⓸Global Sea Ice Coverage from Satellite Data: Annual Cycle and 35-Yr Trends

Claire L. Parkinson

Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland

ABSTRACT

Well-established satellite-derived Arctic and Antarctic sea ice extents are combined to create the global picture of sea ice extents and their changes over the 35-yr period 1979–2013. Results yield a global annual sea ice cycle more in line with the high-amplitude Antarctic annual cycle than the lower-amplitude Arctic annual cycle but trends more in line with the high-magnitude negative Arctic trends than the lower-magnitude positive Antarctic trends. Globally, monthly sea ice extent reaches a minimum in February and a maximum generally in October or November. All 12 months show negative trends over the 35-yr period, with the largest magnitude monthly trend being the September trend, at $-68\,200 \pm 10\,500\,\mathrm{km^2\,yr^{-1}}$ ($-2.62\% \pm 0.40\%\,\mathrm{decade^{-1}}$), and the yearly average trend being $-35\,000 \pm 5900\,\mathrm{km^2\,yr^{-1}}$ ($-1.47\% \pm 0.25\%\,\mathrm{decade^{-1}}$).

1. Introduction

Sea ice has received considerable attention in recent years, largely because of significant decreases in the Arctic sea ice cover (Parkinson et al. 1999; Rothrock et al. 1999; Kwok and Rothrock 2009; Cavalieri and Parkinson 2012; Stroeve et al. 2012) and the fact that those decreases are an important indicator of climate change (Walsh 2013) and have important consequences for climate (Screen et al. 2013; Walsh 2013; Vihma 2014), for the Arctic ecosystem (Post et al. 2013; Meier et al. 2014; Tedesco and Vichi 2014), and for humans (Johnson 1999; Walsh 2013; Meier et al. 2014). Among the most important climate consequences is that as the sea ice expanse lessens, less of the incoming solar radiation strikes the highly reflective ice cover, so that more solar radiation reaches the low-albedo liquid ocean and gets retained in the Earth system rather than being reflected back to space. This warms the ocean, leading to further ice reductions and enhancing the classic ice–albedo feedback (e.g., Kellogg 1975; Screen and Simmonds 2010).

Sea ice has also received attention because of the very different changes that have occurred in the Antarctic region (specifically in the Southern Ocean surrounding Antarctica), where sea ice coverage has increased rather than decreased since the late 1970s (Stammerjohn and Smith 1997; Zwally et al. 2002; Parkinson and Cavalieri 2012), reaching a then-record maximum in September 2012 (Turner et al. 2013) and a new maximum in September 2014. These sea ice increases in the Antarctic have not been as large as the sea ice decreases in the Arctic and have not been as widespread geographically. In fact, sea ice extent has decreased substantially in the Bellingshausen and Amundsen Seas region, immediately to the west of the Antarctic Peninsula (where there has been pronounced warming; Chapman and Walsh 2007), despite increasing overall in the Antarctic (Parkinson and Cavalieri 2012; Turner et al. 2013).

The decreasing areal coverage of Arctic sea ice is in line with Arctic warming (e.g., ACIA 2005; Walsh 2013; Hartmann et al. 2013) and produces feedbacks that tend to enhance that warming (e.g., Screen and Simmonds 2010). It is also in line with an observed thinning of the ice cover (Yu et al. 2004; Kwok and Rothrock 2009; Laxon et al. 2013) and a full suite of additional changes in the Arctic, such as thawing permafrost, increasing coastal erosion, greening tundra, and increased flow into the Arctic of warmer waters from the North Pacific and North Atlantic (ACIA 2005; Jeffries et al. 2013; Walsh 2013). The increasing Antarctic sea ice coverage has not been as readily explained, although insightful suggested explanations include tie-ins with atmospheric circulation changes and the Antarctic ozone hole (Thompson

---

⓸ Denotes Open Access content.

Corresponding author address: Claire L. Parkinson, Cryospheric Sciences Laboratory/Code 615, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
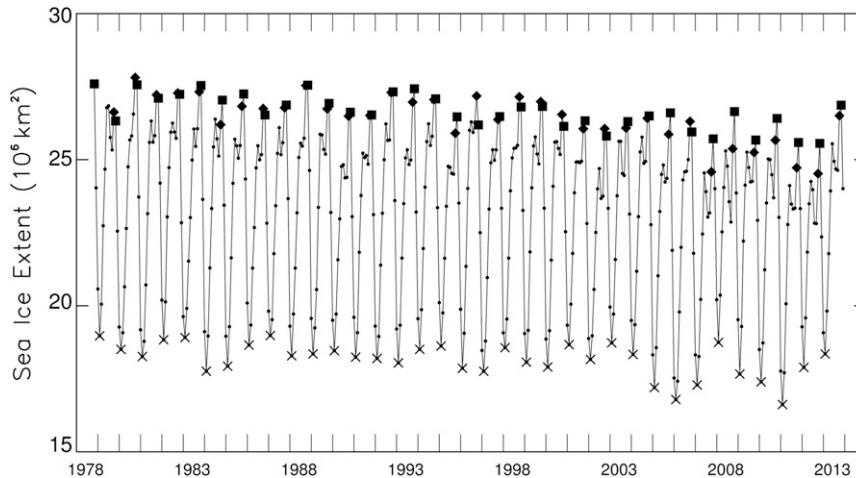E-mail: claire.l.parkinson@nasa.gov

Fig. 1. Monthly average global sea ice extents, November 1978–December 2013, as derived from satellite passive-microwave data. The February ice extents are marked by crosses, October ice extents by diamonds, November ice extents by squares aligned with the axes, and ice extents for all other months by circles. The x-axis tick marks are at January of each year, and the year labels are centered at the middle of the year.

and Solomon 2002; Turner et al. 2009) and the possibility that suppressed convective overturning and/or increased ice shelf meltwater have enhanced sea ice growth (Zhang 2007; Bintanja et al. 2013).

Irrespective of the cause of the increased Antarctic sea ice, the contrast between decreasing sea ice coverage in the Arctic and increasing sea ice coverage in the Antarctic has led at times to unnecessary confusion. Most notably, it is sometimes quite erroneously thought that the increases in Antarctic sea ice cancel out the decreases in Arctic sea ice. To quell that serious misconception, this note presents the global results, generated simply by adding the hemispheric results and calculating the resulting trends.

2. Data

The data used for this study are from the Scanning Multichannel Microwave Radiometer (SMMR) on the National Aeronautics and Space Administration's (NASA's) *Nimbus 7* satellite, the Special Sensor Microwave Imager (SSM/I) on the *F8*, *F11*, and *F13* satellites of the U.S. Department of Defense's Defense Meteorological Satellite Program (DMSP), and the SSM/I Sounder (SSM/IS) on the DMSP *F17* satellite. These datasets begin shortly after the launch of the *Nimbus 7* satellite in late October 1978 and continue to the present time. The data from each sensor are mapped onto rectangular grids overlaid on polar stereographic projections with grid squares (or pixels) sized at approximately 25 km × 25 km (NSIDC 1992). Ice concentration, defined as the percent areal coverage of ice,

is calculated at each grid square through the NASA Team algorithm (Gloersen et al. 1992), and ice extent is calculated as the sum of the area of grid squares with ice concentration at least 15% [as in Parkinson et al. (1999), Zwally et al. (2002), Meier et al. (2007), and numerous other studies of polar sea ice extents].

The passive-microwave data have undergone rigorous intercalibration, first between the SMMR and SSM/I sensors (Cavalieri et al. 1999) and then between the SSM/I and SSM/IS sensors (Cavalieri et al. 2012), to create a homogeneous dataset for long-term trend studies. The resulting intercalibrated datasets are available from the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, and have been widely used. Most pertinently, Cavalieri and Parkinson (2012) and Parkinson and Cavalieri (2012) have used the data for hemispheric studies of the Arctic and Antarctic sea ice extents, respectively, for the period November 1978–December 2010. These data are now updated through 2013 and, in this paper, combined to obtain global results.

3. Results

a. Annual cycle

Adding Arctic and Antarctic sea ice extents month by month for the period November 1978–December 2013 yields a global time series that shows a strong seasonal cycle with minimum global ice extent occurring in February of each year, maximum ice extent occurring in October or November of each year except 1979, and a minor secondary maximum often occurring in the June–July time frame (Fig. 1). In the anomalous year
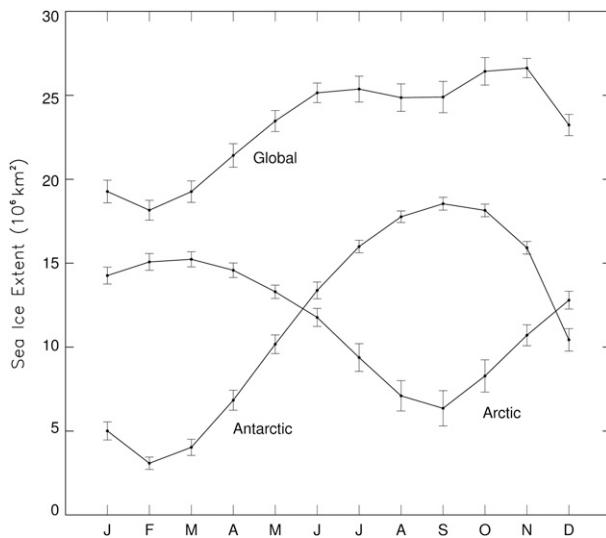
FIG. 2. Average annual cycles of Arctic, Antarctic, and global sea ice extents over the period 1979–2013, with one-standard-deviation bars plotted for each data point.

1979, the customary June/July secondary maximum is instead the primary maximum (Fig. 1).

The fairly systematic annual cycle of global ice extents depicted in Fig. 1 is most readily understood through comparison with the two component annual cycles. With that in mind, Fig. 2 presents the global average annual cycle for the full 1979–2013 period, averaging the 35 full annual cycles in Fig. 1, along with the corresponding curves for the Arctic and Antarctic individually. Both polar regions have large-amplitude annual cycles, with maximum ice extent coming in late winter and minimum ice extent coming in mid-to-late summer for the respective hemispheres. In the Antarctic, on average, monthly ice extents range from a minimum of $3.1 \times 10^6 \, \text{km}^2$ in February to a maximum of $18.5 \times 10^6 \, \text{km}^2$ in September, for an amplitude of $15.4 \times 10^6 \, \text{km}^2$. The month of minimum was February for every year of the 35-yr record, and the month of maximum was September in every year except 1988, when it was October. In the Arctic, the range is from a minimum of $6.4 \times 10^6 \, \text{km}^2$ in September to a maximum of $15.2 \times 10^6 \, \text{km}^2$ in March, for an amplitude of $8.8 \times 10^6 \, \text{km}^2$ (Fig. 2). Here too the timing is quite systematic, with September being the month of minimum Arctic ice extent in each of the 35 years and March the month of maximum ice extent in every year except 1987, 1989, and 1998, when it was February.

Not only is the amplitude of the average annual cycle greater in the Antarctic than in the Arctic (Fig. 2), but the record daily minimum in the Arctic, $3.4 \times 10^6 \, \text{km}^2$ on 17 September 2012, is not as low as the average February ice extent in the Antarctic, and the record

daily maximum in the Arctic, $16.3 \times 10^6 \, \text{km}^2$ on 1 March 1979, is not even close to reaching the level of the average September ice extent in the Antarctic (Fig. 2).

The much greater amplitude of the annual cycle of Antarctic versus Arctic ice extents results in the annual cycle of global sea ice extents being more in line, overall, with the Antarctic cycle than the Arctic cycle (Fig. 2). Globally, on average the monthly ice extents range from a minimum of $18.2 \times 10^6 \, \text{km}^2$ in February to a maximum of $26.6 \times 10^6 \, \text{km}^2$ in November. Hence the global and Antarctic cycles share the February timing of ice extent minimum, while the global maximum comes two months after the Antarctic maximum. Another prominent feature of the global plot is the dip to a secondary minimum in August/September, resulting from the July–September rapid summer retreat of the Arctic ice outweighing the more gradual July–September winter expansion of the Antarctic ice. Both hemispheres have winter maxima that are relatively broad and summer minima that are sharper, resulting in both minima being visible in the global plot (Fig. 2).

b. Trends

In marked contrast to the annual cycle of global ice extents being more in line with the Antarctic ice than with the Arctic ice (Fig. 2), the global trends are more in line with the Arctic trends. With the sea ice losses in the Northern Hemisphere far exceeding the sea ice gains in the Southern Hemisphere [cf. Cavalieri and Parkinson (2012) and Parkinson and Cavalieri (2012)], the global trends have the negative sign of the Arctic trends, although reduced in magnitude by the partial compensation of the Antarctic ice increases. The global sea ice extent trend for 1979–2013 is $-35\,000 \pm 2900 \, \text{km}^2 \, \text{yr}^{-1}$ on the basis of monthly deviations (Fig. 3a) and $-35\,000 \pm 5900 \, \text{km}^2 \, \text{yr}^{-1}$ ($-1.47\% \pm 0.25\%$ decade^{-1}) on the basis of yearly averages (Fig. 3b). When the monthly-deviation calculations incorporate the first two months of the SMMR record, November and December 1978, the trend is slightly larger, at $-35\,200 \pm 2900 \, \text{km}^2 \, \text{yr}^{-1}$, because of the relatively high ice extents in those two months.

The global sea ice extent trends for 1979–2013 are negative not just for the period overall (yearly averages and monthly deviations; Fig. 3) but also for each month, although not all at statistically significant levels. September has the largest amplitude trend, at $-68\,200 \pm 10\,500 \, \text{km}^2 \, \text{yr}^{-1}$ ($-2.62\% \pm 0.40\%$ decade^{-1}), statistically significant at a 99% confidence level, and May has the smallest amplitude trend, at a statistically insignificant $-6100 \pm 10\,600 \, \text{km}^2 \, \text{yr}^{-1}$ ($-0.26\% \pm 0.45\%$ decade^{-1}) (Fig. 4a; Table 1). Monthly trends are consistently
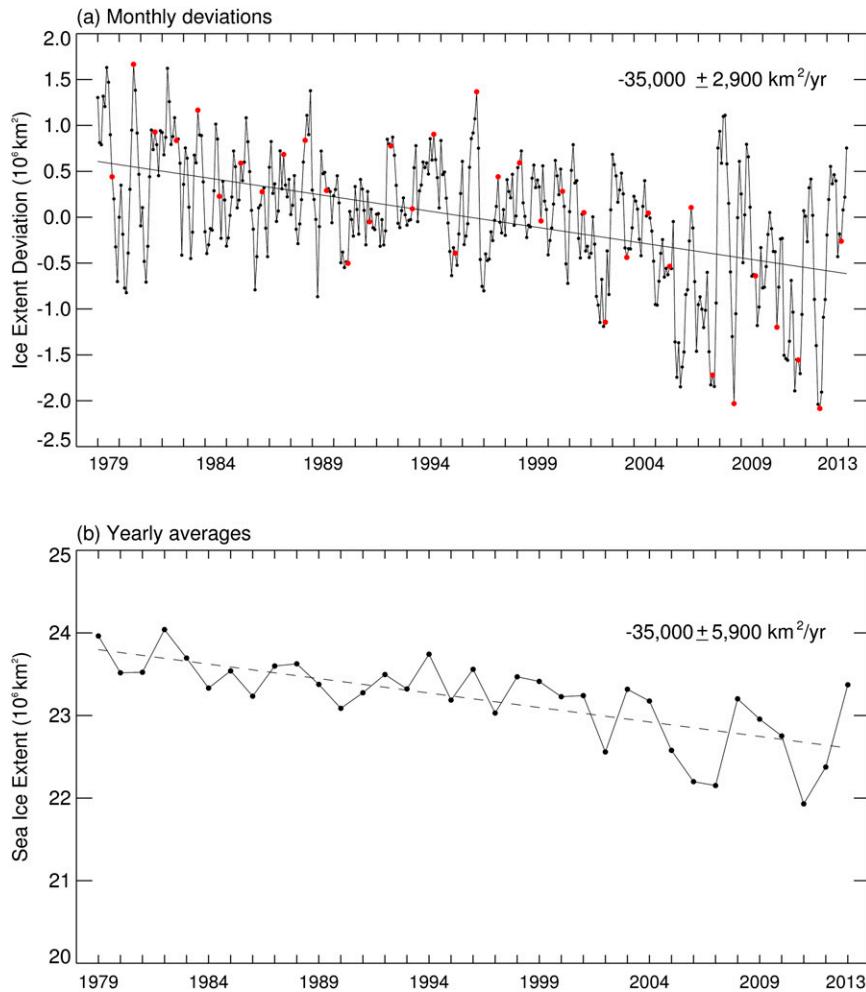
FIG. 3. (a) Global sea ice extent monthly deviations, January 1979–December 2013, calculated from the data plotted in Fig. 1 by subtracting from each individual month's ice extent the average ice extent for that month over the years 1979–2013, along with the line of linear least squares fit through the data points and its slope and standard deviation. September data points are red (and enlarged); all others are black. The x-axis tick marks are at January of each year, and the year labels are centered at the middle of the year. (b) Yearly average global sea ice extents (1979–2013) and the line of linear least squares fit through the data points.

positive in the Antarctic and consistently negative in the Arctic, with every month having a higher magnitude trend in the Arctic (Fig. 4b), leading to the consistently negative global trends (Fig. 4a). Furthermore, with the Antarctic trend values being relatively flat through the year, the pattern of global trends is quite similar to the pattern for the Arctic, including the months of maximum and minimum magnitude (Fig. 4).

Many references have been made in recent years to the speeding up or acceleration of the decline in Arctic sea ice coverage (e.g., Meier et al. 2007; Comiso et al. 2008; Cavalieri and Parkinson 2012; Stroeve et al. 2012). Figure 3 shows that, despite the increases in Antarctic sea ice, an acceleration can also be seen in the global

sea ice decline. For example, for the yearly averages, the trend for the first half of the record (1979–96) is $-21\,500 \pm 10\,600 \text{ km}^2 \text{ yr}^{-1}$, whereas the trend for the second half of the record (1996–2013) is over double that value, at $-50\,500 \pm 20\,000 \text{ km}^2 \text{ yr}^{-1}$.

4. Discussion

As with all datasets, the satellite sea ice data have various sources of errors. Among the factors that can complicate the sea ice records and introduce errors are the possibilities of a snow cover on the ice, meltponding, surface flooding, and microwave signals from the underlying water reaching through very thin ice, along with atmospheric
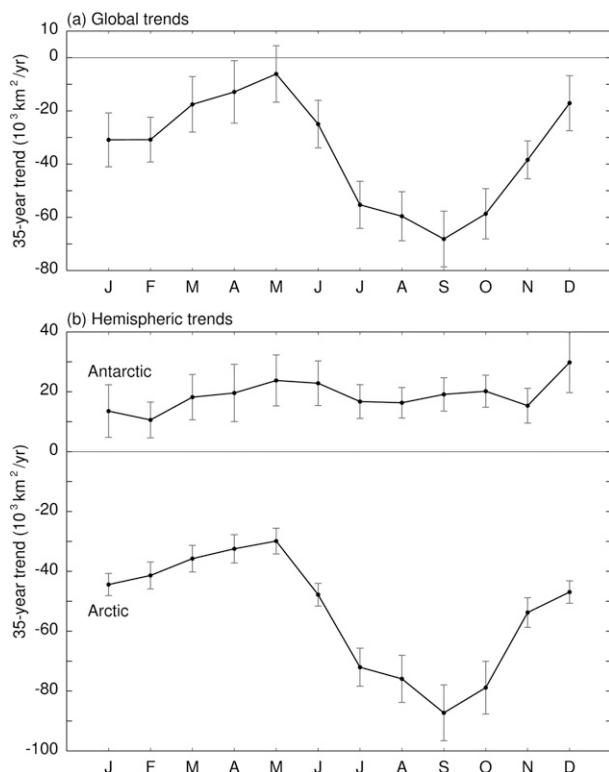
FIG. 4. (a) Monthly sea ice extent trends for the global sea ice cover over the period 1979–2013, with one-standard-deviation error bars. (b) Monthly sea ice extent trends for the Arctic and Antarctic sea ice covers over the period 1979–2013, with one-standard-deviation error bars.

TABLE 1. Slopes and standard deviations of the lines of least squares fit for monthly and yearly global sea ice extents, for the period 1979–2013. Here R is the ratio of the magnitude of the slope to the standard deviation [calculated from the trend ($km^2\,yr^{-1}$) prior to rounding] and provides a rough indication of statistical significance. Using a two-tailed t test with 33 degrees of freedom (2 less than the number of years), slopes with R values above 2.73 are considered statistically significant at a 99% confidence level and are highlighted in boldfaced italics in the R column.

	Trend ($km^2\,yr^{-1}$)	R	Trend (% decade^{-1})
January	$-30\,900 \pm 10\,100$	*3.05*	-1.56 ± 0.51
February	$-30\,800 \pm 8400$	*3.65*	-1.65 ± 0.45
March	$-17\,600 \pm 10\,400$	1.68	-0.90 ± 0.53
April	$-12\,900 \pm 11\,700$	1.10	-0.59 ± 0.54
May	$-6100 \pm 10\,600$	0.58	-0.26 ± 0.45
June	$-25\,000 \pm 8900$	*2.80*	-0.98 ± 0.35
July	$-55\,300 \pm 8800$	*6.25*	-2.10 ± 0.34
August	$-59\,600 \pm 9200$	*6.46*	-2.30 ± 0.36
September	$-68\,200 \pm 10\,500$	*6.50*	-2.62 ± 0.40
October	$-58\,700 \pm 9400$	*6.22*	-2.14 ± 0.34
November	$-38\,400 \pm 7100$	*5.38*	-1.41 ± 0.26
December	$-17\,100 \pm 10\,300$	1.65	-0.73 ± 0.44
Yearly	$-35\,000 \pm 5900$	*5.98*	-1.47 ± 0.25

effects and the low resolution of the passive-microwave data [details can be found in Cavalieri et al. (1999), Comiso and Steffen (2001), and Ivanova et al. (2014)]. However, despite the complexities of the ice cover and additional complications affecting the data, the very strong contrast between the microwave signatures of ice and liquid water has made sea ice an excellent variable to monitor with satellite passive-microwave instruments. The sea ice trends derived from the satellite data have proven to be relatively insensitive both to the choice of ice-concentration algorithm and to the choice of microwave instrument (e.g., Comiso and Parkinson 2008; Parkinson and Comiso 2008; Ivanova et al. 2014). Consequently, there is a high level of confidence in the overall results of decreases in Arctic sea ice extents (e.g., Parkinson et al. 1999; Cavalieri and Parkinson 2012; Stroeve et al. 2012), increases in Antarctic sea ice extents (e.g., Stammerjohn and Smith 1997; Zwally et al. 2002; Parkinson and Cavalieri 2012), and decreases in global sea ice extents since the late 1970s (Figs. 3 and 4).

The 1979–2013 trends in global ice extents are negative not just overall (Fig. 3) but in every season and every month (Fig. 4 and Table 1). This decrease in global

sea ice coverage means a decrease in the area of the global ocean overlain by a highly reflective white covering (albedo generally above 50%). The lost ice area is replaced by a highly nonreflective ice-free ocean (albedo generally below 15%), providing a direct contribution toward decreasing the planetary albedo. Indirect effects, however, could act in the opposite direction, as decreased sea ice coverage could lead to greater evaporation (from the newly exposed ice-free ocean) and hence to greater cloud coverage. A full quantitative analysis of the effects of the reduced sea ice on planetary albedo and the global energy budget will require sophisticated modeling as well as observational efforts. In the meantime, the decrease in global sea ice coverage is one of many important indicators of the changes currently occurring within Earth's climate system.

REFERENCES

ACIA, 2005: *Arctic Climate Impact Assessment.* Cambridge University Press, 1042 pp.

Bintanja, R., G. J. van Oldenborgh, S. S. Drijfhout, B. Wouters, and C. A. Katsman, 2013: Important role for ocean warming and

increased ice-shelf melt in Antarctic sea-ice expansion. *Nat. Geosci.,* **6,** 376–379, doi:10.1038/ngeo1767.

Cavalieri, D. J., and C. L. Parkinson, 2012: Arctic sea ice variability and trends, 1979–2010. *Cryosphere,* **6,** 881–889, doi:10.5194/tc-6-881-2012.

——, ——, P. Gloersen, J. C. Comiso, and H. J. Zwally, 1999: Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets. *J. Geophys. Res.,* **104** (C7), 15 803–15 814, doi:10.1029/1999JC900081.

——, ——, N. DiGirolamo, and A. Ivanoff, 2012: Intersensor calibration between F13 SSMI and F17 SSMIS for global sea ice data records. *IEEE Geosci. Remote Sens. Lett.,* **9,** 233–236, doi:10.1109/LGRS.2011.2166754.

Chapman, W. L., and J. E. Walsh, 2007: A synthesis of Antarctic temperatures. *J. Climate,* **20,** 4096–4117, doi:10.1175/JCLI4236.1.

Comiso, J. C., and K. Steffen, 2001: Studies of Antarctic sea ice concentrations from satellite data and their applications. *J. Geophys. Res.,* **106** (C12), 31 361–31 385, doi:10.1029/2001JC000823.

——, and C. L. Parkinson, 2008: Arctic sea ice parameters from AMSR-E data using two techniques and comparisons with sea ice from SSM/I. *J. Geophys. Res.,* **113,** C02S05, doi:10.1029/2007JC004255.

——, ——, R. Gersten, and L. Stock, 2008: Accelerated decline in the Arctic sea ice cover. *Geophys. Res. Lett.,* **35,** L01703, doi:10.1029/2007GL031972.

Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson, and H. J. Zwally, 1992: Arctic and Antarctic sea ice, 1978–1987: Satellite passive-microwave observations and analysis. NASA SP-511, 290 pp.

Hartmann, D. L., and Coauthors, 2013: Observations: Atmosphere and surface. *Climate Change 2013: The Physical Science Basis,* T. F. Stocker et al., Eds., Cambridge University Press, 159–254.

Ivanova, N., O. M. Johannessen, L. T. Pedersen, and R. T. Tonboe, 2014: Retrieval of Arctic sea ice parameters by satellite passive microwave sensors: A comparison of eleven sea ice concentration algorithms. *IEEE Trans. Geosci. Remote Sens.,* **52,** 7233–7246, doi:10.1109/TGRS.2014.2310136.

Jeffries, M. O., J. E. Overland, and D. K. Perovich, 2013: The Arctic shifts to a new normal. *Phys. Today,* **66,** 35–40, doi:10.1063/PT.3.2147.

Johnson, T., 1999: World out of balance. *Native Americas,* **16** (3), 8–25.

Kellogg, W. W., 1975: Climatic feedback mechanisms involving the polar regions. *Climate of the Arctic,* G. Weller and S. A. Bowling, Eds., University of Alaska, Fairbanks, 111–116.

Kwok, R., and D. A. Rothrock, 2009: Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophys. Res. Lett.,* **36,** L15501, doi:10.1029/2009GL039035.

Laxon, S. W., and Coauthors, 2013: CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophys. Res. Lett.,* **40,** 732–737, doi:10.1002/grl.50193.

Meier, W. N., J. Stroeve, and F. Fetterer, 2007: Whither Arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record. *Ann. Glaciol.,* **46,** 428–434, doi:10.3189/172756407782871170.

——, and Coauthors, 2014: Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity. *Rev. Geophys.,* **52,** 185–217, doi:10.1002/2013RG000431.

NSIDC, 1992: DMSP SSM/I brightness temperatures and sea ice concentration grids for the polar regions on CD-ROM: User's guide. Spec. Rep. 1, National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, 222 pp.

Parkinson, C. L., and J. C. Comiso, 2008: Antarctic sea ice parameters from AMSR-E data using two techniques and comparisons with sea ice from SSM/I. *J. Geophys. Res.,* **113,** C02S06, doi:10.1029/2007JC004253.

——, and D. J. Cavalieri, 2012: Antarctic sea ice variability and trends, 1979–2010. *Cryosphere,* **6,** 871–880, doi:10.5194/tc-6-871-2012.

——, ——, P. Gloersen, H. J. Zwally, and J. C. Comiso, 1999: Arctic sea ice extents, areas, and trends, 1978–1996. *J. Geophys. Res.,* **104** (C9), 20 837–20 856, doi:10.1029/1999JC900082.

Post, E., and Coauthors, 2013: Ecological consequences of sea-ice decline. *Science,* **341,** 519–524, doi:10.1126/science.1235225.

Rothrock, D. A., Y. Yu, and G. A. Maykut, 1999: Thinning of the Arctic sea-ice cover. *Geophys. Res. Lett.,* **26,** 3469–3472, doi:10.1029/1999GL010863.

Screen, J. A., and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature,* **464,** 1334–1337, doi:10.1038/nature09051.

——, ——, C. Deser, and R. Tomas, 2013: The atmospheric response to three decades of observed Arctic sea ice loss. *J. Climate,* **26,** 1230–1248, doi:10.1175/JCLI-D-12-00063.1.

Stammerjohn, S. E., and R. C. Smith, 1997: Opposing Southern Ocean climate patterns as revealed by trends in regional sea ice coverage. *Climatic Change,* **37,** 617–639, doi:10.1023/A:1005331731034.

Stroeve, J. C., M. C. Serreze, M. M. Holland, J. E. Kay, J. Maslanik, and A. P. Barrett, 2012: The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change,* **110,** 1005–1027, doi:10.1007/s10584-011-0101-1.

Tedesco, L., and M. Vichi, 2014: Sea ice biogeochemistry: A guide for modellers. *PLoS ONE,* **9,** e89217, doi:10.1371/journal.pone.0089217.

Thompson, D. W. J., and S. Solomon, 2002: Interpretation of recent Southern Hemisphere climate change. *Science,* **296,** 895–899, doi:10.1126/science.1069270.

Turner, J., and Coauthors, 2009: Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. *Geophys. Res. Lett.,* **36,** L08502, doi:10.1029/2009GL037524.

——, J. S. Hosking, T. Phillips, and G. J. Marshall, 2013: Temporal and spatial evolution of the Antarctic sea ice prior to the September 2012 record maximum extent. *Geophys. Res. Lett.,* **40,** 5894–5898, doi:10.1002/2013GL058371.

Vihma, T., 2014: Effects of Arctic sea ice decline on weather and climate: A review. *Surv. Geophys,* **35,** 1175–1214, doi:10.1007/s10712-014-9284-0.

Walsh, J. E., 2013: Melting ice: What is happening to Arctic sea ice, and what does it mean for us? *Oceanography,* **26,** 171–181, doi:10.5670/oceanog.2013.19.

Yu, Y., G. A. Maykut, and D. A. Rothrock, 2004: Changes in the thickness distribution of Arctic sea ice between 1958–1970 and 1993–1997. *J. Geophys. Res.,* **109,** C08004, doi:10.1029/2003JC001982.

Zhang, J., 2007: Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. *J. Climate,* **20,** 2515–2529, doi:10.1175/JCLI4136.1.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, D. J. Cavalieri, and P. Gloersen, 2002: Variability of Antarctic sea ice 1979–1998. *J. Geophys. Res.,* **107** (C5), 3041, doi:10.1029/2000JC000733.