

A record minimum arctic sea ice extent and area in 2002

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[1] Arctic sea ice extent and area in September 2002 reached their lowest levels recorded since 1978. These conditions likely resulted from (1) anomalous warm southerly winds in spring, advecting ice poleward from the Siberian coast (2) persistent low pressure and high temperatures over the Arctic Ocean in summer, promoting ice divergence and rapid melt. *INDEX TERMS*: 4215 Oceanography: General: Climate and interannual variability (3309); 1620 Global Change: Climate dynamics (3309); 1863 Hydrology: Snow and ice (1827); 1640 Global Change: Remote sensing; 1635 Global Change: Oceans (4203). **Citation**: Serreze, M. C., J. A. Maslanik, T. A. Scambos, F. Fetterer, J. Stroeve, K. Knowles, C. Fowler, S. Drobot, R. G. Barry, and T. M. Haran, A record minimum arctic sea ice extent and area in 2002, *Geophys. Res. Lett.*, 30(3), 1110, doi:10.1029/2002GL016406, 2003.

1. Background and Observations

[2] Arctic sea ice plays a crucial role in Northern Hemisphere climate and ocean circulation. Recent studies point to significant reductions in Arctic sea ice over the past two decades [Cavalieri *et al.*, 1997], and perhaps centuries [Vinje, 2001a]. The 2002 season shows record low sea ice extent (the region with >15% ice cover) and area (extent weighted by ice concentration) for September based on passive microwave measurements (Table 1).

[3] Satellite passive microwave sea ice records from October 1978 through 1987 are from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), and since 1987 from the DMSP Special Sensor Microwave/Imager (SSM/I). Three daily data sets are available from the National Snow and Ice Data Center (NSIDC): the Standard Team product, the Goddard Space Flight Center (GSFC) product, and NSIDC's Near Real Time DMSP SSM/I product (NRTSI, used for 2002). They differ in record length, algorithms to convert brightness temperatures to ice concentration, and methods to remove false sea ice detection due to coastal contamination and weather effects (false ice detection beyond the true ice margin). The latter two issues are minimized in Table 1 by applying a land mask expanded seaward by two pixels and a conservative ice mask based on maximum ice extent from 1978–2001.

[4] The Standard Team product [Cavalieri *et al.*, 1990] applies the NASA Standard Team algorithm [Cavalieri *et*

al., 1984] to data provided by Remote Sensing Systems, Inc. (RSS) three to six months after satellite overpass. A standard weather filter is used, with no special processing to remove land contamination. GSFC [Cavalieri *et al.*, 1999a] combines SMMR and SSM/I records. It uses a modified NASA Team algorithm, with different tie points for sea ice end-members and different weather filters to minimize variations in ice extent and area among different instruments. It also includes a land contamination correction. NRTSI uses the same weather filter and ice algorithm as the Standard Team data set. Processing is done within one to two days of data acquisition, using data from the Marshall Space Flight Center (MSFC). Values from NRTSI [Cavalieri *et al.*, 1999b] are most similar to the Standard Team results. However, the MSFC data have not received the same level of quality control as those from RSS. Comparisons between the NRTSI and NASA Standard Team product for September 1999 and 2001 reveal no appreciable differences. NRTSI area and extent are 3% and 1% greater, respectively, than GSFC values.

[5] Figure 1 shows September 2002 ice extent and concentration anomalies, median extent, extents for June–August 2002, and September extents for the four previous minimum extent years. The 2002 ice margin in the Beaufort Sea is near that for 1998, the previous record for this region [Maslanik *et al.*, 1999]. There is little ice in the East Greenland Sea, as in 1990 [Maslanik *et al.*, 1996]. Similar to 1998, concentrations are low over large parts of the interior pack.

[6] Passive microwave algorithms underestimate summer ice concentration due to meltwater and other effects [e.g., Fetterer and Untersteiner, 1998; Comiso and Kwok, 1996]. Partington *et al.* (The late twentieth century Northern Hemisphere sea-ice record from US National Ice Center ice charts, submitted to *J. Geophys. Res.*, 2002) compared the NASA Team algorithm and ice charts from manual analysis from the U.S. National Ice Center (NIC). Average differences rise to 23% in early August, and fall to 10% by late September. In recognition, we show only ice extent for August in Table 1, and ice extent outlines for June through August 2002 in Figure 1.

[7] The NRTSI observations were compared with NIC charts and visible-band MODIS (Moderate Resolution Imaging Spectroradiometer) images. For the Chukchi and Beaufort Seas during August 2002, NRTSI classifies some melting areas as open water, whereas the NIC posts them with up to 70% concentration. Agreement improves by September. MODIS images indicate significant underestimation in early September, with better agreement later in the month (Figure 2). The MODIS algorithm divides a bimodal brightness histogram into two classes (open water and floes) and estimates ice fraction of mixed pixels by their intermediate brightness. Because of mixed pixels, calculated

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Table 1. Arctic Sea Ice Extents for August and Sea Ice Extents and Areas for September for the Five Minimum Years Since 1979

Arctic Sea Ice, August and September			
Year or Period of mean	August Extent (Std. Dev.) (10 ⁶ km ²)	September Extent (Std. Dev.) (10 ⁶ km ²)	September Area (Std. Dev.) (10 ⁶ km ²)
1979–2000 Mean (GSFC)	6.53(0.33)	6.10 (0.43)	
1987–2001 Mean (NASA Team)	6.58(0.33)	6.09 (0.43)	4.36 (0.41)
1990	5.97 Std. Team 5.81 GSFC	5.51 Std. Team 5.40 GSFC	4.05 Std. Team 3.97 GSFC
1993	6.41 Std. Team 6.17 GSFC	5.74 Std. Team 5.63 GSFC	4.09 Std. Team 3.98 GSFC
1995	5.99 Std. Team 5.80 GSFC	5.47 Std. Team 5.36 GSFC	4.05 Std. Team 3.95 GSFC
1998	6.61 Std. Team 6.41 GSFC	5.98 Std. Team 5.80 GSFC	3.98 Std. Team 3.82 GSFC
2002	5.78 NRSTI	5.26 NRSTI	3.63 NRSTI

Long-term means and standard deviations (in parentheses) are given for 1979–2000 (from the GSFC product) and for 1987–2001 (from the Standard Team product). Computation of ice area excludes the region near the pole not imaged by the sensor. This area is larger for SMMR than for SSM/I (1.19 million square km versus 0.31 million square km). Consequently we did not derive an average GSFC area estimate which combines SMMR and SSM/I data.

MODIS ice concentrations are lower than what the eye would estimate from comparing the brightest and darkest regions of the images.

2. Sea Ice Trends Since 1978

[8] The 2002 anomaly is the most recent manifestation of a general downward trend in Arctic sea ice during the passive microwave era. Through 1996 a trend of $-2.8 \pm 0.3\%$ per decade is reported [Cavalieri *et al.*, 1997; Parkinson *et al.*, 1999], strongly driven by summer and early autumn anomalies. Submarine sonar data collected between 1958 and 1997 suggest significant reductions in end-of-summer ice draft over much of the Arctic, but these results

may in part reflect undersampling [e.g., Holloway and Sou, 2002].

[9] The sea ice trend is part of a larger pattern of recent Arctic change, which includes pronounced warming over sub-Arctic land areas and the Arctic Ocean, warming and increased extent of the Arctic Ocean's Atlantic layer, reductions in winter sea level pressure (SLP) and positive trends in winter indices of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) [Thompson and Wallace, 1998; Serreze *et al.*, 2000; Moritz *et al.*, 2002]. The AO is the leading mode of Northern Hemisphere SLP variability and reflects an exchange of atmospheric mass between the Arctic Ocean and middle latitudes. Time series of the AO and NAO are similar and there is debate whether they are

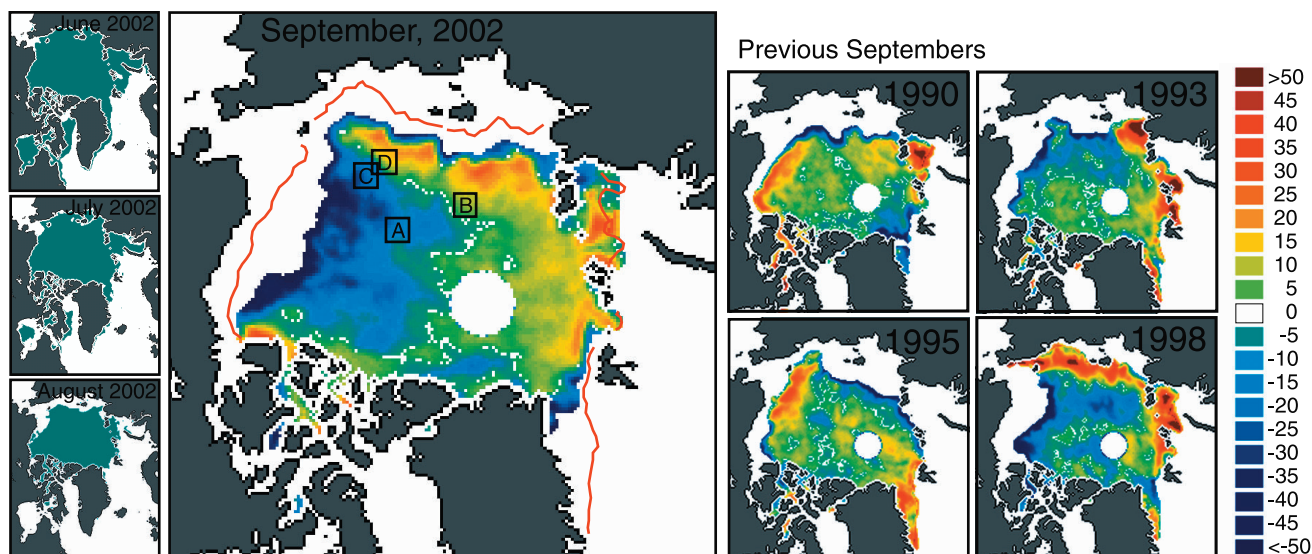


Figure 1. Large panel: NRTSI-derived sea ice extent and concentration anomalies (in %, see color bar) relative to NASA Standard Team means for 1988–2000. Median ice extent over the same period is shown by the red line. Four boxes (A, B, C, and D) show MODIS validation areas (see Figure 2). Ice extent in the months leading to the September minimum are shown at left. At right, September sea ice extent and concentration anomalies for the four previous minimum extent years.

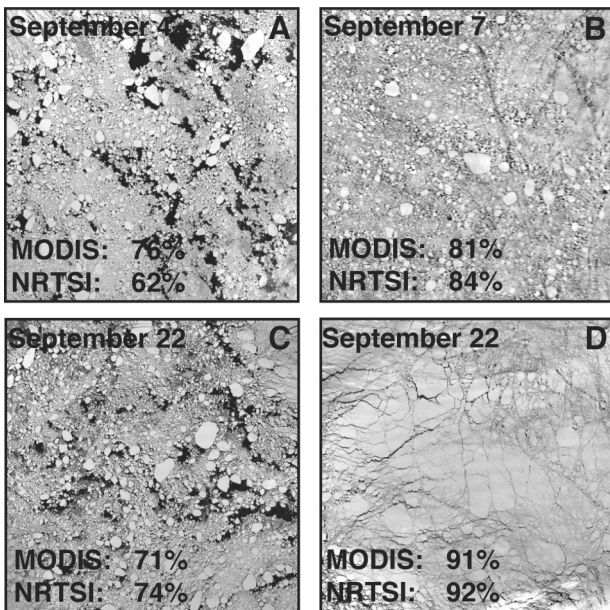


Figure 2. MODIS subsatellite images and ice concentrations compared with NRTSI-derived values for the same area and day (see Figure 1). Each scene is 200 km by 200 km.

separate atmospheric modes. Many of the environmental changes noted above relate to the AO trend. Recent studies [e.g., Overland *et al.*, 2002 and references therein] suggest a link between the AO and stratospheric processes.

3. Causes of the Anomaly

[10] Causes of the anomaly are addressed from near-surface (1000 hPa) wind, 925 hPa temperature and SLP fields from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis. The 925 hPa temperature field is preferred over the 2-m field, which is strongly influenced by the modeled surface energy budget.

[11] Averaged from March through May, strong poleward wind anomalies are found along the Siberian coast, with 925 hPa temperature anomalies of +5 degrees C in the East Siberian Sea. This was associated with large positive pressure anomalies (+9 hPa) over the Alaskan peninsula. The wind field is reflected in offshore ice drift vectors (derived from satellite imagery and drifting buoys), manifested as an early development of coastal leads and polynyas (not shown). Development of such features favors summer ice loss through enhanced absorption of solar radiation [Maslanik *et al.*, 1996; Rigor *et al.*, 2002]. High temperatures may have contributed by inhibiting ice growth and promoting early melt.

[12] Under a cyclonic surface wind stress, Ekman transport at the sea surface to the right of the wind forcing promotes ice divergence [Thorndike and Colony, 1982]. In summer away from coasts, internal ice stresses are small. The turning angle is much greater than for winter, meaning stronger ice divergence under a given cyclonic wind stress [Thorndike and Colony, 1982; Serreze *et al.*, 1989]. Cyclone activity over the central Arctic Ocean normally peaks in summer. Past studies have documented links between the summer cyclone regime and the development

of low ice concentration in the interior pack [e.g., Barry and Maslanik, 1989; Serreze *et al.*, 1989]. Barry and Maslanik [1989] discuss the development in August 1980 of a large area with concentrations of 70% or less in the Canada Basin, under a closed mean low for this month. Similar relationships were observed in 1981, 1982 and 1984.

[13] The mean June through August SLP pattern for 2002 shows a closed central Arctic low (Figure 3a). Low mean pressure prevailed for the three months individually. This is highly unusual, and consistent with the widespread development of low ice concentration. A mean low (1003 hPa) is also found for September 2002 over the Laptev Sea.

[14] By itself, a divergent ice pack will lead to greater ice extent. However, enhanced absorption of solar radiation in open water areas likely fostered melt. A contributing factor was continued warmth during summer, except near the center of mean low pressure (Figure 3b). September temperatures anomalies are negative in the Kara and Barents seas but positive over the rest of the Arctic Ocean.

[15] Ice export out of the Arctic Basin is primarily through Fram Strait (between Svalbard and northeast Greenland). Greenland Sea ice conditions are related to this flux. Vinje [2001b] relates the wind-driven flux component to the

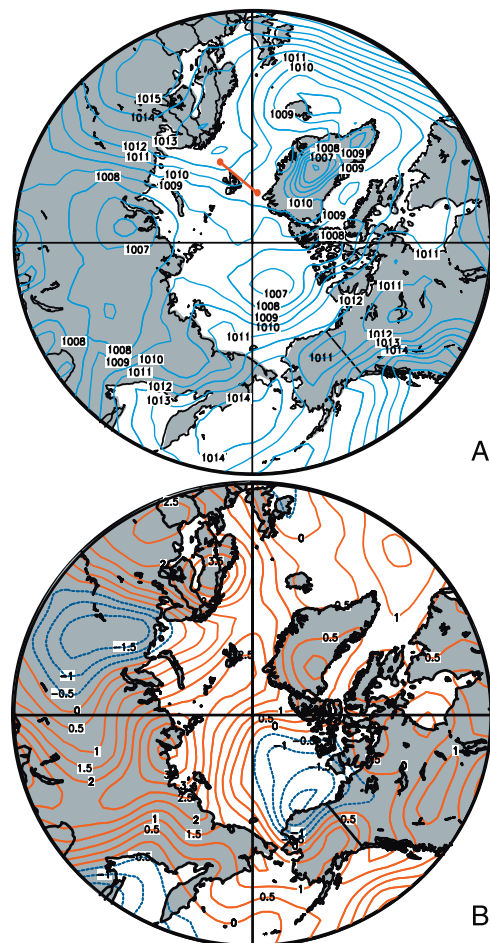


Figure 3. (a) Mean sea level pressure for June through August 2002 and (b) air temperature anomalies for the same period at 925 hPa (both referenced to 1968–1996). The two dots and connecting line define the transect used by Vinje [2001b] to estimate the Fram Strait ice flux (see text).

SLP difference across the northern flank of the northeast Atlantic trough (80°N, 10°W minus 73°N, 20°E, see Figure 3a). The flux is normally lowest in summer, when the mean SLP gradient is weak or negative. Mean pressure differences for June, July and August, 1968–1996, are +0.1, –1.6 and –1.4 hPa, compared to the 2002 values of –3.5, –2.1 and –2.4 hPa. The small implied ice flux likely contributed to reduced ice in the Greenland Sea. However, the gradient for September 2002 was +2.9 hPa compared to the mean value of +2.4 hPa. Not addressed here are possible anomalous ice conditions feeding Fram Strait via the Transpolar Drift Stream.

[16] Can the 2002 sea ice anomaly be linked to the AO? Rigor *et al.* [2002] argue that during positive AO winters, thin ice and coastal leads form along the Siberian coast. This is a response to winds with an anomalous easterly to southeasterly and cyclonic component, advecting ice away from the coast and promoting ice divergence. This preconditions the system to promote enhanced summer ice losses. In turn, while the normalized monthly AO index value for December 2001 was more than one standard deviation negative (–1.32), values for January and February 2002 were strongly positive (+1.38 and +1.30, respectively). The index was modestly positive in March (+0.90) and remained weakly positive from April through July.

[17] The warm southerly wind regime argued as a preconditioning mechanism in 2002 seems broadly consistent with the mechanism outlined by Rigor *et al.* [2002]. However, there is an issue of timing: the southerly wind anomalies occurred from March through May, when the AO was in a weaker, albeit still positive state. While the January SLP anomaly field is indicative of a more cyclonic wind regime, we stress that despite the positive AO state in February, central Arctic Ocean pressures for this month were anomalously high (up to +6 hPa), associated with a pronounced anticyclonic surface wind field.

[18] The cyclonic summer SLP circulation was associated with both weakly positive (June and July) and weakly negative (August) AO states. Recent work indicates that the AO stratospheric link breaks down in summer [e.g., Labitzke and Van Loon, 1999], suggesting that the summer AO has less “value” and that keys to circulation variability should be sought elsewhere. For example, Serreze *et al.* [2001] show that the summer Arctic Ocean cyclone regime is in part maintained by cyclogenesis along northeastern Eurasia in association with the Arctic frontal zone.

4. Conclusions

[19] Climate models are in general agreement: ice extent and thickness will decline over the 21st century as the climate warms. Simulations of the past 30 years agree reasonably well with observations in terms of total ice area, lending some confidence to projections of a ~20% reduction in annual mean sea ice extent by the year 2050 [Vinnikov *et al.*, 1999]. It is reasonable to expect that a general decrease in ice thickness accompanying warming would manifest itself as greater sensitivity of the ice pack to wind forcings and albedo feedbacks. Whether this can help to explain the recent large negative ice anomalies seen over the past decade, exemplified by the year 2002, needs to be further addressed.

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References

- Barry, R. G., and J. A. Maslanik, Arctic sea ice characteristics and associated atmosphere-ice interactions, *Geojournal*, 18, 5–44, 1989.
- Cavalieri, D., P. Gloersen, and J. Zwally, DMSP SSM/I daily polar gridded sea ice concentrations, edited by J. Maslanik and J. Stroeve, *NSIDC, Digital Media*, 1990.
- Cavalieri, D., C. Parkinson, P. Gloersen, and H. J. Zwally, Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I Passive Microwave Data, *NSIDC, CD-ROM*, 1999a.
- Cavalieri, D., P. Gloersen, and J. Zwally, Near Real-Time DMSP SSM/I Daily Polar Gridded Sea Ice Concentrations, edited by J. Maslanik and J. Stroeve, *NSIDC, Digital Media*, 1999b.
- Cavalieri, D. J., P. Gloersen, and W. J. Campbell, Determination of sea ice parameters with the NIMBUS-7 SMMR, *J. Geophys. Res.*, 89(D4), 5355–5369, 1984.
- Cavalieri, D. J., P. Gloersen, C. L. Parkinson, J. C. Comiso, and J. H. Zwally, Observed hemispheric asymmetry in global sea ice changes, *Science*, 278, 1104–1106, 1997.
- Comiso, J. C., and R. Kwok, Surface and radiative characteristics of the summer arctic sea ice cover from multi-sensor satellite observations, *J. Geophys. Res.*, 101(C12), 28,397–28,416, 1996.
- Fetterer, F., and N. Untersteiner, Observations of melt ponds on Arctic sea ice, *J. Geophys. Res.*, 103(C11), 24,821–24,835, 1998.
- Holloway, G., and T. Sou, Has Arctic sea ice rapidly thinned?, *J. Climate*, 15, 1691–1701, 2002.
- Labitzke, K. A., and H. Van Loon, *The Stratosphere*, Springer Press, Berlin, 179 pp., 1999.
- Maslanik, J. A., M. C. Serreze, and R. G. Barry, Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies, *Geophys. Res. Lett.*, 23, 1677–1680, 1996.
- Maslanik, J. A., M. C. Serreze, and T. Agnew, On the record reduction in 1998 western Arctic sea-ice cover, *Geophys. Res. Lett.*, 26, 1905–1908, 1999.
- Moritz, R. E., C. M. Bitz, and E. J. Steig, Dynamics of recent climate change in the Arctic, *Science*, 297, 1497–1502, 2002.
- Overland, J. E., M. Wang, and N. A. Bond, Recent temperature changes in the western Arctic during winter and spring, *J. Climate*, 15, 1702–1716, 2002.
- Parkinson, C. L., D. J. Cavalieri, P. Gloersen, H. J. Zwally, and J. C. Comiso, Arctic sea ice extents, areas and trends, 1978–1996, *J. Geophys. Res.*, 104(C9), 20,837–20,856, 1999.
- Rigor, I. G., J. M. Wallace, and R. L. Colony, Response of sea ice to the Arctic Oscillation, *J. Climate*, 15, 2648–2663, 2002.
- Serreze, M. C., R. G. Barry, and A. S. McLaren, Seasonal variations of ice motion and effects on sea ice concentration in the Canada Basin, *J. Geophys. Res.*, 94(C8), 10,955–10,970, 1989.
- Serreze, M. C., J. E. Walsh, F. S. Chapin III, T. Osterkamp, M. Dyrugerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry, Observational evidence of recent change in the northern high latitude environment, *Climatic Change*, 46, 159–207, 2000.
- Serreze, M. C., A. H. Lynch, and M. P. Clark, The summer Arctic frontal zone as seen in the NCEP/NCAR reanalysis, *J. Climate*, 14, 1550–1567, 2001.
- Thompson, D. W. J., and J. M. Wallace, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, 25, 1297–1300, 1998.
- Thorndike, A. S., and R. Colony, Sea ice motion in response to geostrophic winds, *J. Geophys. Res.*, 87(C8), 5845–5852, 1982.
- Vinje, T., Anomalies and trends of sea ice extent and atmospheric circulation in the Nordic seas during the period 1864–1998, *J. Climate*, 14, 255–267, 2001a.
- Vinje, T., Fram Strait ice fluxes and atmospheric circulation: 1950–2000, *J. Climate*, 14, 3508–3517, 2001b.
- Vinnikov, K. Y., A. Robock, R. J. Stouffer, J. E. Walsh, C. L. Parkinson, D. J. Cavalieri, J. F. B. Mitchell, D. Garrett, and V. F. Zakharov, Global warming and Northern Hemisphere sea ice extent, *Science*, 286, 1934–1937, 1999.
- M. C. Serreze, T. A. Scambos, F. Fetterer, J. Stroeve, K. Knowles, R. G. Barry, and T. M. Haran, National Snow and Ice Data Center, University of Colorado, RL-2, 1540 30th Street, Boulder, CO 80309-0449, USA. (serreze@kryos.colorado.edu)
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