References and Notes

1. Y.-W. Mo, D. E. Savage, B. S. Swartzentruber, M. G. Lagally, *Phys. Rev. Lett.* **65**, 1020 (1990).
2. G. Medeiros-Ribeiro, A. M. Bratkovsky, T. I. Kamins, D. A. A. Ohlberg, R. S. Williams, *Science* **279**, 353 (1998).
3. T. I. Kamins, E. C. Carr, R. S. Williams, S. J. Rosner, *J. Appl. Phys.* **81**, 211 (1997); M. Tomitori, K. Watanabe, M. Kobayashi, O. Nishikawa, *Appl. Surf. Sci.* **76–77**, 322 (1994).
4. J. A. Floro *et al.*, *Phys. Rev. B* **59**, 1990 (1999).
5. T. I. Kamins, G. Medeiros-Ribeiro, D. A. A. Ohlberg, R. S. Williams, *J. Appl. Phys.* **85**, 1159 (1999).
6. F. M. Ross, J. Tersoff, R. M. Tromp, *Phys. Rev. Lett.* **80**, 984 (1998).
7. R. M. Tromp, M. Mankos, M. C. Reuter, A. W. Ellis, M. Copel, *Surf. Rev. Lett.* **5**, 1189 (1998).
8. Z. Gai, X. Li, R. G. Zhao, W. S. Yang, *Phys. Rev. B* **57**, 15060 (1998).
9. M. Goryll, L. Vescan, K. Schmidt, S. Mesters, H. Luth, *Appl. Phys. Lett.* **71**, 410 (1997); M. A. Lutz, R. M. Feenstra, P. M. Mooney, J. Tersoff, J. O. Chu, *Surf. Sci.* **316**, L1075 (1994).
10. R. M. Tromp, F. M. Ross, M. C. Reuter, in preparation.
11. M. Zinke-Allmang, L. C. Feldman, M. Grabow, *Phys. Rev. B* **39**, 7848 (1989).
12. I. Daruka, J. Tersoff, A.-L. Barabasi, *Phys. Rev. Lett.* **82**, 2753 (1999).
13. We thank K. Pope for Rutherford backscattering analysis and J. Tersoff for helpful discussions.

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Global Warming and Northern Hemisphere Sea Ice Extent

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Surface and satellite-based observations show a decrease in Northern Hemisphere sea ice extent during the past 46 years. A comparison of these trends to control and transient integrations (forced by observed greenhouse gases and tropospheric sulfate aerosols) from the Geophysical Fluid Dynamics Laboratory and Hadley Centre climate models reveals that the observed decrease in Northern Hemisphere sea ice extent agrees with the transient simulations, and both trends are much larger than would be expected from natural climate variations. From long-term control runs of climate models, it was found that the probability of the observed trends resulting from natural climate variability, assuming that the models' natural variability is similar to that found in nature, is less than 2 percent for the 1978–98 sea ice trends and less than 0.1 percent for the 1953–98 sea ice trends. Both models used here project continued decreases in sea ice thickness and extent throughout the next century.

The cryosphere is an important component of climate because of its effect on Earth's surface albedo (*1*) and its role in reducing the amount of heat exchanged between the atmosphere and the ocean (or land) beneath the ice. In particular, sea ice extent has long been recognized as an important indicator of the state of the climate system in observational and modeling studies. Early simulations of changes in sea ice coverage and sea ice thickness associated with global warming showed large sea ice reductions (*2*, *3*), but these simulations were not compared with observations. Observations now span a sufficiently long period to show a substantial decrease of Northern Hemisphere (NH) sea ice during the past few decades. Here, we use sea ice extent in an attempt to detect recent global climate change and examine whether it might be attributable to anthropogenic causes by comparing it with model-calculated global warming trends and trendlike low-frequency fluctuations that appear randomly in very long control runs of the same models.

There have been many attempts to use observed trends in NH sea ice extent as an indicator of global climate change (*4–16*). Most of these studies show that, on average, the observed NH sea ice extent has been decreasing during the past few decades. Satellite visible and infrared images, which became available in 1966, were the first sources of global information on sea ice extent. In 1972, the passive microwave satellite sensor was introduced as an additional source of information on sea ice extent and concentration. Nonsatellite observational records have many problems; they are generally not very long, they are not global, and they do not cover the entire year. Very little sea ice cover data are currently available for 1941–45.

We used the following five sources of observations to determine sea ice extent in the NH: the University of Illinois sea ice group, the Russian Arctic and Antarctic Research Institute, the NOAA Climate Prediction Center, the Norwegian Nansen Environmental and Remote Sensing Center, and the NASA Goddard Space Flight Center.

The University of Illinois sea ice group has just revised and updated its data set (*6*, *13*). The most reliable data cover the period since 1953. The recent inclusion of data from the Norwegian Polar Institute added data for the winter months of the 1901–52 period. For the period from 1972 to the present, the primary data source was the digital version of the U.S. National Ice Center (NIC) chart series. The NIC charts, in turn, draw on satellite passive microwave imagery [including the period of continuous coverage by a scanning multichannel microwave radiometer (SMMR) and a special sensor microwave imager (SSM/I) from 1978 to the present], together with other available data from visible and infrared satellite sensors and from any near–real-time aircraft reconnaissance and surface reports. Sea ice extent at the end of each month is estimated as the total ocean area poleward of the sea ice boundary, not taking into account information about its concentration. The averaging domain does not include the Baltic, Caspian, Aral, Black, or Azov seas or the Sea of Okhotsk south of 45°N.

The Russian Arctic and Antarctic Research Institute reports NH monthly mean sea ice extents for 1960–90 (*5*). The spatial domain does not include the Baltic, Azov, Caspian, Aral, Black, or White seas. Ice concentration is not considered. The Russian sea ice data draw increasingly on satellite imagery during recent decades. During the 1960s, the only substantial data sources were aerial reconnaissance and ship reports, including some charts or syntheses (or both) of such information from other sea ice centers. The data for all 12 months are complete only for 1972–90; earlier data have gaps that do not allow reliable estimates of the annual averages.

The NOAA Climate Prediction Center produced end-of-month Northern and Southern Hemisphere sea ice extent data for the period 1973–94 (*8*), using NIC weekly sea ice charts. Ice concentration information is not taken into account.

The Norwegian Nansen Environmental and Remote Sensing Center used passive microwave satellite observations to measure 1978–94 sea ice extent in the latitudinal belt from 50° to 84°N (*14*). They assumed that the area to the north of 84°N is permanently covered with sea ice during the whole year. Sea ice extent is defined as the area with ice concentration of ≥15%.

The NASA Goddard Space Flight Center provides homogeneous data that are based on passive microwave satellite observations for 1978–98 (*15–17*). Sea ice extent is defined as the area with ice concentration of ≥15%. The NASA and Norwegian groups use the same raw observations but use different algorithms for sea ice detection.

Although there are differences in sea ice extent definitions, spatial domains, averaging techniques, and data sources, the five time series are similar (Fig. 1). However, differences caused by sampling and measurement errors are large enough to make the linear trend estimates from each data set unreliable for short time intervals. Random errors are probably the smallest for the satellite-retrieved, passive microwave–based records, but instrument changes from electronically scanning microwave radiometer to SMMR between 1976 and 1978 (*11*), from SMMR to SSM/I in 1987 (*16*, *17*), and later between different SSM/Is (*16*, *17*) are potential sources of inhomogeneity in these time series. Nevertheless, for those periods with sensor overlap, it was possible to intercalibrate the records from the individual sensors, making the time series as homogeneous as possible (*17*). To provide a quantitative measure of the uncertainties in the data for the earlier decades, we have evaluated from each grid in (*13*) the percentage of the longitudes in which there were no available ice-edge data, requiring an estimation of the ice edge by linear interpolation or by climatology. Regions in which the ice boundary is constrained by land were not included in the evaluation. These percentages range from 60% in the 1900s to 0% in the 1990s, provided that one ignores the "hole" of ~2° latitude around the North Pole in the SSM/I data. The percentages for the 1940s, 1950s, and 1960s are 50, 40, and 25%, respectively. These percentages are generally larger for the winter months and smaller for the summer months. Our emphasis on the post-1950 period in this report is guided, in part, by the decrease in the percentage of missing data in the 1950s.

The observed monthly variations and trends of satellite-derived NH sea ice extent (*16*) for 1978–98 and the other data sets (not shown here) display decreasing NH sea ice extent during this period. A comparison of seasonal variations of sea ice extent for different records reveals only small differences between the records, which can be explained by differences in the temporal or spatial averaging (or both) of sea ice observations.

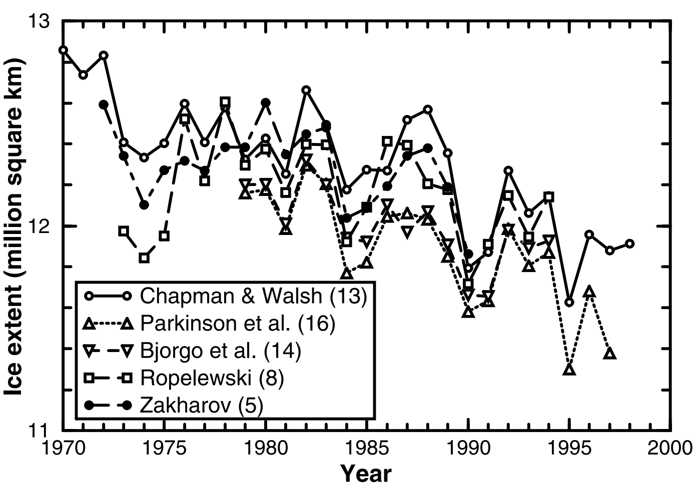
To reveal a long-term systematic climate trend, we need observations from a period long enough so that the influences of natural interannual and interdecadal climate variability, as well as random errors of observation, do not create pseudotrends that are as large as the true climate trend. Before satellite observations were able to provide global coverage, sea ice records contained many regional gaps, which lasted for months or years. Such gaps have been variously filled by climate averages (*6*, *13*) or with a simple linear regression (*5*) between sea ice changes in different parts of the ocean. Neither of these methods, however, works properly in the presence of long-term trends, when all of the statistical parameters of sea ice are changing with time.

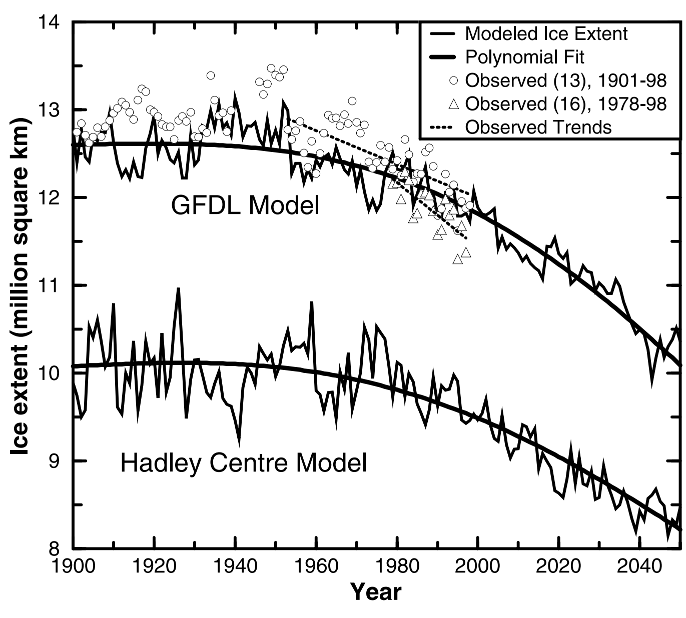
Estimates of trends in annually averaged sea ice extents for three different time intervals (1953–98, 1972–98, and 1978–98) are presented in Table 1. Updated time series of observed annual averages of NH sea ice extent and linear trends in these data by Chapman and Walsh (*13*) and Parkinson *et al.* (*16*) are shown in Fig. 2. All observed data show decreasing NH sea ice extent during the last few decades. The important question is whether we should attribute these observed trends to human-caused global warming, to natural climate variability, or to both. Here, we use two climate models to provide independent assessments of the observed climate trends in sea ice extent.

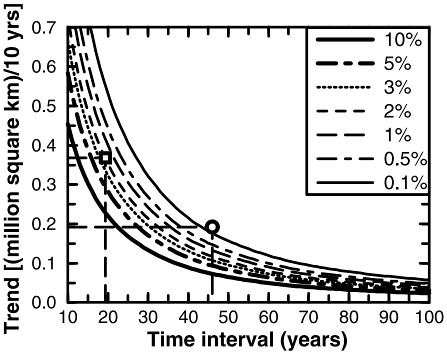
The Geophysical Fluid Dynamics Laboratory (GFDL) low-resolution R15 climate model consists of general circulation models of the atmosphere and ocean and a simple model of land surface processes (*3, 18*). The oceanic and sea ice component models have a spatial resolution of 4.5° latitude by 3.75° longitude. The ice model allows for drift with the ocean currents. It includes a thermodynamic budget between the oceanic mixed layer and sea ice. Thickness is the only predicted variable; leads (openings within the ice pack) are not modeled. We use the monthly averaged sea ice thickness from a 300-year transient run (1766–2065) of the GFDL climate model forced with greenhouse gases and tropospheric sulfate aerosols (*19*, *20*).

For our analysis, model output for ice thicker than 2 cm was used, because the observed sea ice extent (*6*, *13*) averaged for 1953–98 is approximately equal to the area of sea ice that is thicker than 2 cm in the transient model output for the same period. We found that, with this criterion, the model also realistically reproduces the observed seasonal variation.

The modeled temporal variations in sea







ice extent can be interpreted as a combination of greenhouse warming and natural climate variability. The smoothed GFDL modeled time series of sea ice extent for 1801–2065 has been approximated by algebraic polynomials of degree 10 to estimate the trends, and the 1900–2050 portion is shown in Fig. 2. These trends are very small for the first half of the 20th century, but they become much larger during the second half of the century, at least according to this model. A 20 to 50% decrease in area of thick (>2 to 3 m) sea ice is calculated to occur by the end of the 20th century. The lack of comprehensive data on sea ice thickness does not allow us to evaluate this model result, but a recent study with submarine observations shows large downward trends in Arctic sea ice thickness for the past several decades (*21*). The linear components of the trend in NH sea ice extent for 1953–98 and 1978–98 are –140,000 and –190,000 km^2 per 10 years, respectively. They agree well with the observed trend estimates.

The Hadley Centre atmosphere-land-ocean climate model HADCM2 has a horizontal resolution of 2.5° latitude by 3.75° longitude (*22*). The ice model includes sea ice advection by ocean currents and a thermodynamic budget between the oceanic mixed layer and the sea ice. Leads are allowed in this model's parameterizations.

Here, we use the results of the 240-year (1861–2100) transient run forced with the same radiative forcing as that used in the GFDL model, and we use the same criterion as before to estimate modeled sea ice extent. Time series of monthly and annual average sea ice extent for 1861–2065 are approximated by algebraic polynomials of degree 10 to estimate the sea ice extent trend for 1900–2050 (Fig. 2). Although HADCM2 underestimates NH sea ice extent and thickness (*22*), the trends in NH sea ice extent for 1953–98 and 1978–98 are close to those estimated from the GFDL model, –120,000 and –160,000 km^2 per 10 years, respectively. Seasonal variations of the trends for 1953–98 and 1975–2000 estimated from the Hadley Centre and GFDL model transient runs are in good agreement with each other. The observed data show more disagreement in seasonality of the trends.

The modeled and observed linear trends in annual averages of NH sea ice extent are listed in Table 1. To estimate their statistical significance, we used very long control runs of the two climate models described above. We used 5000 years from the control run of the GFDL climate model (*3*, *18*, *23*) to assess the probability that the observed and model-predicted trends in NH sea ice extent occur by chance as the result of natural climate variability. The standard deviation of modeled annual average NH sea ice extent in this control run is 250,000 km^2, almost the same as that estimated from detrended observed variations in NH sea ice extent for 1953–98 (240,000 km^2) (*13, 24*).

To assess the probability of the appearance of trends due to natural variations, we calculated the fraction of occurrence of such linear trends of different amplitudes and lengths from the control run. As the time interval over which the trend is calculated grows longer, the fraction of occurrence by chance of a trend exceeding a given magnitude becomes smaller. Large trends appear for only short time intervals. Figure 3 shows the probability that a trend of a given length of a certain amplitude would occur by natural climate variability, as simulated by the GFDL model. This simple technique was previously used to evaluate observed global surface air-temperature variation (*23*). For the sea ice results, with the model's variability estimates, the probability of the magnitude of a random trend being larger than or equal to the observed 1953–98 trend (–190,000 km^2 per 10 years) is found to be <0.1%. The probability of the magnitude of a trend being larger than or equal to the observed 1978–98 trend in sea ice extent (–370,000 km^2 per 10 years) is <2%. Analogous estimates of the probability of other observed and modeled trends occurring as a result of natural climate variability are given in Table 1.

A 600-year control run of the Hadley Centre climate model was also used to estimate the magnitude of the natural variability in NH sea ice extent. The estimates based on the Hadley Centre model are noisier than those based on the GFDL model, mainly because of the difference in the lengths of the control runs. The variability in both is in very good agreement and almost exactly equal to the observed magnitude.

The probability is very low that the observed and modeled trends are due exclusively to random variations, assuming that the models' natural variability is similar to that found in nature. This strongly suggests that the observed decrease in NH sea ice extent is related to anthropogenic global warming.

Both climate models realistically reproduce the observed annual trends in NH sea ice extent. This suggests that these models can be used with some confidence to predict future changes in sea ice extent in response to increasing greenhouse gases in the atmosphere. Both models predict continued substantial sea ice extent and thickness decreases in the next century.

Table 1. Linear trends in annual averages of NH sea ice extent and the probability that such a trend would occur by chance as the result of natural variability. The estimates for smoothed model output for the specified period are given in parentheses. Probability estimates are based on the GFDL climate model 5000-year control run and are not applicable for Hadley Centre model output.

Time series	Period of observation	Number of years	Linear trend (10^6 km^2 per 10 years)	Probability (%)
GFDL climate model, transient forcing, Haywood *et al.* (1997) (*20*)	1953–98	46	−0.13 (−0.14)	1 (0.4)
	1972–98	27	−0.12 (−0.18)	16 (6)
	1978–98	21	−0.34 (−0.19)	2 (13)
Hadley Centre climate model, transient forcing, Johns *et al.* (1997) (*22*)	1953–98	46	−0.13 (−0.12)	NA
	1972–98	27	−0.32 (−0.15)	NA
	1978–98	21	−0.18 (−0.16)	NA
Chapman and Walsh (1993) (*13*), updated	1953–98	46	−0.19	<0.1
	1972–98	27	−0.27	1
Parkinson *et al.* (1999) (*16*), updated	1978–98	19.4	−0.37	2
Bjorgo *et al.* (1997) (*14*)	1978–95	16.8	−0.32	6
Zakharov (1997) (*5*)	1972–90	19	−0.14	23
Ropelewski (1985) (*8*), updated	1973–94	22	−0.07	32

References and Notes

1. M. I. Budyko, *Tellus* **21**, 611 (1969).
2. S. Manabe and R. J. Stouffer, *Nature* **282**, 491 (1979).
3. S. Manabe, M. J. Spelman, R. J. Stouffer, *J. Clim.* **5**, 105 (1992).

4. R. M. Sanderson, *Meteorol. Mag.* **104**, 313 (1975).
5. V. F. Zakharov, *Technical Document WMO/TD 782* (World Meteorological Organization, Geneva, 1997) [translation from *Morskie l'dy v klimaticheskoi sisteme* (Sea ice in the climate system) (Gidrometeoizdat, St. Petersburg, 1996)].
6. J. E. Walsh and C. M. Johnson, *J. Phys. Oceanogr.* **9**, 580 (1979).
7. K. Y. Vinnikov *et al.*, *Sov. Meteorol. Hydrol.* **6**, 1 (1980).
8. C. F. Ropelewski, *Adv. Space Res.* **5**, 275 (1985).
9. G. Kukla and J. Gavin, *Science* **214**, 497 (1981).
10. P. Gloersen and W. J. Campbell, *J. Geophys. Res.* **93**, 10666 (1988).
11. C. L. Parkinson and D. J. Cavalieri, *J. Geophys. Res.* **94**, 14499 (1989).
12. P. Gloersen *et al.*, *NASA Spec. Publ.* **SP-511**, 1 (1992).
13. W. L. Chapman and J. E. Walsh, *Bull. Am. Meteorol. Soc.* **74**, 33 (1993).
14. E. Bjorgo, O. M. Johannessen, M. W. Niles, *Geophys. Res. Lett.* **24**, 413 (1997).
15. D. J. Cavalieri, P. Gloersen, C. L. Parkinson, J. C. Comiso, H. J. Zwally, *Science* **278**, 1104 (1997).
16. C. L. Parkinson, D. J. Cavalieri, P. Gloersen, H. J. Zwally, J. C. Comiso, *J. Geophys. Res.* **104**, 20837 (1999).
17. D. J. Cavalieri, C. L. Parkinson, P. Gloersen, J. C. Comiso, H. J. Zwally, *J. Geophys. Res.* **104**, 15803 (1999).
18. S. Manabe, R. J. Stouffer, M. J. Spelman, K. Bryan, *J. Clim.* **4**, 785 (1991).
19. S. Manabe and R. J. Stouffer, *Bull. Am. Meteorol. Soc.* **78**, 1177 (1997).
20. J. Haywood *et al.*, *Geophys. Res. Lett.* **24**, 1335 (1997).
21. D. A. Rothrock, Y. Yu, G. A. Maykut, *Geophys. Res. Lett.*, in press.
22. T. C. Johns *et al.*, *Clim. Dyn.* **13**, 103 (1997).
23. R. J. Stouffer, S. Manabe, K. Y. Vinniko, *Nature* **367**, 634 (1994).
24. Battisti *et al.* [D. S. Battisti, C. M. Bitz, R. E. Moritz, *J. Clim.* **10**, 1909 (1997)], using a more complex sea ice model, with explicit snow cover and multiple ice layers, claim that the sea ice model used here underestimates the low-frequency variability of the sea ice thickness. Their model produces a longer time scale of response, resulting in larger low-frequency variability of sea ice, and they claim that it is more realistic. Furthermore, they postulate that the sea ice response to changes in the radiative forcing would be too fast with our simple model. But, they admit that observations are not good enough to distinguish between the high variability of ice they calculate and the lower GFDL variability, and their model is only of ice thickness, not extent, and ignores any spatial heterogeneity. Our findings in this report, which compare the model results to the observations, contradict their conclusions, at least for sea ice extent in the NH. The modeled variability of the sea ice extent agrees quite well with the detrended observations, and the response to increasing greenhouse gases also seems realistic.
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Satellite Evidence for an Arctic Sea Ice Cover in Transformation

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Recent research using microwave satellite remote sensing data has established that there has been a reduction of about 3 percent per decade in the areal extent of the Arctic sea ice cover since 1978, although it is unknown whether the nature of the perennial ice pack has changed. These data were used to quantify changes in the ice cover's composition, revealing a substantial reduction of about 14 percent in the area of multiyear ice in winter during the period from 1978 to 1998. There also appears to be a strong correlation between the area of multiyear ice and the spatially averaged thickness of the perennial ice pack, which suggests that the satellite-derived areal decreases represent substantial rather than only peripheral changes. If this apparent transformation continues, it may lead to a markedly different ice regime in the Arctic, altering heat and mass exchanges as well as ocean stratification.

Enhanced Arctic warming and a retreating sea ice cover are common features in modeled climate change scenarios (*1*, *2*). Quantitative observational evidence for changes in the sea ice cover may be obtained from satellite-borne sensors measuring low-frequency microwave (millimeter to meter wavelength) radiation. Microwave-derived sea ice time series are now among the longest continuous satellite-derived geophysical records, extending over two decades. The Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) provided data from 1978 to 1987, and the follow-up Special Sensor Microwave/Imagers (SSM/I) onboard Defense Meteorological Satellite Program (DMSP) satellites F8, F11, and F13 have provided data since 1987. The multifrequency brightness temperature (T_B) data are used to calculate total ice concentration (the percent of ice-covered ocean), from which total ice area (the area of ice-covered ocean) and total ice extent (the area within the ice-ocean margin) are derived. Analyses of SMMR and SSM/I data have detected a reduction of about 3% per decade in total ice area (*3*, *4*) and extent (*3–5*) in the Arctic since 1978. The observed decreases are due largely to reduced summer ice extent in the Eurasian Arctic in the 1990s, with record low arctic ice minima observed in 1990, 1993, and 1995, linked to regional atmospheric circulation anomalies (*6*). The reduced summer ice extent implies a consequential transformation of the winter ice cover toward thinner seasonal ice. There have been fragmentary indications of unusual conditions in recent years [such as reduced ice concentration in the Siberian sector of the perennial ice pack in the 1990s (*6*) and reduced ice thickness in parts of the Arctic since the 1970s, based on submarine sonar data (*7*)]. However, it has remained unknown whether the nature of the perennial ice pack as a whole has changed. Perennial multiyear (MY) ice (ice that has survived the summer melt) is about three times thicker than seasonal or first-year (FY) ice (~1 to 2 m), so that changes in ice type distribution could both reflect and effect climate change.

Because MY ice, FY ice, and open water have different radiative properties, algorithms applied to multichannel microwave data can separate each of these surface components, at least in winter when the signatures are relatively stable (*8–11*). The possibility of monitoring interannual variations in MY ice area with satellite microwave data has been explored (*8*, *9*) but remains underrealized. We produced and analyzed spatially integrated time series of MY and FY ice areas in winter derived from SMMR and SSM/I data from 1978 to 1998, revealing the ice cover's changing composition.

In general, combined SMMR-SSM/I time series are produced at the geophysical parameter level rather than the sensor radiance or T_B level. The methods used here are based on the approach we used previously (*4*) for merging SMMR-SSM/I sea ice time series, with additional methods used for robust estimation of MY and FY ice areas. Briefly, the NORSEX (*11*, *12*) algorithm is used to calculate ice concentration from SMMR (18 and 37 GHz) and SSM/I (19 and 37 GHz) T_B data, with the SMMR T_Bs adjusted for slight sensor drift (*3*, *4*). Total ice concentration, area, and extent are iteratively calculated and adjusted (*4*) for the SMMR-SSM/I overlap period (July to August 1987) to less than 1% difference for all parameters. No adjustments are made to the F8, F11, and F13 SSM/I T_Bs because (i) the individual sensor drifts are negligible (*13*); (ii) relative SSM/I T_B inter-calibrations are not advantageous (*14*); and (iii) biases are not significant for hemispheric sea ice parameters, notwith-