INVITED PAPER[*]

Microcosm of Global Climate Change

Claire L. Parkinson

NASA Goddard Space Flight Center, Greenbelt, Maryland

Abstract

Polar sea ice is a key element of the climate system and has now been monitored through satellite observations for more than three and a half decades. The satellite observations reveal considerable information about polar ice and its changes since the late 1970s, including a prominent downward trend in Arctic sea ice coverage and a much lesser upward trend in Antarctic sea ice coverage, illustrative of the important fact that climate change entails spatial contrasts. The decreasing ice coverage in the Arctic corresponds well with contemporaneous Arctic warming and exhibited particularly large decreases in the summers of 2007 and 2012, influenced by both preconditioning and atmospheric conditions. The increasing ice coverage in the Antarctic is not as readily explained, but spatial differences in the Antarctic trends suggest a possible connection with atmospheric circulation changes that have perhaps been influenced by the Antarctic ozone hole. The changes in the polar ice covers and the issues surrounding those changes have many commonalities with broader climate changes and their surrounding issues, allowing the sea ice changes to be viewed in some important ways as a microcosm of global climate change.

Introduction

SEA ICE IS A VITAL COMPONENT of the global climate system, spreading over vast areas of the polar oceans, reflecting much of the incident solar radiation back to space, and hindering ocean-atmosphere exchanges of heat, mass, and momentum. In fact, sensitivity studies with the global climate model of NASA's Goddard Institute for Space Studies (GISS) determine that 37% of the global warming calculated for a doubling of atmospheric carbon dioxide (CO_2) in that model is explicitly due to the inclusion of sea ice in the calculations (Rind *et al*., 1995).

---

[*] This paper was a plenary presentation at the Washington Academy of Sciences' Capital Science 2014 Conference, March 29-30, 2014, at Marymount University in Arlington, Virginia.

Prior to the advent of satellite observations, knowledge of the large-scale coverage of sea ice and its changes were based on limited, largely anecdotal data. The pre-satellite sea ice records were even more incomplete than the temperature records, many of which omit the majority of the Earth's vast ocean area. However, since the late 1970s, satellites have provided such a clear view of sea ice coverage that sea ice has shifted from being among the least well documented of major Earth system components to being among the best documented. Passive-microwave satellite instruments in particular have allowed routine measurements of sea ice year round — under dark as well as sunlit conditions and under cloudy as well as cloud-free conditions.

Results from the satellite record show that sea ice has many commonalities with the records of other elements of the climate system, such as interannual variability, long-term trends that are significant but by no means monotonic, and spatial differences that are not fully understood and can complicate the interpretation of the overall trends. These commonalities in the behaviors have led to further commonalities in how the sea ice and broader climate results are discussed in the media and by the general public: They have given ammunition both to people concerned about climate change and to those rejecting those concerns, and they have led to a mixture of exaggerated statements and attempts at balance. Such commonalities allow the changes in the Arctic and Antarctic sea ice to be viewed as a microcosm of the changes in the more complete and complicated climate system as a whole. This paper examines these issues through sections on the data sources, the predictions, the observational records, and a discussion of the commonalities.

Data Sources

Temperature reconstructions for times prior to the advent of satellite technology are based in large part on land-based records, reflecting the difficulties of obtaining routine measurements over the ocean, and are weighted toward the Northern Hemisphere (Easterling *et al*., 1997; Hansen *et al*., 1999). With oceans covering 70% of the Earth's surface area, the slighting of the oceans in the temperature record is a serious limitation. Still, impressive attempts have been made at estimating the global temperature trends since the late 1880s from instrumental records and over that period and longer periods from proxy records (*e.g.*, Mann and Jones, 2003; Hansen *et al*., 2010; Anderson *et al*., 2013). Not unexpectedly, impressive as they are, these attempts at reconstructing past global temperature values with limited input data have received criticism both for the lack of sufficient data and for the methodology, as epitomized by the heated controversy over the so-called 'hockey-stick' plot of temperatures from the past 1,000 years, which shows a very sharp increase in temperatures in the past 100 years (see Mann *et al*., 1999, for the original plot, and Jansen *et al*., 2007, for discussion of the controversy).

Impressive attempts have also been made to reconstruct sea ice conditions, at least in the Arctic, for several decades prior to the satellite record (*e.g.*, Walsh and Chapman, 2001). These records are based largely on ship reports and aircraft measurements, both of which are limited in terms of how much of the ice is measured and how frequently. The remoteness of sea ice from human habitations and the harsh conditions (cold, instability, expansive area, etc.) make regular long-term sea ice measurements of the full Arctic and/or Antarctic ice covers extremely difficult through any surface-based or aircraft-based system. However, the harsh conditions at the surface are not limitations for satellite sensing. In fact, polar-orbiting and near-polar-orbiting satellites get particularly frequent coverage of the polar regions.

Sea ice can be viewed from a variety of satellite instruments, each with its own advantages and disadvantages. For instance, instruments measuring visible radiation are particularly good at obtaining spatially detailed views of the type that the human eye can see on a clear day from an aircraft. However, those advantages of visible radiation are only realized under daylight conditions and without clouds obscuring the view. Similarly, other instrument types also have their various advantages and disadvantages. So far, the data source that has proven most valuable in obtaining a climate data record of sea ice coverage is passive-microwave radiometry, and it is therefore the passive-microwave data sets that are used for the sea ice results presented in this paper.

The microwave data being recorded by satellite passive-microwave instruments derive from the Earth system and hence do not require sunlight, allowing data collection at any time of the day and any day of the year, thereby providing a major advantage over visible radiative data. Furthermore, with careful selection of microwave wavelength, the microwave data can be collected under most cloud conditions, as well as under cloud-free conditions, as portions of the microwave spectrum can pass nearly uninhibited through most clouds. The fact that sea ice imagery can be collected day or night and under cloudy or cloud-free conditions, combined with the fact that sea ice and liquid water have quite different microwave signatures, makes sea ice monitoring with passive-microwave instruments particularly effective for obtaining a long-term sea ice record.

The first major passive-microwave imager in space was NASA's Electrically Scanning Microwave Radiometer (ESMR), launched in December 1972 on board the Nimbus 5 satellite. This was a single-channel, proof-of-concept instrument, measuring at a wavelength of 1.55 cm (a frequency of 19.35 GHz), and it obtained a four-year record of sea ice coverage in both the Arctic (Parkinson *et al*., 1987) and the Antarctic (Zwally *et al*., 1983). Although the record contained major data gaps (including some entire months without data) and the limitation to a single channel prevented sorting out issues regarding sea ice types, the Nimbus 5 ESMR was a tremendous success in establishing the potential of satellite passive-microwave instruments for monitoring sea ice and other climate variables.

The ESMR was followed by more advanced passive-microwave instruments that have been flown successfully in space by several different countries. The data used for the results presented in this paper are from NASA's Scanning Multichannel Microwave Radiometer (SMMR), launched in October 1978 and obtaining a record through mid-August 1987, and from the Department of Defense's Special Sensor Microwave Imager (SSMI) and Special Sensor Microwave Imager Sounder (SSMIS) instruments, launched on a sequence of satellites starting in June 1987 and continuing to the present.

The passive-microwave data are used to calculate estimated sea ice concentrations, defined as the areal percentage sea ice coverage; and the ice concentrations are used in turn to derive sea ice extents, calculated as the sum of the areas of all pixels (in the region of interest) having ice concentrations of at least 15%. There are several different ice concentration algorithms in use, reflecting in part the fact that which algorithm is best depends on such factors as whether the algorithm is being applied globally or only to a specific region. When applied only to a specific region, tuning of the algorithm for that region can be quite helpful (e.g., Cho *et al*., 1996). Still, the strong contrast between the microwave signatures of ice and liquid water leads to very similar ice extents and trends irrespective of which algorithm is used (*e.g.*, Comiso and Parkinson, 2008; Parkinson and Comiso, 2008), and hence no major controversies have arisen regarding the basics of the satellite-derived sea ice results. [This contrasts with the temperature records, where controversies have arisen (*e.g.*, Hurrell *et al.*, 2000; Mears and Wentz, 2005).]

Predictions

Many factors are known to contribute to environmental and climate change, with the changes induced by some factors being quite opposite to those induced by others. For instance, among the human contributions, our emissions of particulate matter have a tendency overall to cool climate (and also to damage many people's health), whereas our emissions of greenhouse gases have a tendency to warm climate. Many studies have been carried out incorporating the different factors into numerical models used to predict future conditions based on various assumptions, such as the magnitude of future greenhouse gas emissions and particulate emissions. Most of these studies have concluded that the effects of the greenhouse gases will dominate over countering effects, hence predicting climate warming (Collins *et al.*, 2013; Kirtman *et al.*, 2013; Wolff *et al.*, 2014).

Predictions of warming from human activities go back at least to Svante Arrhenius (1859-1927), who in 1896 calculated the predicted amount of warming from a doubling or tripling of CO_2 and for increases to 150% and 250% and decreases to 67% of the values at the time (Arrhenius, 1896). Arrhenius was living in a century when Europe was emerging from the centuries-long period of cold conditions termed the Little Ice Age and understandably welcomed the anticipated warming, considering it a positive impact of human activities (Weart, 2003).

Today it is widely thought that if warming continues to the anticipated levels, the favorable aspects, like fewer deaths from freezing and more CO_2 for plant photosynthesis, will be outweighed by the unfavorable aspects, like sea level rise and more deaths from heat stroke. Not everyone agrees either with the projected warming or with the expectation that warming would be more unfavorable than favorable, but the scientific consensus for those views is strong, as reflected in the 2013 report of the Intergovernmental Panel on Climate Change (IPCC) (Collins *et al.*, 2013; Kirtman *et al.*, 2013) and in a 2014 overview on climate change from the Royal Society and the U.S. National Academy of Sciences (Wolff *et al.*, 2014).

In light of the expected warming, sea ice has long been expected to decrease (Parkinson and Kellogg, 1979; Collins *et al.*, 2013), although in some cases with a much greater decrease predicted for the Arctic than for the Antarctic (Gordon and O'Farrell, 1997). The 2013 summary predictions from the IPCC include that it is "very likely" that Arctic sea ice will continue to decrease and that it is "expected, but with low confidence" that Antarctic sea ice will decrease (Collins *et al*., 2013).

Observational Record

Records of atmospheric CO_2 show an extremely systematic annual cycle and upward trend. In fact, it is so systematic that in the iconic Mauna Loa curve, started in 1957 by Charles David Keeling at the Mauna Loa Observatory in Hawaii and continued since then by Keeling and others, almost every year shows higher CO_2 values than the previous year (http://www.esrl.noaa.gov/gmd/obop/mlo/). The temperature record since the late 1800s shows the expected upward trend in the long term; but it is nowhere near as systematic as the Mauna Loa CO_2 record, instead showing many years cooler than the previous year and little warming since 1998 (*e.g.*, Hansen *et al*., 2010; IPCC, 2013). The fact of many years having cooler conditions than the previous year was fully expected, on account of the well-known facts of many differing influences on the climate and much interannual variability. However, the lack of marked warming since 1998 was not expected and has added to the ammunition of those unconvinced by the model predictions of upcoming serious problems with further warming.

As detailed in the following subsections, the sea ice records for both polar regions are far more similar to the global temperature record than to the CO_2 record in terms of showing considerable interannual variability and some significant changes outside of the model predictions, along with a long-term trend, at least in the Arctic, that is in large part qualitatively in line with the predictions. The next two subsections provide details on the sea ice record for the period November 1978 – December 2013, as determined from the data of the SMMR, SSMI, and SSMIS satellite passive-microwave instruments.

Arctic Sea Ice

In the Arctic, annual maximum sea ice extent typically comes in March and minimum sea ice extent typically comes in September, with an average March ice extent of 15,200,000 km^2 over the 1979-2013 period and an average September ice extent of 6,360,000 km^2 over the same period. The March ice covers not just the Arctic Ocean but many of the surrounding seas and bays, while the September ice is confined largely to the central Arctic, the Canadian Archipelago, and the northern portion of the Greenland Sea to the east of Greenland (Figure 1). The smallest daily ice extent over the 35 years was 3,400,000 km^2, which occurred on September 16, 2012, and the largest daily ice extent was 16,300,000 km^2, which occurred on March 1, 1979.

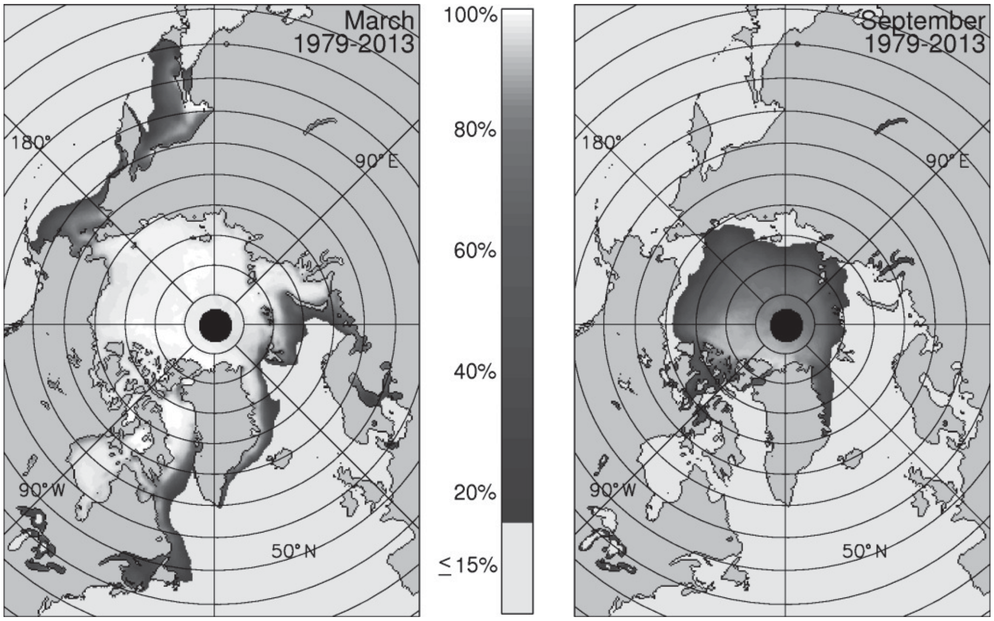

Figure 1. Average March and September sea ice concentrations in the Arctic region over the period 1979-2013, as derived from satellite passive-microwave SMMR, SSMI, and SSMIS data.

Because of the magnitude of the annual cycle, this cycle dominates plots of multi-year time series of either monthly average or daily average ice extents (*e.g.*, Figure 2). However, when the annual cycle is removed, as done in Figure 3 by taking monthly deviations, a clear trend emerges, showing decreasing Arctic sea ice coverage over the course of the satellite record since the late 1970s (Figure 3). The downward trend was apparent by the middle and late 1990s (Johannessen *et al*., 1995; Parkinson *et al*., 1999), although it has become far more convincing since then (*e.g.*, Figure 3). The trend (slope of the line of least squares fit) and standard deviation for the November 1978 - December 2013 period is -53,800 ± 1,900 km^2/yr. This equates to an areal loss of ice extent each year greater than the area of the country of Costa Rica or the combined area of the states of

Vermont, New Hampshire, and Rhode Island. When the annual cycle is removed instead by taking yearly averages, the trend is nearly identical to the trend calculated from monthly deviations, although with a larger standard deviation, the yearly average trend for 1979-2013 being -53,900 ± 3,800 km^2/yr (-4.3 ± 0.3 %/decade). (Note that the yearly average trend does not include the data from November and December 1978, whereas the monthly-deviation trend in Figure 3 does include those first two months of the SMMR record.)

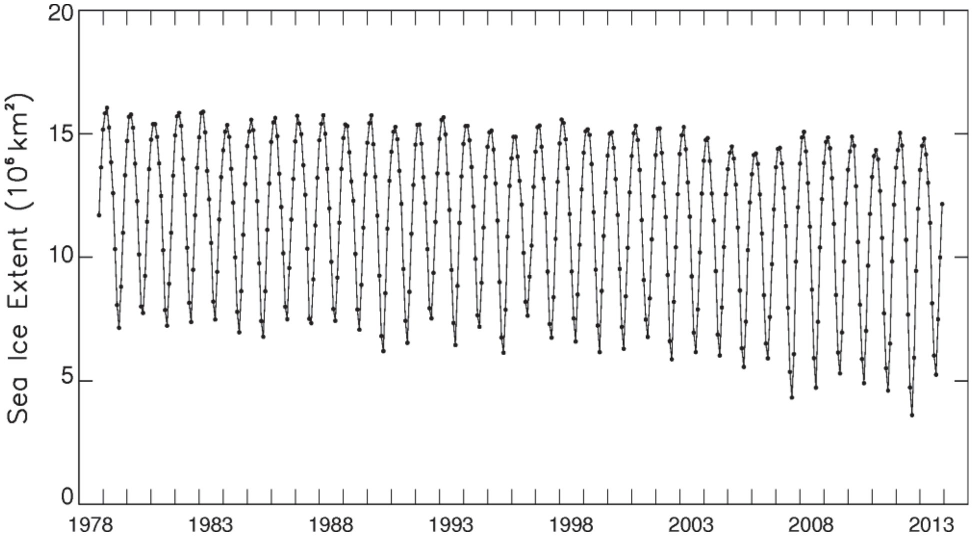

Figure 2. Arctic monthly average sea ice extents, November 1978 – December 2013, as derived from SMMR, SSMI, and SSMIS data.

The downward trend in Arctic sea ice coverage occurs in every season and every month, with September being the month that has experienced the greatest declines. For September, the 35-year trend, 1979-2013, is -87,300 ± 9,300 km^2/yr (-11.1 ± 1.2 %/decade). Even for May, which is the month with the lowest magnitude trend, the value is a sizeable -29,900 ± 4,300 km^2/yr (-2.2 ± 0.3 %/decade).

The fact of a downward trend in the Arctic ice cover was expected and is in line with a suite of additional changes in the Arctic in recent decades, including increasing temperatures, lessened land ice, thawing permafrost, greening tundra, greater coastal erosion, and altered predominant wind patterns (*e.g.*, Jeffries *et al*., 2013). The magnitude of the trend, however, has been greater than expected, at least in September (Stroeve *et al*., 2007), which is the month receiving the most attention, both because of being the month of minimum ice coverage, and hence the month most likely to become ice-free in coming decades, and because of having the greatest ice losses.

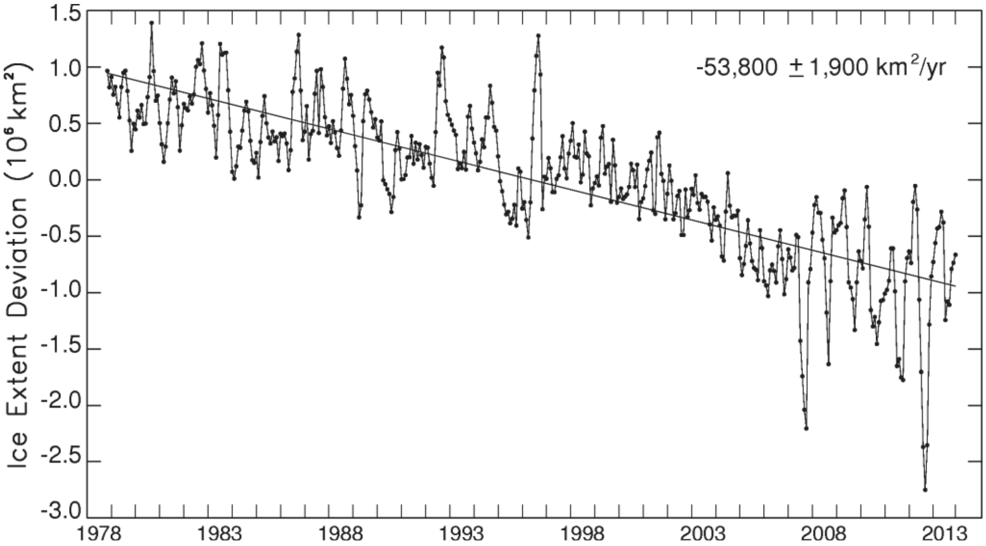

Figure 3. Arctic sea ice extent monthly deviations, November 1978 – December 2013, calculated from the data plotted in Figure 2. (Monthly deviations are calculated by subtracting from each individual month's ice extent the average ice extent for that month throughout the record. For example, the value plotted for the first point, November 1978, is the November 1978 ice extent minus the average ice extent for all 36 Novembers 1978-2013.)

Two particularly large decreases in ice coverage, in the summers of 2007 and 2012, stand out on the plot of monthly ice-extent deviations (Figure 3). Both of these have generated interest among scientists as well as various media outlets. The plummeting of the Arctic ice extent in 2007 was astonishing to sea ice experts, as it was such a dramatic change from anything seen before in the satellite record (Figure 3), descending to 76 % of the lowest recorded ice extent in any previous year. Studies examining this decrease generally conclude that its unusual magnitude involved a combination of factors, including that the ice cover was weakened from decades of ice reductions ("preconditioning") and that the Arctic weather conditions in the late summer of 2007 were warmer than normal and had predominant wind directions that pushed the ice in one direction, toward the northern Greenland and Canadian coasts, leaving ice-free waters behind (Comiso *et al*., 2008; Lindsay *et al*., 2009).

In 2012, the Arctic ice cover plummeted even further than in 2007, after several years with some rebounding from the 2007 then-record minimum (see Figures 2 and 3). Here too, analysis of the conditions suggest that the ice decreases were caused by a combination of preconditioning and weather, with a large storm in early August 2012 helping to speed the seasonal August retreat of the ice (Simmonds and Rudeva, 2012; Parkinson and Comiso, 2013). In this case, however, the decay to a new minimum might well have occurred even without the early August storm, as simulated in a numerical modeling study by Zhang *et al*. (2013). Zhang and his colleagues reduce the surface wind speeds in their numerical model by 50% for the August 5-9 period of the storm, then compare the results with a control case incorporating the full strength of the storm. They conclude, in part, that the storm had a major impact on the ice during the period of the storm but that even without the storm, the ice cover would have reached a new record low (Zhang *et al*., 2013).

Antarctic Sea Ice

Like the Arctic sea ice, Antarctic sea ice undergoes a very large annual cycle and has considerable interannual variability. In fact, the annual cycle is even larger in the Antarctic than in the Arctic. In the Antarctic, annual minimum ice coverage typically comes in February, in the midst of the austral summer, and maximum ice coverage typically comes in September, at the end of the austral winter. The average February ice extent over the 1979-2013 period is 3,100,000 km^2, even lower than the record minimum (so far) in the Arctic, and the average September ice extent is 18,500,000 km^2, well above the Arctic's record maximum. The Antarctic's February ice is confined largely to the near-coastal region, with the greatest expanse of ice occurring to the immediate east of the Antarctic Peninsula, in the western Weddell Sea, while the September ice extends much farther north, even equatorward to beyond 55ºS just east of the Greenwich meridian, in the far eastern Weddell Sea (Figure 4). The smallest daily ice extent in the Antarctic over the 35 years was 2,300,000 km^2, which occurred on February 27, 1997, and the largest daily ice extent was 19,600,000 km^2, which occurred on October 1, 2013, for a full range of 17,300,000 km^2, 34% higher than the corresponding 12,900,000 km^2 range for the Arctic.

As in the Arctic, the large annual cycle dominates plots of time series of Antarctic monthly average or daily average ice extents (*e.g.*,

Figure 5) and a clear trend appears after removing the annual cycle through calculating monthly deviations (Figure 6). However, in the Antarctic case, the trend is toward increasing rather than decreasing ice coverage (Figure 6). The trend in this case is 18,600 ± 2,100 km^2/yr. Once again, when yearly averages are calculated, the resulting trend, at 18,900 ± 4,000 km^2/yr (1.67 ± 0.35 %/decade), is close to the trend calculated through monthly deviations, and every month has a trend of the same sign, in the Antarctic case all positive. In the Antarctic, the month with the largest trend for the 35-year period is December, at 29,800 ± 10,100 km^2/yr (3.0 ± 1.0 %/decade), and the month with the smallest trend is February, at 10,600 ± 6,000 km^2/yr (3.65 ± 2.06 %/decade), *i.e.*, substantial trends but considerably smaller in magnitude than the trends for the Arctic.

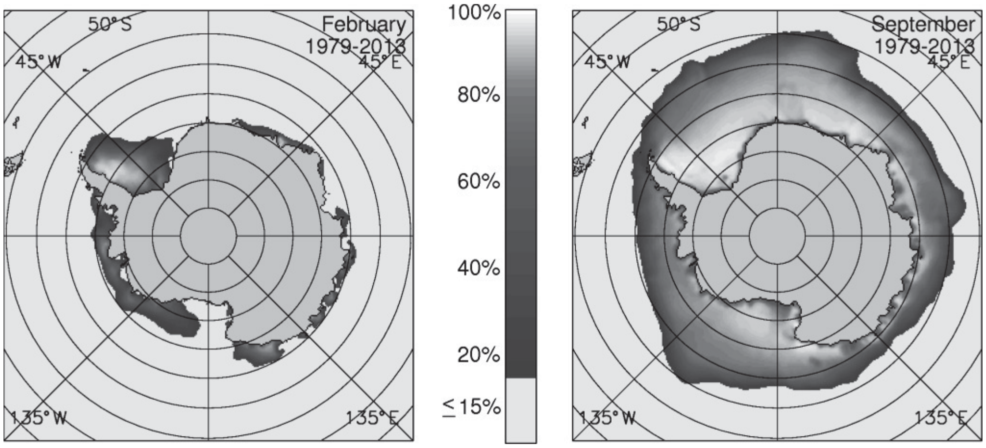

Figure 4. Average February and September sea ice concentrations in the Antarctic region over the period 1979-2013, as derived from satellite passive-microwave SMMR, SSMI, and SSMIS data.

Besides the major contrast that the Arctic has lost ice while the Antarctic has gained ice since the late 1970s, another important difference is that in the Antarctic there exists a sizeable region with significant ice trends opposite in sign to the trends for the Antarctic as a whole. This is the region of the Bellingshausen/Amundsen Seas to the west of the Antarctic Peninsula. In this region, and also in a smaller region directly to the east of the Peninsula, in the western Weddell Sea, the sea ice has retreated, both decreases corresponding well with temperature increases that have been reported along the Antarctic Peninsula (e.g., O'Donnell *et* *al*., 2011). The sea ice decreases in the Bellingshausen/Amundsen Seas have a trend in monthly deviations of -6,000 ± 1,100 km^2/yr (and a yearly average trend of -5,700 ± 2,200 km^2/yr, equating to -3.7 ± 1.4 %/decade), partly offsetting the increases around the rest of the Antarctic continent. (In the Arctic, there is also one region with trends of opposite sign to the overall Arctic trends, but for that region, the Bering Sea, the trends are much smaller in magnitude, at only 1,000 ± 400 km^2/yr in monthly deviations and 900 ± 800 km^2/yr in yearly averages.)

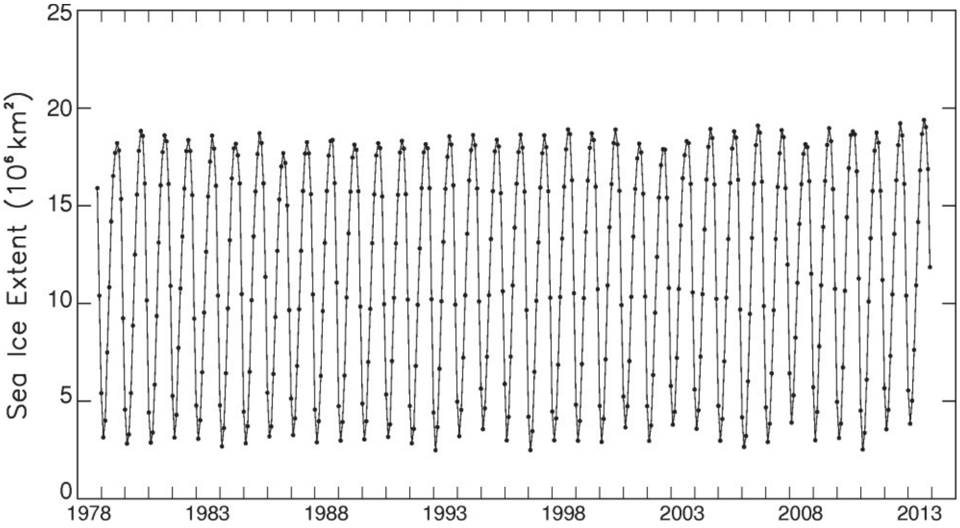

Figure 5. Antarctic monthly average sea ice extents, November 1978 – December 2013, as derived from SMMR, SSMI, and SSMIS data.

Because the increases in overall Antarctic sea ice coverage were unexpected, several attempts have been made to explain them. For this, the pattern of changes in the Antarctic ice have been informative. In particular, the largest ice decreases have occurred in the region of the Bellingshausen/Amundsen Seas and the largest ice increases have occurred immediately to the west of that region, in the Ross Sea. This pattern suggests the possible impact of increased cyclonic (clockwise in the Southern Hemisphere) atmospheric flow centered on the Amundsen Sea. Thompson and Solomon (2002) and Turner *et al*. (2009) suggest a possible connection with stratospheric ozone depletion and the resulting atmospheric circulation changes. This remains a possibility, although in a climate modeling study Sigmond and Fyfe (2010) found that stratospheric ozone depletion led to decreased overall Antarctic sea ice, at least in their model. The various possible causes for the Antarctic sea ice increases and pattern of increases and decreases remain areas of active research.

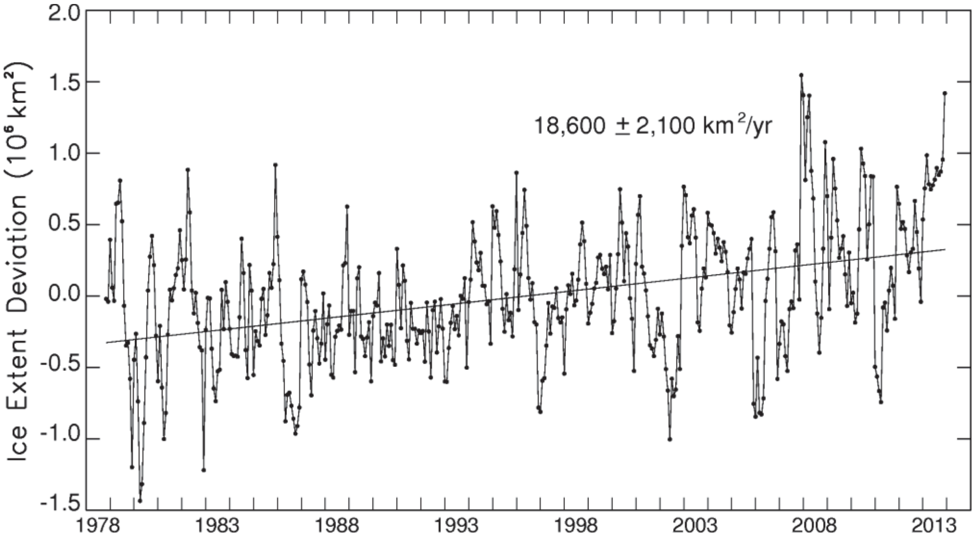

Figure 6. Antarctic sea ice extent monthly deviations, November 1978 – December 2013, calculated from the data plotted in Figure 5.

Discussion

There are many ways in which the record of sea ice coverage (*e.g.*, previous section) can be seen as a microcosm of the record of what has happened in the larger climate system. Some major commonalities on the technical side are:

- The records prior to satellites were quite incomplete.
- The records from satellites are imperfect but are much improved over the pre-satellite records.
- There are robust mainstream predictions. These predictions, from a wide range of models, include global warming overall and sea ice decreases.
- Observations in recent decades are partly but not fully in line with the predictions. This includes global warming overall but with spatial differences and a very non-monotonic upward trend and sea ice decreases overall but with sea ice increases in the

Antarctic and non-monotonic decreases in the Arctic that are occurring faster than the predictions.

- Considerable effort has been expended to explain unexpected features of the observations. This includes studies of the warming hiatus since 1998 (*e.g.*, Meehl *et al*., 2011; Clement and DiNezio, 2014) and of the Antarctic sea ice increases since the late 1970s (*e.g.*, Turner *et al*., 2009; Sigmond and Fyfe, 2010).

In addition to the technical commonalities, other key commonalities include:

- The mainstream view is that the minuses from the predicted changes will outweigh the pluses. For instance, the increase in deaths from heat stroke, dislocations from sea level rise, ocean acidification, and other minuses from warming and greenhouse gas increases are expected to outweigh the decrease in deaths from freezing, the increased CO_2 for photosynthesis, and other pluses from increased greenhouse gases and warming. Similarly, the minuses from sea ice decreases, such as lessened reflectance of solar radiation and habitat damage for polar bears and other animals dependent on sea ice, are expected to outweigh the pluses, such as opening shipping lanes through the Arctic (with both pluses and minuses). In the cases of both warming and sea ice decreases, not everyone agrees that the minuses would outweigh the pluses, but the mainstream view does say so.

- Public discussion and media attention have at times overhyped different aspects of the issues and increased polarization. Polarization on the seriousness of expected warming has been extreme, ranging from statements that the situation will be catastrophic by the middle of the current century if we fail to change course to statements that there is nothing to worry about from coming changes because they are likely to be beneficial rather than detrimental. Sea ice has not generated the same level of polarization, but still it has generated strikingly erroneous statements, such as assertions in August 2000 that ice-free conditions right at the North Pole were occurring for the first time in 50 million years (see discussion in Parkinson, 2010).

The overhyping of results and related polarization at times hinder the balanced discussion needed for making wise policy decisions. They also sometimes obscure the progress that has been made. Helped tremendously by advances in computer capabilities, both the numerical models and the measurement techniques have improved tremendously over the past several decades, and these have both helped to advance the understanding of the Earth system. We cannot be certain about what will happen in the future, and indeed there could be significant surprises left to come, but the measurements show quite convincingly that the greenhouse gas CO_2 has increased at least since 1957, when measurements began at the Mauna Loa Observatory, that global temperatures have warmed since the 1880s, that Arctic sea ice has decreased overall since late 1978, when the multi-channel satellite passive-microwave record began, and that although Antarctic sea ice has increased overall since late 1978, those increases are far less than the sea ice decreases in the Arctic.

Acknowledgements

The author thanks Don Cavalieri for many years of collaboration in updating the satellite passive-microwave data sets, Nick DiGirolamo for help both in updating the data and in generating the figures, and the NASA Cryospheric Sciences Program for funding the work.

References

Anderson, D. M., E. M. Mauk, E. R. Wahl, C. Morrill, A. J. Wagner, D. Easterling, and T. Rutishauser, 2013: Global warming in an independent record of the past 130 years, *Geophys. Res. Lett.*, 40, 189-193, doi:10.1029/2012GL054271.

Arrhenius, S., 1896: On the influence of carbonic acid in the air upon the temperature of the ground, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, fifth series, 41 (251), 237-276.

Cho, K., N. Sasaki, H. Shimoda, T. Sakata, and F. Nishio, 1996: Evaluation and improvement of SSM/I sea ice concentration algorithms for the Sea of Okhotsk, *J. Remote Sens. Jpn.*, 16 (2), 47–58.

Clement, A., and P. DiNezio, 2014: The tropical Pacific Ocean – Back in the driver's seat?, *Science*, 343 (6174), 976-978.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W. J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A. J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. In: IPCC, 2013, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 1029-1136.

Comiso, J. C., 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.

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

Easterling, D. R., B. Horton, P. D. Jones, T. C. Peterson, T. R. Karl, D. E. Parker, M. J. Salinger, V. Razuvayev, N. Plummer, P. Jamason, and C. K. Folland, 1997: Maximum and minimum temperature trends for the globe, *Science*, 277 (5324), 364–367.

Gordon, H. B., and S. P. O'Farrell, 1997: Transient climate change in the CSIRO coupled model with dynamic sea ice, *Mon. Weather Rev*., 125, 875–907.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato, 1999: GISS analysis of surface temperature change, *J. Geophys. Res*., 104 (D24), 30,997–31,022.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change, *Rev. Geophys.*, 48, RG4004, doi:10.1029/2010RG000345.

Hurrell, J. W., S. J. Brown, K. E. Trenberth, and J. R. Christy, 2000: Comparison of tropospheric temperatures from radiosondes and satellites: 1979-98, *Bull. Amer. Meteorol. Soc.*, 81 (9), 2165-2177.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley], Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 1535 pp.

Jansen, E., J. Overpeck, K. R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W. R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba, and D. Zhang, 2007: Palaeoclimate. In Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom, pp. 433–497.

Jeffries, M. O., J. E. Overland, and D. K. Perovich, 2013: The Arctic shifts to a new normal, *Physics Today*, 66 (10), 35-40, doi:10.1063/PT.3.2147.

Johannessen, O. M., M. Miles, and E. Bjorgo, 1995: The Arctic's shrinking sea ice, *Nature*, 376 (6536), 126-127.

Kirtman, B., S. B. Power, A. J. Adedoyin, G. J. Boer, R. Bojariu, I. Camilloni, F. J. Doblas-Reyes, A. M. Fiore, M. Kimoto, G. A. Meehl, M. Prather, A. Sarr, C. Schar, R. Sutton, G. J. van Oldenborgh, G. Vecchi, and H. J. Wang, 2013: Near-term climate change: Projections and predictability. In: IPCC, 2013, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 953-1028.

Lindsay, R. W., J. Zhang, A. Schweiger, M. Steele, and H. Stern, 2009: Arctic sea ice retreat in 2007 follows thinning trend, *J. Climate*, 22, 165–176.

Mann, M. E., and P. D. Jones, 2003: Global surface temperatures over the past two millennia, *Geophys. Res. Lett*., 30 (15), 1820, doi:10.1029/2003GL017814.

Mann, M. E., R. S. Bradley, and M. K. Hughes, 1999: Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations, *Geophys. Res. Lett*., 26 (6), 759-762.

Mears, C. A., and F. J. Wentz, 2005: The effect of diurnal correction on satellite-derived lower tropospheric temperature, *Science*, 309 (5740), 1548-1551.

Meehl, G. A., J. M. Arblaster, J. T. Fasullo, A. Hu, and K. E. Trenberth, 2011: Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods, *Nature Climate Change*, 1, 360-364.

O'Donnell, R., N. Lewis, S. McIntyre, and J. Condon, 2011: Improved methods for PCA-based reconstructions: Case study using the Steig *et al*. (2009) Antarctic temperature reconstruction, *J. Climate*, 24, 2099–2115, doi:10.1175/2010JCLI3656.1.

Parkinson, C. L., 2010: *Coming Climate Crisis? Consider the Past, Beware the Big Fix*, Rowman & Littlefield Publishers, Lanham, Maryland, 411 pp., ISBN: 978-0-7425-5615-7.

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.

Parkinson, C. L., and J. C. Comiso, 2013: On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm, *Geophys. Res. Lett.*, 40, 1-6, doi:10.1002/grl.50349.

Parkinson, C. L., and W. W. Kellogg, 1979: Arctic sea ice decay simulated for a CO_2-induced temperature rise, *Climatic Change*, 2, 149-162.

Parkinson, C. L., J. C. Comiso, H. J. Zwally, D. J. Cavalieri, P. Gloersen, and W. J. Campbell, 1987: *Arctic Sea Ice, 1973-1976: Satellite Passive-Microwave Observations*, NASA SP-489, National Aeronautics and Space Administration, Washington, D.C., 296 pp.

Parkinson, C. L., D. J. Cavalieri, P. Gloersen, H. J. Zwally, and J. C. Comiso, 1999: Arctic sea ice extents, areas, and trends, 1978-1996, *J. Geophys. Res.*, 104 (C9), 20,837-20,856.

Rind, D., R. Healy, C. Parkinson, and D. Martinson, 1995: The role of sea ice in 2 x CO_2 climate model sensitivity. Part 1: The total influence of sea ice thickness and extent, *J. Climate*, 8 (3), 449-463.

Sigmond, M., and J. C. Fyfe, 2010: Has the ozone hole contributed to increased Antarctic sea ice extent?, *Geophys. Res. Lett*., 37, L18502, doi:10.1029/2010GL044301.

Simmonds, I., and I. Rudeva, 2012: The great Arctic cyclone of August 2012, *Geophys. Res. Lett*., 39, L23709, doi:10.1029/2012GL054259.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett*., 34, L09501, doi:10.1029/2007GL029703.

Thompson, D. W. J., and S. Solomon, 2002: Interpretation of recent Southern Hemisphere climate change, *Science*, 296 (5569), 895–899.

Turner, J., J. C. Comiso, G. J. Marshall, T. A. Lachlan-Cope, T. Bracegirdle, T. Maksym, M. P. Meredith, Z. Wang, and A. Orr, 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.

Walsh, J. E., and W. L. Chapman, 2001: 20th-century sea-ice variations from observational data, *Ann. Glaciol*., 33, 444-448.

Weart, S. R., 2003: *The Discovery of Global Warming*, Harvard University Press, Cambridge, Massachusetts, 228 pp.

Wolff, E., I. Fung, B. Hoskins, J. Mitchell, T. Palmer, B. Santer, J. Shepherd, K. Shine, S. Solomon, K. Trenberth, J. Walsh, and D. Wuebbles, 2014: *Climate Change: Evidence and Causes, An Overview from the Royal Society and the US National Academy of Sciences*, National Academy of Sciences, Washington, D.C., 36 pp.

Zhang, J., R. Lindsay, A. Schweiger, and M. Steele, 2013: The impact of an intense summer cyclone on 2012 Arctic sea ice retreat, *Geophys. Res. Lett*., 40, doi:10.1002/grl.50190.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, W. J. Campbell, F. D. Carsey, and P. Gloersen, 1983: *Antarctic Sea Ice, 1973-1976: Satellite Passive-Microwave Observations*, NASA SP-459, National Aeronautics and Space Administration, Washington, D.C., 206 pp.

Bio

Claire Parkinson is a climate scientist at NASA’s Goddard Space Flight Center, where her research emphasis is on polar sea ice and its connections to the rest of the climate system and on climate change. She is also Project Scientist for the Earth-observing Aqua satellite mission and has written several books, including ones on climate change, satellite observations, and the history of science. She is a member of the National Academy of Engineering, and a Fellow of the American Association for the Advancement of Science (AAAS) and Phi Beta Kappa.