A 21-Year Record of Arctic Sea Ice Extents and Their Regional, Seasonal, and Monthly Variability and Trends

Claire L. Parkinson and Donald J. Cavalieri
Oceans and Ice Branch/Code 971
NASA Goddard Space Flight Center
Greenbelt, MD 20771, USA

Abstract. Satellite passive-microwave data have been used to calculate sea ice extents over the period 1979-1999 for the north polar sea ice cover as a whole and for each of nine regions. Over this 21-year time period, the trend in yearly average ice extents for the ice cover as a whole is –32,900 ± 6,100 km^2/yr (–2.7 ± 0.5 %/decade), indicating a reduction in sea ice coverage that has decelerated from the earlier reported value of –34,000 ± 8,300 km^2/yr (–2.8 ± 0.7 %/decade) for the period 1979-1996. Regionally, the reductions are greatest in the Arctic Ocean, the Kara and Barents Seas, and the Seas of Okhotsk and Japan, whereas seasonally, the reductions are greatest in summer, for which season the 1979-1999 trend in ice extents is –41,600 ± 12,900 km^2/yr (–4.9 ± 1.5 %/decade). On a monthly basis, the reductions are greatest in July and September for the north polar ice cover as a whole, in September for the Arctic Ocean, in June and July for the Kara and Barents Seas, and in April for the Seas of Okhotsk and Japan. Only two of the nine regions show overall ice extent increases, those being the Bering Sea and the Gulf of St. Lawrence. For neither of these two regions is the increase statistically significant, whereas the 1979-1999 ice extent decreases are statistically significant at the 99% confidence level for the north polar region as a whole, the Arctic Ocean, the Seas of Okhotsk and Japan, and Hudson Bay.

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Submitted to the *Annals of Glaciology*, February 23, 2001

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Introduction

Sea ice is an integral component of the Arctic climate system, restricting exchanges of heat, mass, and momentum between the ocean and the atmosphere, reflecting most solar radiation incident on it, releasing salt to the underlying ocean, and transporting freshwater equatorward. It is also of vital importance to the ecology of the Arctic, serving as a habitat for organisms living within it, a platform for animals wandering over it, and either a help or a hindrance to numerous marine plant and animal species. Hence changes in the sea ice cover can have many outreaching effects on other elements of the polar climate and ecological systems.

Considerable attention has been given recently to decreases in Arctic sea ice extents detected through analysis of satellite passive-microwave data since late 1978 (e.g., Johannessen and others, 1995; Maslanik and others, 1996; Bjørgo and others, 1997; Parkinson and others, 1999). These studies have emphasized decreases examined for the record length as a whole or for annual or seasonal averages. Here we update the annual and seasonal decreases to a 21-year record, through the end of 1999, and additionally present time series and trends for each month. Results are given for the Northern Hemisphere as a whole and for each of nine regions, identified in Figure 1.

Data and Methodology

The data used in this study are satellite passive-microwave data from the Nimbus 7 Scanning Multichannel Microwave

Radiometer (SMMR) and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imagers (SSMIs). Microwave data are particularly applicable for sea ice research because the microwave emissions of sea ice and liquid water differ significantly, thereby allowing a ready distinction between ice and water from the satellite microwave data. Complications arise from the diversity of ice surfaces and from meltponding and snow cover on the ice, but the satellite passive-microwave data still allow a clear depiction of the overall distribution of the ice and thereby allow a calculation of ice extents (areas covered by ice of concentration at least 15%).

The SMMR was operational on an every-other-day basis for most of the period from October 26, 1978, to August 20, 1987, and the sequence of SSMIs has been operational on a daily basis for most of the period since July 9, 1987. The SMMR and SSMI data have been used to create a consistent data set of sea ice concentrations (percent areal coverages of ice) and extents through procedures described in Cavalieri and others (1999). The ice concentrations are gridded to a resolution of approximately 25 km x 25 km (NSIDC, 1992), and the ice extents are calculated by adding the areas of all grid cells containing ice with calculated concentration of at least 15%. This is done for each of the nine regions identified in Figure 1 and for the total.

Trends in the ice extents are determined through linear least squares fits separately on the monthly averaged, seasonally averaged, and yearly averaged data. The trends are calculated for each of the nine regions and the total, and in each case an estimated standard deviation of the trend (σ) is calculated following Taylor (1997). Trends are considered statistically significant in those cases when the trend magnitude exceeds 1.96σ, signifying a 95% confidence level that the slope is non-0. Trends with magnitudes exceeding 2.58σ are considered significant at a 99% confidence level (Taylor, 1997).

Results

Sea Ice Extents

Results show that over the 21-year period 1979-1999, the average annual cycle of north polar ice extents ranges from a minimum of 6.9 x 10^6 km^2 in September to a maximum of 15.3 x 10^6 km^2 in March. All the monthly average ice extents over the 21 years are plotted in Figure 2 for the Northern Hemisphere total and in Figure 3 for each of the nine regions of Figure 1. Monthly averages through the end of 1996 are plotted chronologically in Parkinson and others (1999), highlighting the strong annual cycle each year. Here rather than simply updating the earlier time series, which would indeed show a continued strong annual cycle in each year, we instead provide plots that emphasize the interannual changes in each month (Figs. 2-3). By doing so, we highlight several aspects of the seasonal cycle that are not readily apparent in the time series of Parkinson and others (1999), such as the variability in the timing of maximum and minimum ice coverage.

The month of minimum ice coverage is consistently September for the Northern Hemisphere as a whole (Fig. 2) and regionally is consistently either August or September except in the cases of the Seas of Okhotsk and Japan and the Gulf of St. Lawrence, where the ice cover is reduced to 0 for the three months July-September, and in the case of Hudson Bay for 1993, when the minimum occurs in October (Fig. 3). September is the month of minimum ice coverage in each year for Baffin Bay/Labrador Sea and the Kara and Barents Seas, in each year except 1993 for Hudson Bay, in each year except 1980 and 1997 for the Canadian Archipelago, in 18 of the 21 years for the Arctic Ocean, and in 16 of the 21 years for the Greenland Sea. The one anomalous region is the Bering Sea, in which the month of minimum ice coverage is consistently August rather than September, although with near-0 ice coverage throughout the four months July-October (Fig. 3).

The month of maximum ice coverage is considerably more variable than the month of minimum ice coverage. For the Northern Hemisphere as a whole, the month of maximum coverage is March in 17 of the 21 years but February in 1981, 1987, 1989, and 1998 (Fig. 2). Hudson Bay, the Arctic Ocean, and the Canadian Archipelago have their ice extents capping out at the full area of the region for February and March of each year and often for January, December, and/or April as well (Fig. 3). In the Seas of Okhotsk and Japan, the month of maximum ice coverage is March for 16 of the years and February for the remaining 5 years; in Baffin Bay/Labrador Sea, it is March for 12 years and February for 9 years; and in the Gulf of St. Lawrence, it is February for 16 years and March for 5 years. The variability is greater in the Bering Sea, Greenland Sea, and Kara and Barents Seas, in each of which each of the first four months of the year is the month of maximum for at least one of the years of the 21-year record. In the Greenland Sea, there is even one year (1995) when May is the month of maximum (Fig. 3).

The greater variability observed for the month of maximum ice coverage than for the month of minimum ice coverage results from the presence of ice at lower latitudes during winter. Regions that have open southern boundaries are particularly susceptible to the passage of storms and thus increased variability. For instance, the particularly high variability in the Greenland Sea and the Kara and Barents Seas is almost certainly related to the high frequency and interannual variability in the storm systems in this general area, which tends to experience the strongest and most frequent winter cyclones of the high northern latitudes (e.g., Serreze and others, 1993). Similarly, the Bering Sea is particularly susceptible to variations in the Aleutian Low and associated storm tracks (e.g., Overland and Pease, 1982).

Ice Extent Trends

Table 1 lists the trends, calculated as the slopes of the lines of linear least squares fit, in the yearly averaged ice extents for each of the nine regions of Figure 1, plus the trends in the yearly and seasonally averaged ice extents for the Northern Hemisphere total. All trends are for the 21-year period 1979-1999 and are updated from the 18-year results presented in Parkinson and others (1999). The Northern Hemisphere total continues to show negative trends for each season and for the yearly averages, although the overall, annual trend has decelerated from the 18-year value of –34,000 ±

8,300 km^2/yr (-2.8 ± 0.7 %/decade) (Parkinson and others, 1999) to −32,900 ± 6,100 km^2/yr (-2.7 ± 0.5 %/decade) (Table 1). Summer, defined as in Parkinson and others (1999) as July through September, is the season with the greatest negative trend, both in absolute terms and on a percentage basis, although all four seasons have statistically significant negative trends (Table 1).

Regionally, the largest contributor to the negative yearly average trend is the Arctic Ocean, at −9,400 ± 3,400 km^2/yr, and the next largest contributors are the Kara and Barents Seas and the Seas of Okhotsk and Japan (Table 1). When the record had extended only through 1996, the largest contributor to the negative trend had been the Kara and Barents Seas (Parkinson and others, 1999), but relatively high ice extents in the Kara and Barents Seas in 1999 and especially 1998 (Fig. 3) weakened the negative slope for that region, while relatively low ice extents in the Arctic Ocean in 1998 and 1999 (Fig. 3) led to a strengthening of its negative trend (Table 1 versus Parkinson and others, 1999).

The ice-extent trend values for each month are plotted in Figure 4, for each of the regions and the Northern Hemisphere total. Summer trends are 0 in the Seas and Okhotsk and Japan and the Gulf of St. Lawrence due to the disappearance of the ice in those regions in each summer; and winter trends are 0 in Hudson Bay, the Arctic Ocean, and the Canadian Archipelago due to the complete coverage of each of those regions by ice of at least 15% concentration in the winter months (Fig. 4). In general, with the exception of the 0 and near-0 trends, the sign of the trend tends to be the same throughout the year for any individual region; i.e., a region with a negative January trend tends to have negative or 0 trends in each month. The two primary exceptions to this are the positive February trend for Baffin Bay/Labrador Sea, a region for which the remaining months have negative or 0 trends (Fig. 4d), and the seasonal contrast in the Bering Sea, where the trends are clearly positive in December through April but near 0 or negative in May through November (Fig. 4b).

The timing of the strongest trends varies from region to region (Fig. 4). For the Arctic Ocean, the ice reductions are strongest in the late summer, with September experiencing reductions, on average, of 33,300 ± 13,000 km^2/yr and the magnitude of the reductions for the rest of the non-winter months being approximately symmetric about the September peak (Fig. 4h). By contrast, reductions in the Kara and Barents Seas peak in June and July (Fig. 4g) and those in the Seas of Okhotsk and Japan peak in April (Fig. 4a). The varied regional responses combine to a Northern Hemisphere total that has 21-year linear least squares reductions of at least 23,600 km^2/yr in all 12 months, with the greatest reductions coming in July, at 45,700 ± 12,200 km^2/yr, and the second greatest in September (Fig. 4j).

From an analysis of Arctic surface air temperature data for the period 1979-1997, Rigor and others (2000) report seasonal and spatial trends in their data that are generally consistent with the sea ice extent trends shown in this study. For the months December-February they report a warming trend over the Eurasian land mass and over the Laptev and East Siberian seas to the north of Russia, whereas for eastern Siberia and north of the Canadian Archipelago they report cooling trends. During the months September-November, the regions showing cooling trends are Alaska and the Beaufort Sea. The months March-May show warming trends over the entire Arctic region. However, during June-August there are no significant trends in the temperature data (Rigor and others, 2000), which is interesting because June-September are the months for which we find the strongest negative trends for the ice cover as a whole (Fig. 4j).

Discussion

Satellite technology provides a powerful resource for monitoring the Arctic sea ice cover's distribution and extent, and we have taken advantage of this by using this technology to quantify changes in the Arctic ice cover since the late 1970s, with results presented in Table 1 and Figures 2-4 for the 21-year period 1979-1999. Most notably, the ice cover as a whole has negative trends for every month, with a trend in the annual averages of $-32{,}900 \pm 6{,}100$ km^2/yr.

Because of the sharp contrast between the microwave emissivities of liquid water and ice, the satellite passive-microwave data are particularly good at revealing the distribution of the sea ice cover, which in turn allows calculation of the ice extent and determination of changes in ice extent. The satellite data cannot, however, explain the causes of the changes or predict future changes. If the decreasing ice extents reported here are tied most closely to an ongoing Arctic warming (as reported, e.g., by Martin and others, 1997; Serreze and others, 2000) that continues, then the ice extent is likely to continue to decrease as well; but if the sea ice changes are tied more closely to oscillatory behaviors in the climate system, such as the North Atlantic Oscillation and the Arctic Oscillation (as suggested, e.g., by Deser and others, 2000; Morison and others, 2000), then fluctuations between periods of ice-extent decrease and periods of ice-extent increase are likely.

Acknowledgments. We thank Nick DiGirolamo and John Eylander of Science Systems and Applications, Inc. for their help in generating the figures and the NASA Cryospheric Processes and Earth Observing System programs for providing funding for the work.

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Table 1. Trends in 1979-1999 yearly averaged sea ice extents for the nine regions of Figure 1 and in 1979-1999 yearly and seasonally averaged sea ice extents for the Northern Hemisphere total. Trends and their estimated standard deviations are listed both as 10^3 km^2/yr and as %/decade. The Averaging Period (AP) column indicates yearly (Y), winter (W, January-March), spring (Sp, April-June), summer (Su, July-September), and fall (F, October-December) averages, while the S column identifies those cases having statistical significance at a 99% confidence level. The remaining cases satisfy neither a 99% nor a 95% confidence criterion.

Region	AP	Trend		
		10^3 km^2/yr	S	%/decade
Seas of Okhotsk and Japan	Y	-6.8 ± 2.0	99	-14.6 ± 4.4
Bering Sea	Y	1.7 ± 1.4		6.1 ± 4.9
Hudson Bay	Y	-4.3 ± 1.4	99	-5.1 ± 1.7
Baffin Bay/Labrador Sea	Y	-2.1 ± 3.2		-2.5 ± 3.8
Gulf of St. Lawrence	Y	0.8 ± 0.5		12.0 ± 6.8
Greenland Sea	Y	-4.3 ± 2.4		-5.9 ± 3.2
Kara and Barents Seas	Y	-7.4 ± 4.2		-5.3 ± 3.0
Arctic Ocean	Y	-9.4 ± 3.4	99	-1.4 ± 0.5
Canadian Archipelago	Y	-1.1 ± 0.6		-1.6 ± 0.9
Northern Hemisphere	Y	-32.9 ± 6.1	99	-2.7 ± 0.5
Northern Hemisphere	W	-26.9 ± 8.5	99	-1.8 ± 0.6
Northern Hemisphere	Sp	-32.1 ± 6.8	99	-2.3 ± 0.5
Northern Hemisphere	Su	-41.6 ± 12.9	99	-4.9 ± 1.5
Northern Hemisphere	F	-29.6 ± 9.0	99	-2.6 ± 0.8

Figure Captions

Figure 1. Identification of the nine regions used in the analysis.

Figure 2. Time series of monthly sea ice extents, arranged by month, for the total ice cover of the regions identified in Figure 1. The top plot presents the ice cover decay from March through September, and the bottom plot presents the ice cover growth from September through March. Lines of linear least squares fit are included for each month.

Figure 3. Time series of monthly sea ice extents, arranged by month, for each of the nine regions of Figure 1. For each region, the top plot presents the results for the months March through September and the bottom plot presents the results for the months September through March. Lines of linear least squares fit are included for each month.

Figure 4. Trends, by month, in the sea ice extents of the nine regions of Figure 1 and the total, calculated over the 21 years 1979-1999. The trend values in each case are the slopes of the lines of linear least squares fit through the appropriate 21 monthly average ice extents.

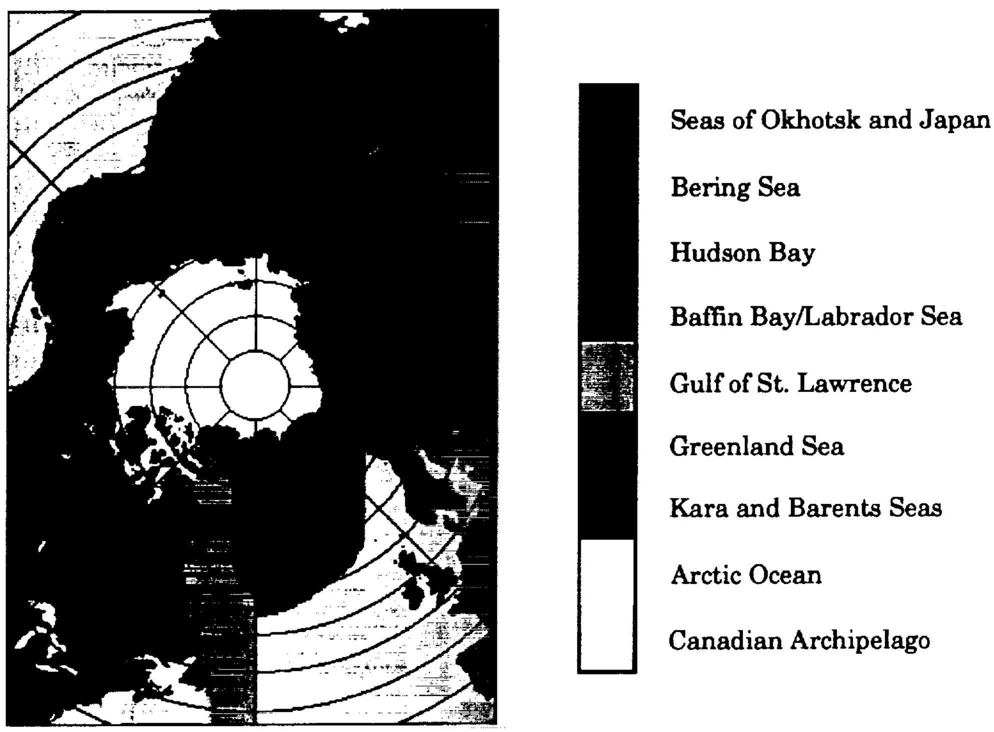

Seas of Okhotsk and Japan
Bering Sea
Hudson Bay
Baffin Bay/Labrador Sea
Gulf of St. Lawrence
Greenland Sea
Kara and Barents Seas
Arctic Ocean
Canadian Archipelago

Figure 1

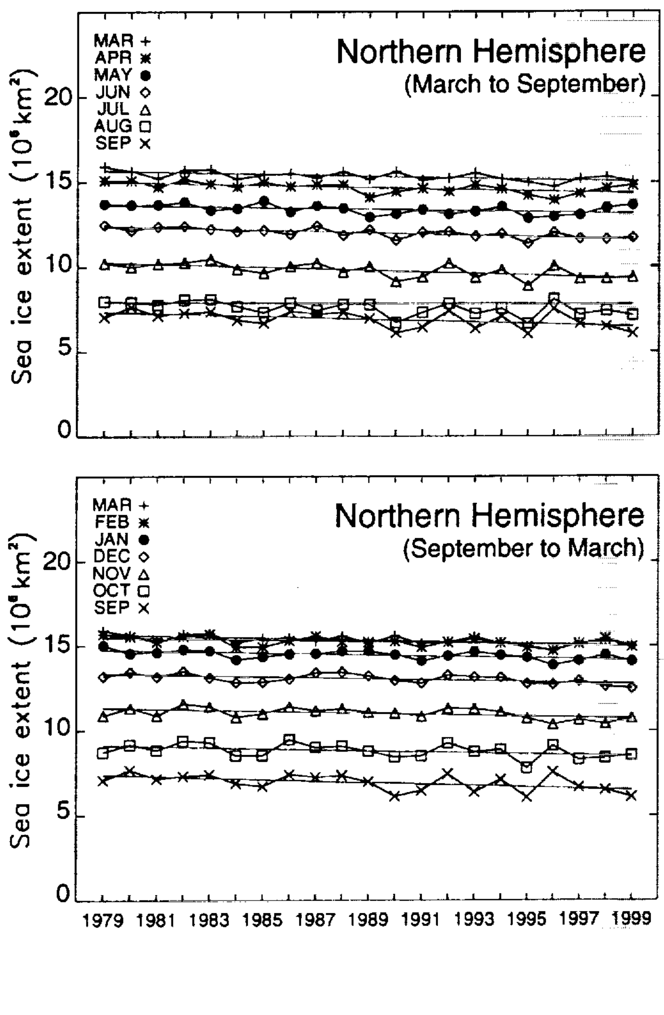

Northern Hemisphere
(March to September)
MAR
APR
MAY
JUN
JUL
AUG
SEP
Northern Hemisphere
(September to March)
MAR
FEB
JAN
DEC
NOV
OCT
SEP
Sea ice extent (10^6 km^2)
0
5
10
15
20
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999

Figure 2

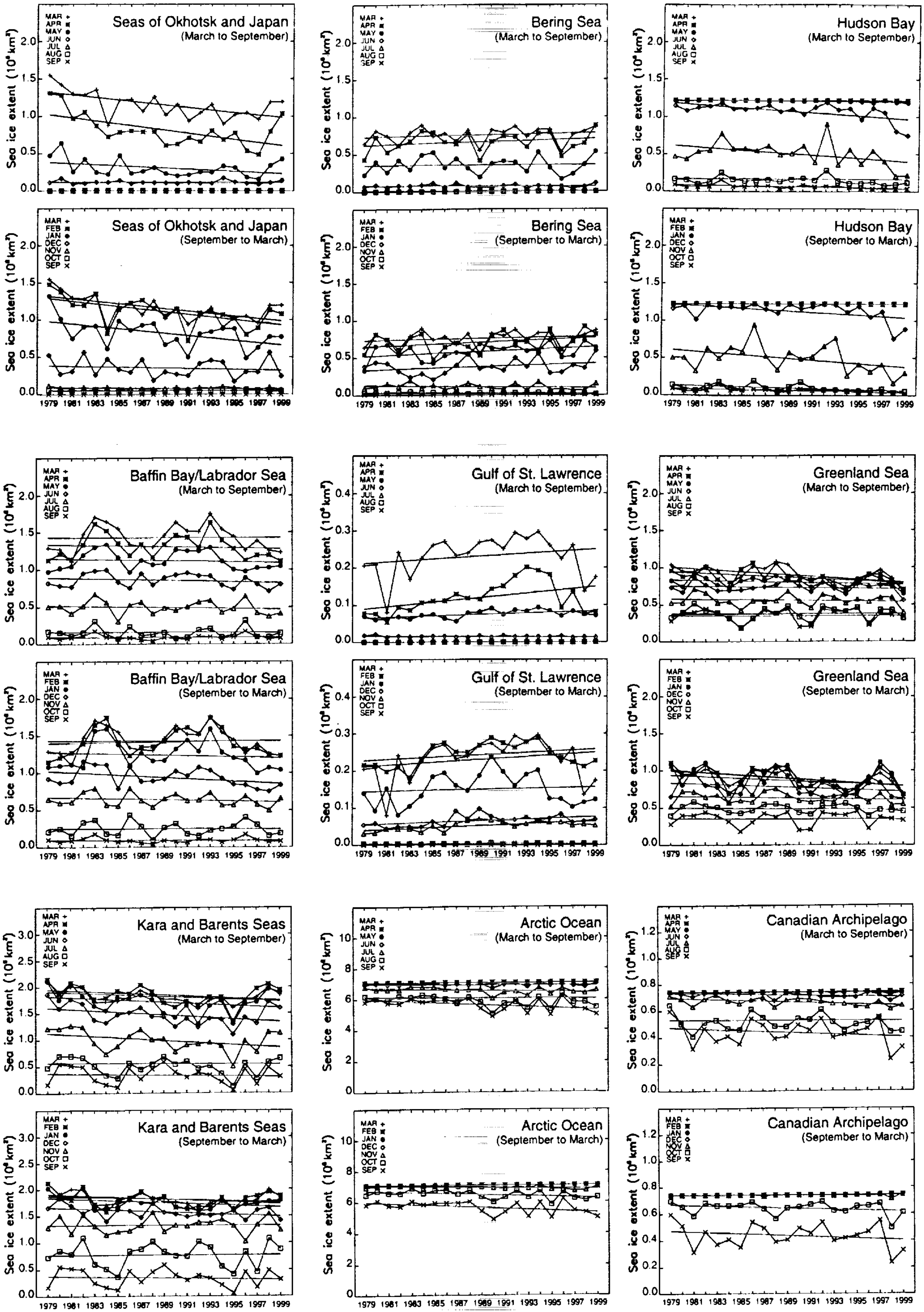
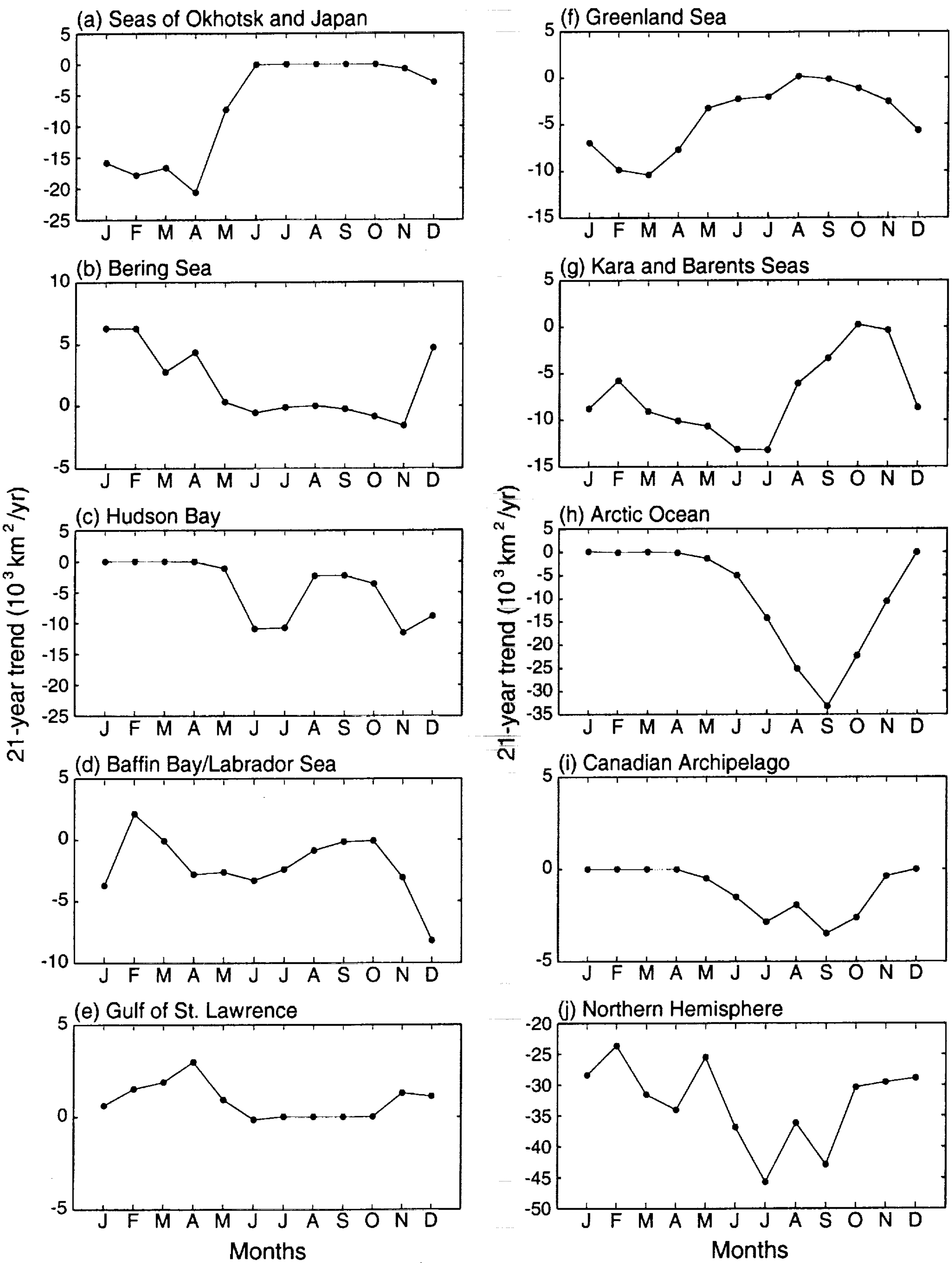

Seas of Okhotsk and Japan
(March to September)
MAR + APR ✱ MAY ● JUN ◇ JUL △ AUG □ SEP ×
Sea ice extent (10⁶ km²)
Bering Sea
(March to September)
Hudson Bay
(March to September)
Seas of Okhotsk and Japan
(September to March)
MAR + FEB ✱ JAN ● DEC ◇ NOV △ OCT □ SEP ×
Bering Sea
(September to March)
Hudson Bay
(September to March)
Baffin Bay/Labrador Sea
(March to September)
Gulf of St. Lawrence
(March to September)
Greenland Sea
(March to September)
Baffin Bay/Labrador Sea
(September to March)
Gulf of St. Lawrence
(September to March)
Greenland Sea
(September to March)
Kara and Barents Seas
(March to September)
Arctic Ocean
(March to September)
Canadian Archipelago
(March to September)
Kara and Barents Seas
(September to March)
Arctic Ocean
(September to March)
Canadian Archipelago
(September to March)
1979 1981 1983 1985 1987 1989 1991 1993 1995 1997 1999

Figure 3



(a) Seas of Okhotsk and Japan
(b) Bering Sea
(c) Hudson Bay
(d) Baffin Bay/Labrador Sea
(e) Gulf of St. Lawrence
(f) Greenland Sea
(g) Kara and Barents Seas
(h) Arctic Ocean
(i) Canadian Archipelago
(j) Northern Hemisphere
21-year trend (10³ km²/yr)
J F M A M J J A S O N D
Months

Figure 4

"Popular Summary" for the paper "A 21-year record of Arctic sea ice extents and their regional, seasonal, and monthly variability and trends" by Claire L. Parkinson and Donald J. Cavalieri, submitted to the *Annals of Glaciology*:

Sea ice is an important component of the Arctic climate system, for instance reflecting back to space most of the solar radiation reaching it and restricting heat exchanges between the ocean and the atmosphere. Furthermore, changes in the Arctic sea ice cover can provide information about broader issues of climate change.

Since late 1978, satellite data have allowed a monitoring of the Arctic sea ice cover on a daily or near-daily basis. These data have been used to calculate sea ice extents over the period 1979-1999 for the north polar sea ice cover as a whole and for each of nine regions within the ice cover. Over this 21-year period, the data reveal a trend in yearly average ice extents for the ice cover as a whole of $-32{,}900 \pm 6{,}100$ km^2/yr (-2.7 ± 0.5 %/decade), indicating a reduction in sea ice coverage. This reduction, however, has decelerated from the earlier reported value of $-34{,}000 \pm 8{,}300$ km^2/yr (-2.8 ± 0.7 %/decade) for the period 1979-1996. Seasonally, the reductions are greatest in summer, for which season the 1979-1999 trend in ice extents is $-41{,}600 \pm 12{,}900$ km^2/yr (-4.9 ± 1.5 %/decade).

Regionally, the sea ice reductions are greatest in the Arctic Ocean, the Kara and Barents Seas (north of Scandinavia and far western Russia), and the Seas of Okhotsk and Japan (north and west of Japan). Only two of the nine regions show overall ice extent increases, those being the Bering Sea (between Alaska and Siberia) and the Gulf of St. Lawrence. For neither of these two regions is the increase statistically significant, whereas the 1979-1999 ice extent decreases are statistically significant at the 99% confidence level for the north polar region as a whole, the Arctic Ocean, the Seas of Okhotsk and Japan, and Hudson Bay.