The Arctic on the fast track of change

Mark C. Serreze[1]
Jennifer A. Francis[2]

1 Co-operative Institute for Research in Environmental Sciences, National Snow and Ice Data Center University of Colorado, Boulder, Colorado
2 Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey

Dramatic changes have occurred in the Arctic during recent decades. Not only has one of its most defining substances – sea-ice – declined, but shifts have been observed in nearly all aspects of the environment (e.g. Serreze *et al.* 2000). Climate models tell us that warming caused by increased concentrations of atmospheric greenhouse gases will be seen first and will be most pronounced in the Arctic. The primary basis of these projections is that the loss of sea-ice and snow-cover will expose more sunlight-absorbing surfaces so that the initial heating will be enhanced – a positive feedback in the climate system. As this feedback takes hold, warming should become especially strong over the Arctic Ocean in autumn and winter. Are we seeing the emerging signs of this 'Arctic amplification'?

A rapidly changing Arctic

Global average surface temperature has risen approximately 0.7 degC since the 1880s (Jones and Moberg 2003), which is generally interpreted as evidence of greenhouse warming. The rise in mean annual surface temperature averaged over northern high latitudes for the past 30 years or so has, in turn, been larger than for the globe or Northern Hemisphere as a whole (Polyakov *et al.* 2002). Although there have been only modest reductions in Northern Hemisphere snow-cover (Armstrong and Brodzik 2001; Comiso 2006), satellite records beginning in 1979 document a striking decline in the extent of floating sea-ice (Fig. 1), with extreme minima for every September since 2002 (Stroeve *et al.* 2005). The sea-ice cover also appears to be thinning (Rothrock *et al.* 2003; Lindsay and Zhang 2005). Other research documents warming of Arctic soils and permafrost, changes in vegetation from tundra to shrubs, and increased discharge from Arctic-draining rivers in Siberia (e.g. Peterson *et al.* 2000). Paleoclimate evidence suggests that Arctic temperatures in recent decades are the highest of the past 400 years (Overpeck *et al.* 1997). It is possible that the Arctic climate system is heading toward an entirely new state (Overpeck *et al.* 2005).

While this evidence is broadly consistent with early signs of Arctic amplification, several factors complicate the picture. Nearly all computer models used to simulate global climate predict an Arctic amplification as greenhouse gas concentrations continue to rise, but there are discrepencies between different models regarding the onset, seasonality, magnitude, and spatial patterns of surface temperature change (Holland and Bitz 2003). Efforts to document emerging signs of Arctic amplification from observations are hindered by sparse and often short records, especially over the Arctic Ocean, where comprehensive data are only available for about the past 25 years from drifting buoys and satellite observations.

The diagnosis (and prognosis) of change is also complicated by natural climate cycles. For example, the temperature trend from 1970 to present is clearly larger in the Arctic than that for the entire Northern Hemisphere, but the same calculation using data from the beginning of the twentieth century (while sparse in the early part of the record) reveals little difference between Arctic and Northern Hemisphere trends (Polyakov *et al.* 2002). Shifts in large-scale atmospheric circulation patterns, such as the Arctic Oscillation and Pacific Decadal Oscillation, explain part of the recent change. A shift in the Arctic Oscillation towards its positive mode, associated with lower surface pressures over the Arctic, especially in the vicininty of the Icelandic low, is linked to winter warming over Siberia

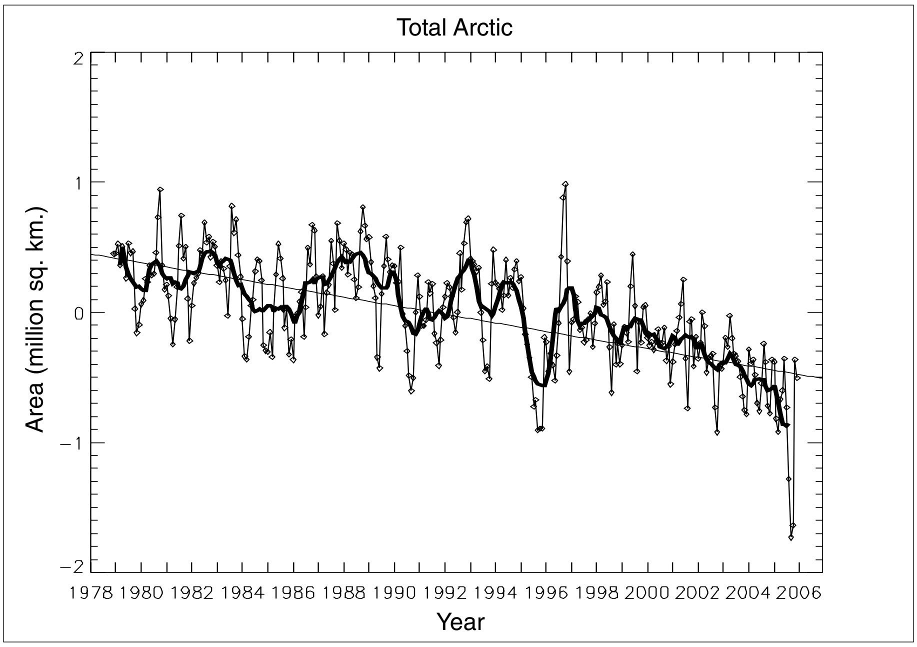

Fig. 1 Time-series of monthy anomalies (thin curve) in sea-ice extent for the Arctic, 1979 through 2004. The thick solid line represents 12-month running means while the thin solid line is the linear trend (courtesy of J. Stroeve, National Snow and Ice Data Center, Boulder, Colorado).

Weather – March 2006, Vol. 61, No. 3

from about 1970 through the mid-1990s and cooling in north-eastern North America (e.g. Hurrell 1996; Thompson and Wallace 1998). Accompanying changes in wind fields helped to break up the sea-ice cover (Rigor *et al.* 2002). Warming over Alaska from 1951 to 2001 can be linked in part to the abrupt shift in the Pacific Decadal Oscillation from its negative phase, characterised by a weak Aleutian low (1951–1976), to a primarily positive phase and a deeper low (1977–2001). The deep Aleutian low in the latter period transported warm, moist air into the region (Hartmann and Wendler 2005).

Large fluctuations in Arctic surface temperature are clearly evident in Fig. 2, which shows anomalies by time and for latitudes north of 30° N (from Johanessen *et al.* 2004). Figure 2 blends information from land stations, buoys drifting on sea-ice (1979 onwards), scattered Russian meteorological stations on the sea-ice (1950–1991) and data from the European Centre for Medium-Range Weather Forecasts ERA-40 re-analysis project. Although records are sparse in the early part of the record, it seems that the Arctic was cooler than average from about 1890 to 1920. From about 1920 to 1940, it warmed dramatically, apparently associated with changes in ocean circulation and sea-ice extent (Bengtsson *et al.* 2004). This was followed by another period of cooling and then warming that is especially strong from about 1990 to the present. The recent strong warming differs from the earlier episode in two important ways: it occurs at essentially all latitudes (similar figures show that it is part of a global signal), which is consistent with expected consequences of increased greenhouse gases; and it increases to the north into the Arctic Ocean, which is the fingerprint of Arctic amplification.

Figure 3 documents spatial patterns of high-latitude surface temperature trends since 1982 for each season, based on clear-sky retrievals from satellites. Warming clearly dominates. Summer changes over the ocean are small, as the melting sea-ice keeps air temperatures near the freezing point. However, rising temperatures during spring and autumn point to lengthening of the sea-ice melt season. Areas of strong warming over the ocean in winter, spring, and autumn (e.g. north of Alaska) correspond to areas where sea-ice is known to have retreated. While there is cooling over some land areas for this time period, trends calculated from 1970 to present exhibit warming. Part of this difference is associated with the shift in the Arctic Oscillation discussed previously, which is better captured in the longer record.

In the remainder of this paper, we examine some of the major points of debate surrounding Arctic amplification. We compare and contrast observed changes in surface temperature and sea-ice with expectations

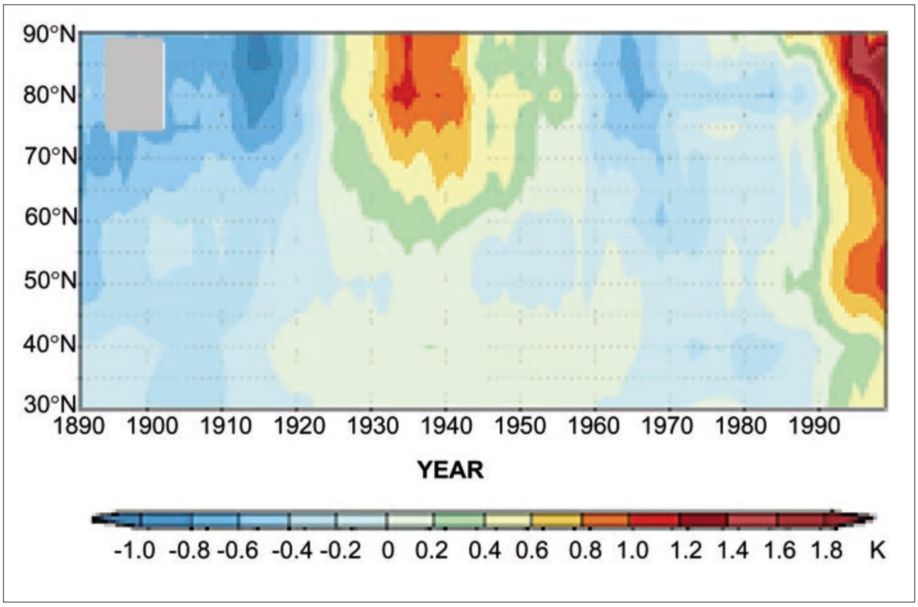

Fig. 2 Zonally-averaged time series of annual surface temperature anomalies (degC) from 1891 to 1999 north of 30 °N (from Johanessen et al. *2004).*

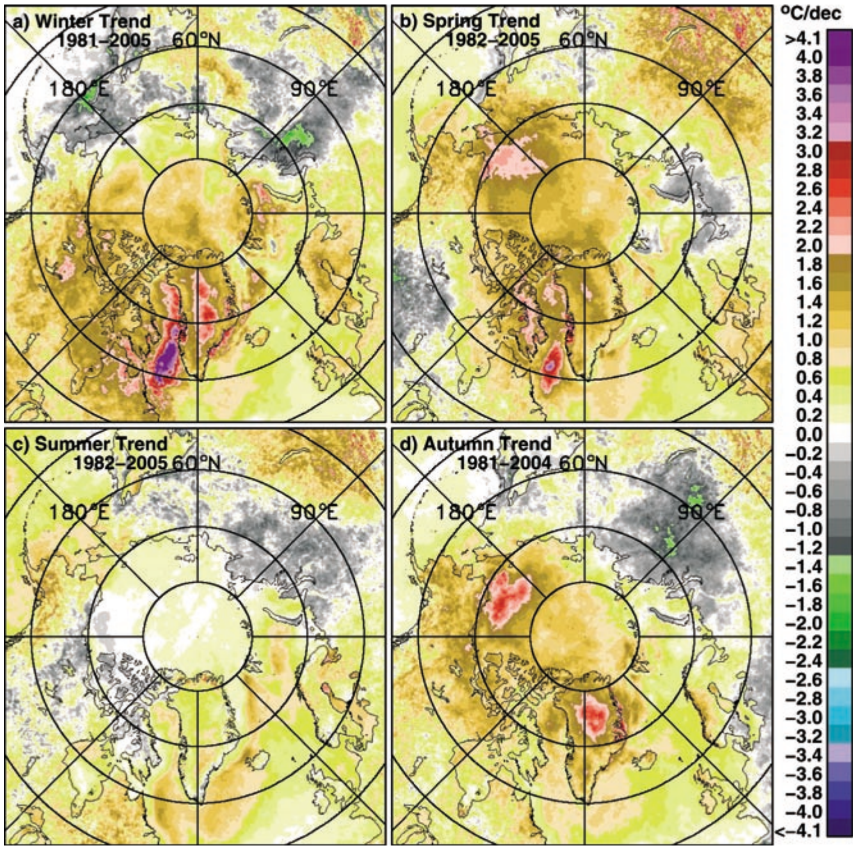

Fig. 3 Trends (degC per decade) in Arctic surface temperature by season from 1981 to 2005 based on clear-sky Advanced Very High Resolution Radiometer (AVHRR) retrievals (updated from Comiso, 2003, using improved retrieval algorithms).

based on physical reasoning and predictions from climate models. Further details are available in Serreze and Francis (2006).

What is Arctic amplification?

We begin by returning to the concept of a positive climate feedback, in which an initial change in the climate system triggers a chain of events that amplify the change. When we consider Arctic amplification in the context of increased greenhouse gases, we are primarily concerned with the so-called ice-albedo feedback. The simple view is that warming melts sea-ice and snow, which exposes surfaces (dark land and ocean) that are more effective absorbers of solar radiation (they have a lower albedo, or reflectivity). This increases the warming, meaning further melt of snow and ice, hence further warming. The feedback will be strongest in the polar regions, where most of the Earth's snow and ice is found, and where for much of the year one finds strong low-level temperature inversions (atmospheric temperature increasing with height), which limit mixing and thus focus the heating near the surface. The Arctic is more sensitive than the Antarctic because it is warmer and closer to the melting point, making it easier to remove ice and snow. However, when examined more closely, the feedback is not so simple. When the surface temperature is at the freezing point, a number of processes occur (e.g. Curry *et al.* 1995; Grenfell and Perovich 2004). When snow melts, the snow grains increase in size, which reduces the snow albedo, accelerates the melt rate, and further reduces the albedo. When sea-ice melts, puddles of water form on the surface that also reduce albedo. If more openings in the sea-ice form (leads and polynyas, the former are roughly linear openings while the latter are irregularly shaped), additional absorption of solar radiation will occur and enhance melt of both the edges and undersides of ice floes.

For the feedback to work, some of the extra heat that is absorbed must be carried through winter (when there is little or no solar energy entering the Arctic) to the following year. Interactions between heating of the Arctic Ocean and the extent and thickness of the floating sea-ice cover are especially important in this regard (Lindsay and Zhang 2005). From autumn through spring, sea-ice (which is typically 1–4 m thick) insulates the Arctic Ocean from the much colder atmosphere. If more sea-ice is lost during summer, the ocean will absorb more heat. Sea-ice will still grow in autumn and winter, but ice growth will be delayed, and the ice that does form will be thinner than it was the previous year. The insulating effect therefore weakens. Part of the extra heat that was added to the ocean in summer then escapes to warm the atmosphere, mostly through leads and polynyas. This loss of ocean heat explains why surface temperature changes are expected to be strongest over the ocean in autumn and winter. However, some of that extra ocean heat is retained, so that come spring, the thinner ice will begin to melt sooner, exposing a larger area of dark ocean in summer which will absorb even more solar energy. The heat content of the ocean rises further. Ice growth the next autumn and winter is again delayed, and the ice is even thinner. Again some of the ocean heat escapes to the atmosphere, but some is retained, perpetuating the feedback. At the same time, the 'direct' radiative effects of the greenhouse gases are becoming stronger. Ultimately, none of the sea-ice will survive the melt season, resulting in an ice-free Arctic Ocean in summer. Some climate models project that this will occur by about the year 2070.

Arctic amplification in global climate models

Arctic amplification comes through clearly in model simulations. As mentioned previously, however, there is disagreement among models as to the timing, location, and strength of the amplification. Holland and Bitz (2003) examined surface temperature changes predicted by 15 of these global climate models as carbon dioxide was increased by 1% per year. They compared 20-year averages of temperature at the time when carbon dioxide reached levels twice as high as today's values, and examined how these changes varied by latitude. Temperature increases in the Arctic were found to exceed those at low latitudes by 200% to 400%. The strongest warming tends to be focused over the Arctic Ocean, but the timing varies between autumn, winter and spring.

Five of these models participated in the Arctic Climate Impact Assessment program (ACIA 2004; www.acia.uaf.edu). The projections were forced by the B-2 emissions scenario – a 'middle of the road' expectation for future increases in greenhouse gas concentrations. The B-2 case is one of a number of scenarios developed by the Intergovernmental Panel on Climate Change (www.ipcc.ch) based on varying assumptions of population, economic and technological development. The model simulations were averaged over three 20-year time slices: 2010–2029 (emerging greenhouse state), 2040–2059 (intermediate greenhouse state), and 2070–2089 (mature greenhouse state). These simulations are shown as differences in surface temperature compared to the 1980–1999 reference period for each model.

Figure 4(a) illustrates the predicted change in autumn, represented by November values, for the intermediate greenhouse state (2040–2059) by averaging results from the five models. Warming exceeds 4 degC in most areas and is focused over the Arctic Ocean. Temperature changes projected for July are small (Fig. 4(b)) because the melting ice surface is constrained to the freezing point. When examined separately, four of the five models have maximum autumn warming over the Arctic Ocean, but the magnitudes and spatial patterns range widely. One model (from the National Center for Atmospheric Research) projects very little temperature change over the Arctic Ocean. In simulations for the mature greenhouse state (2070–2089, not shown), the Arctic Ocean warming is much more pronounced, although differences among models are still evident.

There are many reasons for differences among model simulations: horizontal and vertical resolution of their grids, initial specifications of sea-ice thickness, the way the atmosphere and oceans interact, and how they represent clouds and dust particles. The complex behaviours and seasonal cycles of sea-ice and snow-cover tend to be oversimplified. Furthermore, for any 20-year time slice, different models may be in different phases of their own natural oscillation patterns, and the strength and character of these patterns varies among models.

Predicted temperature changes for the emerging greenhouse state (2010–2029 as compared to the 1980–1999 reference period, i.e. the difference between two 20-year periods whose mid-points are 30 years apart) are more appropriate for comparisons with observed changes during recent decades. Warming is again strongest in autumn, but as expected, it is much less dramatic than for 2040 to 2059. In November, the warming averaged over the five models is focused in the eastern Arctic Ocean north of Siberia, and ranges from 1 to 2 degC. Some areas outside the Arctic show change of comparable magnitude. Observations (Fig. 3) show comparable autumn trends of over 1 degC per decade (over 2 degC change over the past 20+ years) for much of the Arctic Ocean. Model-to-model differences are again notable, but they agree that changes over the ocean in summer are small. Like observations, all of the models also predict areas of cooling. Pointing further to influences of natural variability, some of the models show that up to about 2025, there are years for which temperatures averaged over the entire Arctic are near or even lower than present-day values.

Are feedbacks involved in recent change?

Is the recent warming just another natural climate swing or are we seeing emerging

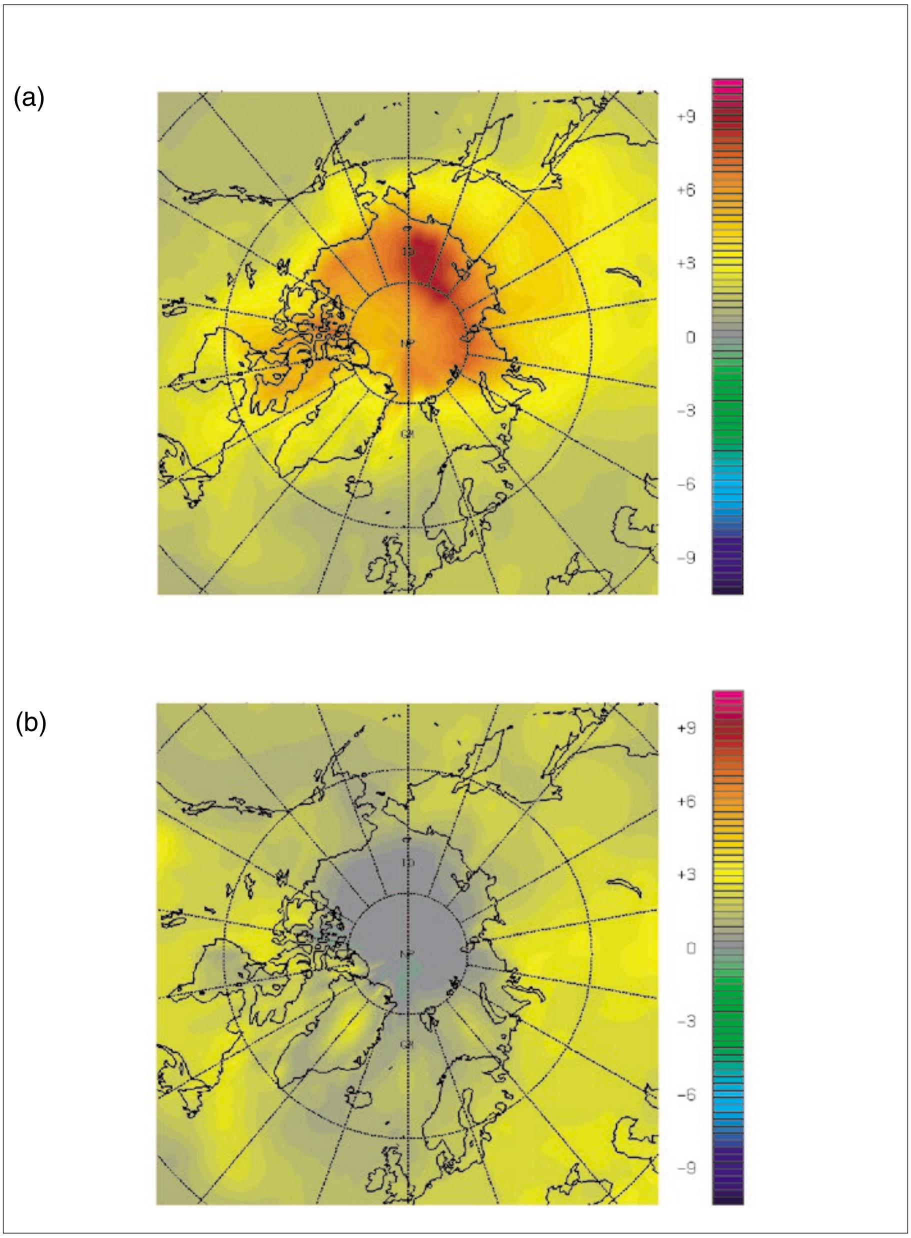

Fig. 4 Surface temperature changes for (a) November and (b) July from the ensemble of five models participating in the Arctic Climate Impact Assessment (ACIA) project. The plot displays mean surface temperatures (degC) predicted for the so-called intermediate greenhouse runs, 2040 to 2059, minus those for 1980 to 1999. The figures were obtained from the University of Illinois ACIA site at http://zubov.atmos.uiuc.edu/ACIA/.

signs of greenhouse-induced Arctic amplification? According to the ACIA models, it will be 30 to 40 years until the Arctic Ocean fingerprint of amplification becomes prominent. The next decade or so should see general warming with an emerging Arctic Ocean signal as sea-ice thins and retreats, accompanied by natural climate variability. The observed trajectory is similar. Recent Arctic warming is part of a global signal. Sea-ice is on the decline, which helps explain regional warming maxima over the Arctic Ocean. Natural variations are strongly expressed.

There are complicating factors. A number of studies argue that increased greenhouse gas concentrations will favour the positive mode of the winter Arctic Oscillation that promotes a warm Arctic (see the review by Gillett *et al.* 2003). While intriguing, observations show that the shift in the Arctic Oscillation to its strong positive state in the mid-1990s has been followed by a decline to more neutral conditions (see Fig. 2 in Overland, this issue, pp. 78–83). If these studies are right, this recent decline would be viewed as natural variability superimposed upon a greenhouse forcing. Issues also remain regarding links between the Arctic Oscillation, sea-ice and temperature.

As noted, the positive shift in the Arctic Oscillation contributed to strong warming over parts of the Arctic, especially Siberia. This resulted from altered patterns of heat transport. The positive shift also contributed to sea-ice loss and warming over the Arctic Ocean, but the link is different. As argued by Rigor *et al.* (2002), altered winds helped to physically break up winter sea-ice along the Siberian and Alaskan coasts. This led to thinner ice in spring that is more vulnerable to summer melt. This thinner ice also allowed for larger vertical heat fluxes to the atmosphere, contributing to regional warming over the Arctic Ocean.

As the Arctic Oscillation retreated from its positive state, the Arctic should arguably have seen recovery of the ice cover and a return towards cooler conditions. This has not been observed. The Arctic has continued to warm (Serreze and Francis 2006) and the loss of sea-ice has actually accelerated (Stroeve *et al.* 2005). September ice coverage in 2005 was the lowest yet seen in the satellite record (nsidc.org/data/seaice_index). Perhaps we are seeing persisting effects of the past high state. Rigor and Wallace (2004) argue that from 1989 to 1995, when the Arctic Oscillation was strongly positive, altered winds flushed out much of the Arctic's thicker ice into the North Atlantic, leaving it with thinner ice more liable to melt out in summer. Despite regression of the Arctic Oscillation, the Arctic has not recovered from this flushing episode.

More recent studies give a different view. Using an ice-ocean model driven by winds and temperatures produced by the National Center for Environmental Prediction, Rothrock and Zhang (2004) simulated sea-ice thickness and volume changes over the period 1948 to 1999. They conclude that although altered winds can be implicated for much of the rapid decline in thickness from the late 1980s through the mid-1990s, the overall downward trend is more closely related to the general rise in Arctic temperatures. Lindsay and Zhang (2005) and Francis *et al.* (2005) arrive at similar conclusions. Warming has led to more open water in summer, allowing more solar energy to be absorbed by the ocean. Less ice grows in autumn and winter, and melts more easily the following summer. In other words, the ice-albedo feedback is taking hold.

Conclusions

Arctic amplifiation has and will continue to be a prominent issue in the climate change debate. While many issues remain to be resolved, our guarded interpretation of the available evidence is that the Arctic is in a state of 'preconditioning', setting the stage for larger changes in coming decades. This preconditioning is characterised by general warming in all seasons, a longer melt season, and retreat and thinning of sea-ice, upon which the effects natural variability are superimposed. Before the projected widespread increase in surface temperatures over the Arctic Ocean can clearly emerge, more sea-ice must be removed. Extreme sea-ice losses in recent years seem to be sending a message: the ice-albedo feedback is starting. With greenhouse gas concentrations on the rise, there may be no counteracting mechanism in the climate system powerful enough to stop it.

Acknowledgements

This study was supported by NSF (J. Francis: OPP-0240791, M. Serreze: OPP-0242125, OPP-0229769, OPP-0229651) and NASA. We are grateful to Drs James Overland, Marika Holland, Cecilia Bitz, and Ron Lindsay for helpful discussions, to Elias Hunter for technical assistance, and to Dr John Walsh for use of the ACIA simulations. We also thank the anonymous reviewers for their many helpful suggestions.

References

ACIA (2004) *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press.

Armstrong, R. L. and Brodzik, M. J. (2001) Recent Northern Hemisphere snow extent: a comparison of data derived from visible and microwave sensors. *Geophys. Res. Lett.*, **28,** pp. 3673–3676

Bengtsson, L., Semenov, V. A., and Johannessen, O. M. (2004) The early twentieth-century warming in the Arctic – a possible mechanism. *J. Clim.*, **17,** pp. 4045–4057

Comiso, J. (2003) Warming trends in the Arctic from clear-sky surface temperature satellite observations. *J. Clim.*, **16,** pp. 3498–3510

Comiso, J. (2006) Arctic warming signals from satellite observations. *Weather*, **61,** pp. 70–76

Curry, J. A., Schramm, J. E. and Ebert, E. E. (1995) On the ice albedo climate feedback mechanism. *J. Clim.*, **8,** pp. 240–247

Francis, J. A., Hunter, E., Key, J. R. and Wang, X. (2005) Clues to variability in Arctic minimum sea-ice extent, *Geophys. Res. Lett.*, 32, L21501, doi: 10.1029/2005GLO24376

Gillett, N. P., Graf, H. F. and Osborn, T. J. (2003) Climate change and the North Atlantic Oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M. (Eds.) *The North Atlantic Oscillation: Climatic Significance and Environmental Impact,* Geophysical Monograph 134, American Geophyiscal Union

Grenfell, T. C., and Perovich, D. K. (2004) Seasonal and spatial evolution of albedo in a snow-ice-land- ocean environment. *J. Geophys. Res*., **109** (C01001), doi: 10.1029/2003JC001866

Hartmann, B. and Wendler, G. (2005) On the significance of the 1976 Pacific climate shift in the climatology of Alaska. *J. Clim.,* (In Press)

Holland, M. M and Bitz, C. M. (2003) Polar amplification of climate change in coupled models. *Clim. Dyn.,* **21,** pp. 221–232

Hurrell, J. W. (1996) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Geophys. Res. Lett.,* **23,** pp. 665–668

Johanessen, O. M., Bengtsson, L., Miles, M. W., Kuzmina, S. I., Semenov, V. A., Aledseev, G. V., Nagumyi, A. P., Zakharov, V. F., Bobylev, L. P., Pettersson, L. H., Hasselmann, K., and Cattle, H. P. (2004) Arctic climate change: observed and modelled temperature and sea-ice variability. *Tellus*, **56A,** pp. 328–341

Jones, P. D. and Moberg, A. (2003) Hemispheric and large scale surface air temperature variations: an extensive revision and an update to 2001. *J. Clim.,* **16,** pp. 206–223

Lindsay, R. W. and Zhang, J. (2005) The thinning of arctic sea-ice, 1988–2003: have we passed a tipping point? *J. Clim.* (In Press)

Overpeck, J. T., Sturm., Francis, J. A., Perovich, D. K., Serreze, M. C., Benner, R., Carmack, E. C., Chapin III, F. S., Gerlach, S. C., Hamilton, L. C., Hinzman, L. D., Holland, M., Huntington, H. P., Key, J. R., Lloyd, A. H., Macdonald, G. M., McFadden, J., Noone, D., Prowse, T. D., Schlusver, P. and Vörösmarty, ?. (2005) Arctic system on trajectory to new state. *Eos Trans.,* **86,** pp. 309, 312–313

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamourex, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A. and Zielinski, G. (1997) Arctic environmental change of the last four centuries. *Science*, **278,** pp. 1251–1256

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vorosmarty, C. J., Lammers, R. B., Shicklomanov, A. I., Shiklomanov, I. A. and Rahmstorf, S. (2002) Increasing river discharge to the Arctic Ocean. *Science*, **298,** pp. 2171–2173

Polyakov, I. V., Alekseev, G. V., Bekryaev, R. V., Bhatt, U., Colony, R., Johnson, M. A., Karklin, V. P., Makshtas, A. P., Walsh, D. and Yulin, A. V. (2002) Observationally based assessment of polar amplification of global warming. *Geophys. Res. Lett.,* **29,** 1878, doi: 1029/2001GL011111

Rigor, I. G. and Wallace, J. M. (2004) Variations in the age of Arctic sea-ice and summer sea-ice extent. *Geophys. Res. Lett.,* **31,** L09401, doi: 10.1029/2004GL019492

Rigor, I. G., Wallace, J. M. and Colony, R. L. (2002) Response of sea-ice to the Arctic Oscillation. *J. Clim.,* **15,** pp. 2648–2663

Rothrock, D. A., Zhang, J. and Yu, Y. (2003) The Arctic ice thickness anomaly of the 1990s: A consistent view from observations and models. *J. Geophys. Res.,* **108**(C3), 3083, doi: 10.1029/2001JC001208

Rothrock, D. A. and Zhang, J. (2004) Arctic Ocean sea-ice volume: What explains its recent depletion? *J. Geophys. Res.,* **110,** C01002, doi:10.1029/2004JC002282

Serreze, M. C. and Francis, J. A. (2006) The Arctic amplification debate. *Clim. Change* (In Press).

Serreze, M. C., Walsh, J. E., Chapin, F. S. III, Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W. C., Morison, J., Zhang, T. and Barry, R. G. (2000) Observational evidence of recent change in the northern high-latitude environment. *Clim. Change,* **46,** pp. 159–207

Stroeve, J. C., Serreze, M. C., Fetterer, F., Arbetter, T., Meier, M., Maslanik, J., and Knowles, K. (2005) Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004. *Geophys. Res. Lett.,* **32,** doi: 10.1029/2004GL021810

Thompson, D. W. J. and Wallace, J. M. (1998) The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res., Lett.,* **25,** pp. 1297–1300

Correspondence to: Dr Mark C. Serreze, Co-operative Institute for Research in Environmental Sciences, National Snow and Ice Data Center, Campus Box 449, University of Colorado, Boulder, CO 80309-0449

e-mail: serreze@kryos.colorado.edu

doi: 10.1256/wea.197.05