearbooks* 1890–1956.

b. Ice edge definition

To obtain the presumably best homogeneity in the series, the outer ice edge has been used as a limit for the ice extent estimations. This means that a degradation of recent observations has not been made to obtain a possible better match with the ship observations. The observations previous to ~1950 are based almost entirely on reports from sealers. They operated mainly along the outer boundary or in the marginal ice zone where they reported ice concentrations, $C > 0.3$ to 0.6. Since the event of satellites the outer ice edge is defined by $C > 0.1$. This means that the actual area encompassing sea ice during the time of ship observations is somewhat smaller than the area encompassed by sea ice after the advent of satellites. A typical width of the area with ice concentrations ($0.1 < C < 0.3$), or the error in the position for estimating the outer ice edge, is 30 km along the whole ice border in the Nordic Seas; a rough estimate of the error would render the following: mean April ice extent 1920–98 $= 1.72 \times 10^3$ km^2, mean error $= 0.11 \times 10^3$ km^2, or ~6% of the April mean ice extent. A similar calculation for the August month renders a percentage error ~18% of the August mean ice extent, 0.52×10^3 km^2. This means that the ice extent during the ship observations period should have been somewhat increased to match the recent observation series. If accounted for, this difference in definition of the outer ice edge would have caused an increase in the temporal trend in the ice extent time series over the 135-yr-long period.

The April and August ice extents are generally based on observations collected during the last 14 days of the month. When April and August observations were not available for the whole length of the ice edge, observations from adjacent months were used for completion. The mean seasonal variation of the ice edge during the period in question was then used as support for the interpolation.

c. Future plans and data accessibility

The ice map series is currently being improved by inclusion of German and Dutch historic observations under the project ''Sea Ice Charts of the Arctic'' established in 1999 by the Arctic Climate System Study (ACSYS) of the World Climate Research Programme. The ice map series may be obtained from Norsk Polarinstitutt, N-9296, Tromsø, Norway.

REFERENCES

Blindheim, J., V. Borokov, B. Hansen, S. A. Malmberg, W. R. Turrell, and S. Østerhus, 2000: Upper layer cooling and freshening in the Norwegian Sea in relation to atmospheric forcing. *Deep-Sea Res.,* **47,** 655–680.

Deser, C., J. E. Walsh, and M. S. Timlin, 2000: Arctic sea ice variability in the context of recent wintertime atmospheric circulation trends. *J. Climate,* **13,** 617–633.

Dickson, R. R., T. J. Osborne, J. W. Hurrel, J. Meincke, J. Blindheim, B. Ådlandsvik, T. Vinje, G. Alekseev, and W. Maslowski, 2000: The Arctic Ocean response to the North Atlantic oscillation. *J. Climate,* **13,** 2671–2696.

Gammelsrød, T., S. Østerhus, and Ø. Godøy, 1992: Decadal variations of ocean climate in the Norwegian Sea observed at Ocean Station ''Mike'' (66°N, 2°E). *ICES Mar. Sci. Symp.,* **195,** 68–75.

Hansen, B., and S. Østerhus, 2000: North-Atlantic–Nordic Seas exchanges. *Progress in Oceanography,* Vol. 45, Pergamon Press, 100 pp.

Hanssen-Bauer, I., and E. J. Førland, 1998: Long-term trends in precipitation and temperature in the Norwegian Arctic: Can they be explained by changes in atmospheric circulation patterns? *Climate Res.,* **10,** 143–153.

Helland-Hansen, B., and F. Nansen, 1909: The Norwegian Sea. *Fisk. Dir. Skr. Ser. Havunders.,* **2,** 1–360.

Hill, B., 1998: Historical record of sea ice and iceberg distribution around Newfoundland and Labrador, 1810–1998. Institute for Marine Dynamics Rep. LM-1998, St. John, Newfoundland, Canada, 14 pp. [Available from Institute for Marine Dynamics, P. O. Box 12093, St. John, NF, Canada.]

Hilmer, M., M. Harder, and P. Lemke, 1998: Sea ice transport: A highly variable link between Arctic and North Atlantic. *Geophys. Res. Lett.,* **25,** 3359–3362.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation. *Science,* **269,** 676–679.

Johannessen, O. M., M. Miles, and E. Bjørgo, 1995: The Arctic's shrinking sea ice. *Nature,* **376,** 126–127.

Kahl, J. D., D. J. Charlevoix, N. A. Zaitseva, R. C. Schnell, and M. C. Serreze, 1993: Absence of evidence for greenhouse warming over the Arctic Ocean in the past 40 years. *Nature,* **362,** 335–337.

Lamb, H. H., 1995: *Climate History and the Modern World.* 2d ed. Routledge, 433 pp.

Loeng, H., 1991: Features of the physical oceanographic conditions of the Barents Sea. *Polar Res.,* **10,** 5–18.

Mysak, L. A., and D. K. Manak, 1989: Arctic sea-ice extent and anomalies, 1953–1984. *Atmos.–Ocean,* **27,** 376–405.

——, and S. A. Venegas, 1998: Decadal climate oscillations in the Arctic: A new feedback loop for atmosphere–ice–ocean interactions. *Geophys. Res. Lett.,* **25,** 3607–3610.

——, R. G. Ingram, J. Wang, and A. van der Baaren, 1996: The anomalous sea-ice extent in Hudson Bay, Baffin Bay and the Labrador Sea during three simultaneous NAO and ENSO episodes. *Atmos.–Ocean,* **34,** 313–343.

Nicholls, N., G. V. Gruza, J. Jouzel, T. R. Karl, L. A. Ogallo, and D. E. Parker, 1996: Observed climatic variability and change. *Climate Change 1995. The Science of Climate Change,* J. T. Hougthon et al., Eds., Cambridge University Press, 133–192.

Ogilvie, A., 1992: Documentary evidence for changes in the climate of Iceland, A.D. 1500 to 1800. *Climate Since A.D. 1500,* R. S. Bradley and P. D. Jones, Eds., Routledge, 92–115.

——, 1999: Historical sea ice records from Iceland ca. AD 1145 to ca. 1850. *Extended Abstracts, Workshop on Sea-Ice Charts of the Arctic,* Seattle, WA, World Meteorological Organization, WMO/TD No. 949, 7–8.

Østerhus, S., and T. Gammelsrød, 1999: The abyss of the Nordic Seas is warming. *J. Climate,* **12,** 3297–3304.

Parkinson, C. L., D. J. Cavalieri, P. Gloersen, H. J. Zwally, and J. C. Comiso, 1999: Arctic sea ice extents, areas, and trends, 1978–1996. *J. Geophys. Res.,* **104,** 20 837–20 856.

Proshutinsky, A. Y., and M. A. Johnson, 1997: Two circulation regimes of the wind-driven Arctic Ocean. *J. Geophys. Res.,* **102,** 12 493–12 514.

Radionov, V. F., N. N. Bryazgin, and E. I Alexandrov, 1997: The snow cover of the Arctic Basin. Tech. Rep. APL-UW TR 9701, University of Washington, Seattle, WA, 95 pp.

Rogers, J. C., 1997: North Atlantic storm track variability and its association to the North Atlantic oscillation and climate variability of northern Europe. *J. Climate,* **10,** 1635–1647.

——, and H. van Loon, 1979: The seesaw in winter temperatures between Greenland and northern Europe. Part II: Some oceanic and atmospheric effects in middle and high latitudes. *Mon. Wea. Rev.,* **107,** 509–519.

Slonosky, V. C., L. A. Mysak, and J. Derome, 1997: Linking Arctic sea-ice and atmospheric circulation anomalies on interannual and decadal timescales. *Atmos.–Ocean,* **35,** 333–366.

Vinje, T., 1976: Sea ice conditions in the European sector of the marginal seas of the Arctic, 1966–1975. *Norsk Polarinst. Årbok 1975,* Norwegian Polar Institute, 163–174.

——, 1999: Barents Sea ice edge variation over the past 400 years. *Extended Abstracts, Workshop on Sea-Ice Charts of the Arctic,* Seattle, WA, World Meteorological Organization, WMO/TD No. 949, 4–6.

——, N. Nordlund, and Å. Kvambekk, 1998: Monitoring ice thickness in Fram Strait. *J. Geophys. Res.,* **103,** 10 437–10 449.

Vinnikov, K. Y., 1986: *Climate Sensitivity* (partial translation). Gidrometeoizdat, 219 pp.

Walsh, J. E., and C. M. Johnson 1979: An analysis of Arctic sea ice fluctuations. *J. Phys. Oceanogr.,* **9,** 580–591.

——, W. L. Chapman, and T. L. Shy, 1996: Recent decrease of sea level pressure in the central Arctic. *J. Climate,* **9,** 480–486.

Yi, D., A. Mysak, and S. A. Venegas, 1999: Decadal-to-interdecadal fluctuations of Arctic sea ice cover and the atmospheric circulation during 1954–1994. *Atmos.–Ocean,* **37,** 389–415.

Zakharov, V. F., 1976: Cooling of the Arctic and ice cover in the Arctic Seas (partial translation). *Trudi AANI,* **337,** 1–95.

——, 1996: *Sea Ice in the Climatic System.* World Meteorological Organization, WMO/TD No. 782, 80 pp.