LETTERS

The central role of diminishing sea ice in recent Arctic temperature amplification

James A. Screen[1] & Ian Simmonds[1]

The rise in Arctic near-surface air temperatures has been almost twice as large as the global average in recent decades[1–3]—a feature known as 'Arctic amplification'. Increased concentrations of atmospheric greenhouse gases have driven Arctic and global average warming[1,4]; however, the underlying causes of Arctic amplification remain uncertain. The roles of reductions in snow and sea ice cover[5–7] and changes in atmospheric and oceanic circulation[8–10], cloud cover and water vapour[11,12] are still matters of debate. A better understanding of the processes responsible for the recent amplified warming is essential for assessing the likelihood, and impacts, of future rapid Arctic warming and sea ice loss[13,14]. Here we show that the Arctic warming is strongest at the surface during most of the year and is primarily consistent with reductions in sea ice cover. Changes in cloud cover, in contrast, have not contributed strongly to recent warming. Increases in atmospheric water vapour content, partly in response to reduced sea ice cover, may have enhanced warming in the lower part of the atmosphere during summer and early autumn. We conclude that diminishing sea ice has had a leading role in recent Arctic temperature amplification. The findings reinforce suggestions that strong positive ice–temperature feedbacks have emerged in the Arctic[15], increasing the chances of further rapid warming and sea ice loss, and will probably affect polar ecosystems, ice-sheet mass balance and human activities in the Arctic[2].

The Arctic region has long been expected to warm strongly as a result of anthropogenic climate change[1,2], owing to positive feedbacks in the Arctic climate system. It is widely accepted that changes in the surface albedo associated with melting snow and ice enhance warming in the Arctic[3,15,16], but other processes may contribute. In some global climate models, changes in cloud cover and atmospheric water vapour content are more important for Arctic amplification than the surface albedo feedback[17–19]. However, the same climate models significantly underestimate the recent Arctic sea ice decline[5] and surface warming[20], in part due to unrealistic negative feedbacks[20]. One reanalysis data set suggests that Arctic warming may have been enhanced by an increase in the atmospheric poleward transport of heat and moisture[8]. However, another reanalysis data set reveals a decrease in poleward heat transport since the early 1980s[21], which was a period of rapid sea ice declines[5–7]. Changes in Arctic storm behaviour[9] may have also enhanced the warming.

The vertical profile of recent warming can provide insight into its underlying causes. For instance, retreating snow and sea ice cover is expected to induce maximum warming at the surface[15,22], whereas changes in atmospheric poleward heat transport may cause warming with large vertical extent[8]. The ERA-40 reanalysis has been used to show[8] that Arctic warming trends aloft were of equal or greater magnitude than those at the surface, leading to the conclusion that atmospheric circulation changes were a more important cause of recent Arctic amplification than retreating snow and sea ice cover. However, notable discrepancies exist between the vertical profiles of warming in different reanalysis data sets[15]. The findings of ref. 8 have been contested[15,23–25], and concerns have been expressed over the validity of trends in ERA-40 that may reflect inhomogeneities or artefacts in the reanalysis rather than true climate signals[23,24].

Here we present results from a new reanalysis data set, ERA-Interim[26]. Some of the key improvements over the ERA-40 data set include higher resolution, improved model physics, a better hydrological cycle, four-dimensional variational data assimilation and variational bias correction of satellite radiance data[26]. The last feature is of particular relevance for this study because the scarcity of direct temperature measurements over the Arctic Ocean dictates that the majority of observations come from satellite radiances. The variational bias correction of satellite radiance data accounts for biases that change in time, for instance owing to changes in the observing network or drift of satellite orbits. ERA-Interim depicts more realistic Arctic tropospheric temperatures and probably suffers less from spurious trends than any previous reanalysis data set[26] (Supplementary Information). Furthermore, we build on the results of ref. 8 by including the post-2001 period, during which sea ice retreat has accelerated[5–7].

Arctic amplification is a clear feature of the warming over the 1989–2008 period based on the ERA-Interim reanalysis (Fig. 1). We diverge considerably from ref. 8 in finding that the maximum Arctic warming is at the surface and that warming lessens with height in all seasons except summer. This vertical structure suggests that changes at the surface, such as decreases in sea ice and snow cover, are the primary causes of recent Arctic amplification. The trends at the near-surface (herein the atmospheric levels at 950–1,000 hPa) are 1.6, 0.9, 0.5 and 1.6 °C per decade, averaged over the Arctic (herein latitudes 70–90° N) during winter, spring, summer and autumn, respectively. The near-surface warming is modest in summer because energy is used to melt remaining sea ice and warm the upper ocean[3,15]. The surface amplification, defined here as the ratio of the near-surface warming to that of the whole tropospheric column (below 300 hPa), averaged over the Arctic, is greatest in autumn, with a value of 2.3. The surface amplification is aided by strong low-level stability that limits vertical mixing. The corresponding values of surface amplification for winter and spring are 2.1 and 1.8, respectively. We note that amplified Arctic warming, above ~700 hPa, is confined to winter and is still consistently weaker than the near-surface warming (Fig. 1a). However, the presence of amplified warming aloft hints that processes in addition to the increased transfer of heat from the ocean to the atmosphere resulting from sea ice loss have had a contributing role in winter.

The surface amplified warming is closely linked to diminishing sea ice cover over the 1989–2008 period (linear trends of −2.6, −1.4, −5.8 and −7.9% per decade relative to the 1989–2008 means for winter, spring, summer and autumn, respectively). The components

[1]School of Earth Sciences, University of Melbourne, Melbourne, Victoria 3010, Australia.

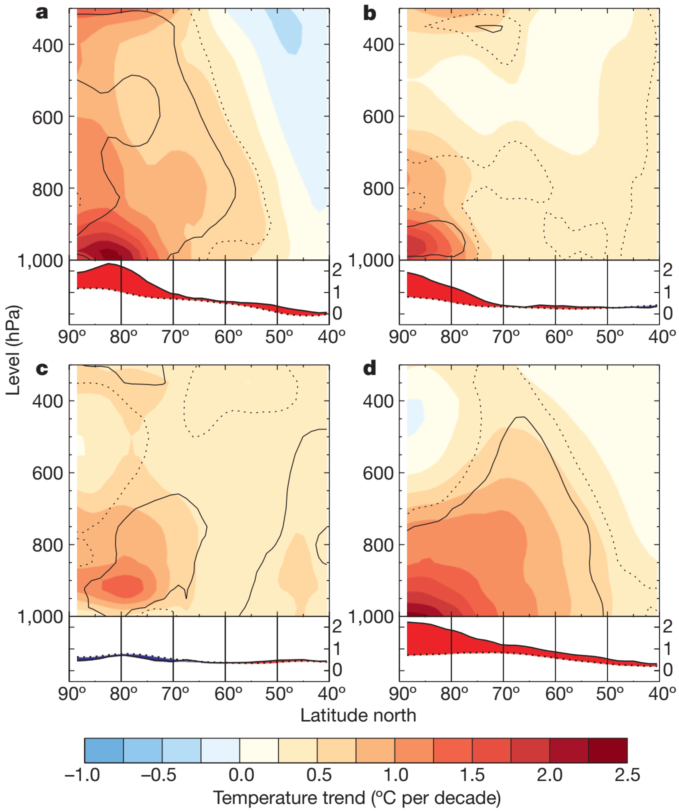

Figure 1 | Surface amplification of temperature trends, 1989–2008. Temperature trends averaged around circles of latitude for winter (December–February; **a**), spring (March–May; **b**), summer (June–August; **c**) and autumn (September–November; **d**). The black contours indicate where trends differ significantly from zero at the 99% (solid lines) and 95% (dotted lines) confidence levels. The line graphs show trends (same units as in colour plots) averaged over the lower part of the atmosphere (950–1,000 hPa; solid lines) and over the entire atmospheric column (300–1,000 hPa; dotted lines). Red shading indicates that the lower atmosphere has warmed faster than the atmospheric column as whole. Blue shading indicates that the lower atmosphere has warmed slower than the atmospheric column as a whole.

of the seasonal temperature trends that are linearly congruent with changes in sea ice (Fig. 2) show remarkable resemblance to the vertical profiles of the total temperature trends (Fig. 1). North of 70° N, a large portion of each total trend is linked to reduced Arctic sea ice cover (Fig. 2). The majority of the winter warming is associated with changes in sea ice cover (Fig. 2a) even though the sea ice declines are relatively small and the albedo feedback is weak during this season. Strong winter warming is consistent with the atmospheric response to reduced sea ice cover[22,27] and reflects the seasonal cycle of ocean–atmosphere heat fluxes[22]: during summer, the atmosphere loses heat to the ocean whereas during winter the flux of heat is reversed. Thus, reduced summer sea ice cover allows for greater warming of the upper ocean but atmospheric warming is modest (Fig. 2c). The interaction is undoubtedly two-way because warmer upper-ocean temperatures will further enhance sea ice loss. The excess heat stored in the upper ocean is subsequently released to the atmosphere during winter[20,22]. Reduced winter sea ice cover, in part a response to a warmer upper ocean and delayed refreezing[6,7], facilitates a greater transfer of heat to the atmosphere. The observed thinning of Arctic sea ice[28,29], albeit not explicitly represented in ERA-Interim, is also likely to have enhanced the surface heat fluxes.

Another potential contributor to the surface amplified warming could be changes in cloud cover. Clouds decrease the incoming short-wave (solar) radiation. However, this shading effect is partly offset, or exceeded, by a compensating increase in incoming long-wave

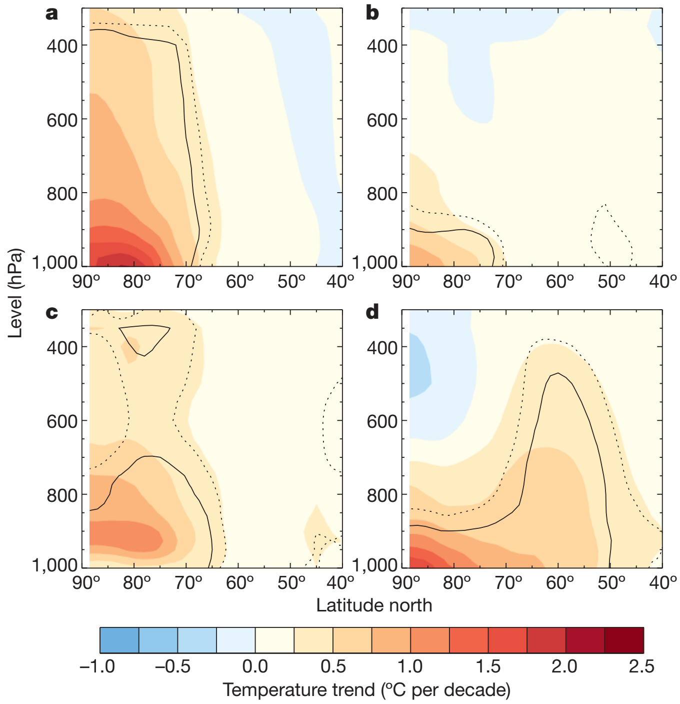

Figure 2 | Temperature trends linked to changes in sea ice. Temperature trends over the 1989–2008 period averaged around circles of latitude for winter (**a**), spring (**b**), summer (**c**) and autumn (**d**). The trends are derived from projections of the temperature field on the sea ice time series (Methods Summary). The black contours indicate where the ice–temperature regressions differ significantly from zero at the 99% (solid lines) and 95% (dotted lines) uncertainty levels.

radiation. In the Arctic, this greenhouse effect dominates during autumn, winter and spring (Fig. 3), in agreement with *in situ* observations[30]. In summer, the shading effect dominates in the lower-latitude regions of the Arctic basin whereas north of 80° N the two competing effects approximately cancel out (Fig. 3c). Spring is the only season that exhibits significant trends in Arctic average cloudiness in ERA-Interim, and these are negative (the ERA-Interim cloud-cover trends are consistent with satellite estimates; see Supplementary Information).

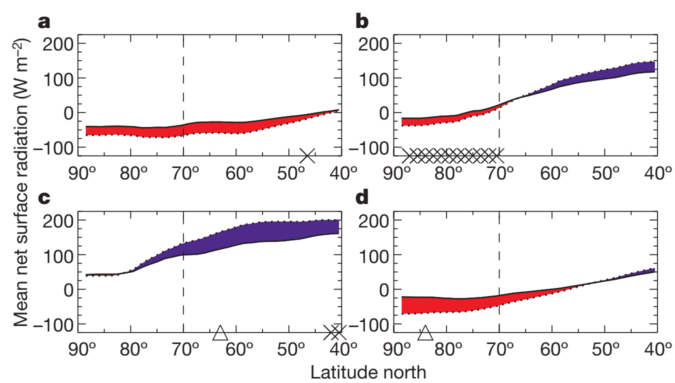

Figure 3 | Impacts of cloud-cover changes on the net surface radiation. Mean net surface radiation (short-wave plus long-wave) over the 1989–2008 period under cloudy-sky (solid lines) and clear-sky (dotted lines) conditions. Means are averaged around circles of latitude for winter (**a**), spring (**b**), summer (**c**) and autumn (**d**). The fluxes are defined as positive in the downward direction. Red shading indicates that the presence of cloud has a net warming effect at the surface. Blue shading indicates that the presence of cloud has a net cooling effect at the surface. The dashed lines show the approximate edge of the Arctic basin. Symbols show latitudes where increases (triangles) and decreases (crosses) in total cloud cover significant at the 99% uncertainty level are found.

Rather than contribute to the warming, decreased cloud cover would be expected to promote surface cooling because clouds have a warming influence in spring (Fig. 3b). It is likely that the temperature response to reduced cloud cover is exceeded by warming due to other processes. The radiative effect of cloud-cover changes is small in comparison with compensating changes in the temperature and humidity profiles associated with varying ice conditions[11]. We find that the large majority of spring warming occurs in the Siberian sector of the Arctic basin (not shown), where ice clouds are the predominant cloud type[12]. In ice-cloud-dominated regions, the radiative effects of changes in cloud cover are less important than changes in water vapour content[12]. In short, we find no evidence of changes in cloud cover contributing to recent near-surface Arctic warming.

A final consideration arises from model simulations which suggest that changes in atmospheric water vapour content may amplify Arctic warming[17–19]. Increases in water vapour are expected with increasing air temperatures and reduced sea ice cover[19,27]. In turn, water vapour is a powerful greenhouse gas[1] and can lead to further warming and sea ice loss. In ERA-Interim, specific humidity trends are found only during the summer and early autumn, and are confined to the lower part of the atmosphere (Fig. 4a). The largest humidity increases are found in the Arctic basin. An associated increase in incoming long-wave radiation has probably enhanced warming in summer and early autumn. It is of further interest to determine whether these increases in humidity are locally driven or are a result of increased moisture transport into the Arctic. It is worth noting that the humidity trends coincide with the months of lowest sea ice coverage and largest sea ice declines. The pronounced warming in winter and spring is not accompanied by increases in humidity. A large portion of each total humidity trend is linked to changes in sea ice (Fig. 4b) and, furthermore, to significant increases in the surface latent-heat flux (that is, evaporation) in the Arctic basin (Fig. 4a). The humidity increases at latitudes 50–65° N show weaker links to sea ice and are probably influenced by other processes. However, within the Arctic these lines of evidence support the notion that part of the humidity increase is driven by enhanced surface moisture fluxes associated with sea ice reductions.

The evidence from the past two decades, based on ERA-Interim, reveals that recent reductions in sea ice cover and thickness have been great enough to enhance Arctic warming strongly during most of the year. Our results suggest that the majority of the recent Arctic temperature amplification is due to diminishing sea ice cover. The amplification is strongest in the lowermost part of the atmosphere, where modified surface heat fluxes have their greatest influence. The emergence of strong ice–temperature positive feedbacks increases the likelihood of future rapid Arctic warming and sea ice decline.

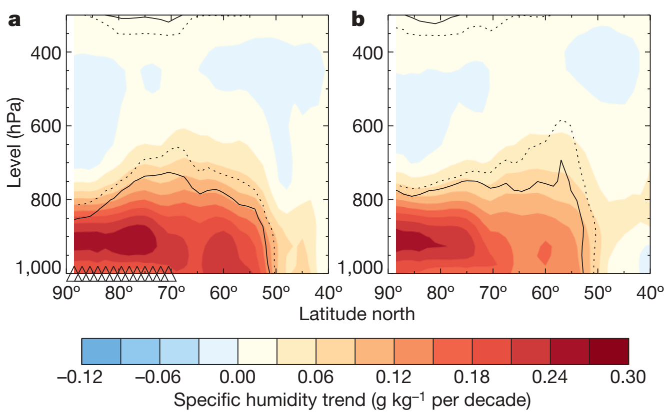

Figure 4 | Atmospheric moisture trends, 1989–2008. Specific humidity trends averaged around circles of latitude for June–October: total trends (**a**); trends that are linked to changes in sea ice (**b**). The black contours indicate where trends (**a**) or humidity–ice regressions (**b**) differ significantly from zero at the 99% (solid lines) and 95% (dotted lines) uncertainty levels. In **a**, triangles show latitudes where increases in the surface latent-heat flux significant at the 99% uncertainty level are found.

METHODS SUMMARY

The raw data we used were monthly mean fields from the ERA-Interim[26] reanalysis for the period 1989–2008. A discussion of the data quality and comparisons with the older ERA-40 reanalysis data set are given in the Supplementary Information. These data were averaged around circles of latitude (at 1.5° resolution). Standard seasonal means were computed and used in Figs 1, 2 and 3 (the winter mean for 1989 contains no data for December 1988), and June–October means were used in Fig. 4. We estimated trends using least-squares linear regression. The statistical significances of the regressions were calculated from a two-tailed t-test. Changes in sea ice cover were calculated by averaging sea ice concentrations over the Arctic Ocean (north of 70° N). To construct Fig. 2, we regressed the temperature field against the index of Arctic-wide sea ice cover. These regressions were then multiplied by the sea ice time series to give a projection of the temperature field onto the sea ice time series. The linear trends of these projections (Fig. 2) represent the temperature trends statistically linked to changes in sea ice cover. We used the same procedure for specific humidity data (Fig. 4b).

Caution is required when interpreting regressions between two variables that both show pronounced trends—as is the case with recent Arctic temperatures and sea ice cover. It is plausible that two variables linked statistically are physically independent in reality. To address this possibility, we recalculated the regressions using detrended data. We found that year-to-year variations in sea ice cover are linked to approximately the same patterns of temperature and humidity anomalies as found in the raw data. This gives us further confidence that the associations revealed here are physically meaningful.

Received 10 November 2009; accepted 12 March 2010.

1. Solomon, S. *et al.* (eds) *Climate Change 2007: The Physical Science Basis* (Cambridge Univ. Press, 2007).
2. Symon, C., Arris, L. & Heal, B. (eds) *Arctic Climate Impact Assessment* (Cambridge Univ. Press, 2004).
3. Serreze, M. C. & Francis, J. A. The Arctic amplification debate. *Clim. Change* **76,** 241–264 (2006).
4. Gillett, N. P. *et al.* Attribution of polar warming to human influence. *Nature Geosci.* **1,** 750–754 (2008).
5. Stroeve, J., Holland, M. M., Meir, W., Scambos, T. & Serreze, M. Arctic sea ice decline: faster than forecast. *Geophys. Res. Lett.* **34,** doi:10.1029/2007GL029703 (2007).
6. Serreze, M. C., Holland, M. M. & Stroeve, J. Perspectives of the Arctic's shrinking ice cover. *Science* **315,** 1533–1536 (2007).
7. Comiso, J. C., Parkinson, C. L., Gersten, R. & Stock, L. Accelerated decline in the Arctic sea ice cover. *Geophys. Res. Lett.* **35,** doi:10.1029/2007GL031972 (2008).
8. Graversen, R. G., Mauritsen, T., Tjernström, M., Källén, E. & Svensson, G. Vertical structure of recent Arctic warming. *Nature* **451,** 53–56 (2008).
9. Simmonds, I. & Keay, K. Extraordinary September Arctic sea ice reductions and their relationships with storm behavior over 1979–2008. *Geophys. Res. Lett.* **36,** doi:10.1029/2009GL039810 (2009).
10. Chylek, P., Folland, C. K. & Lesins, G. Dubey, M. K. & Wang, M. Arctic air temperature change amplification and the Atlantic multidecadal oscillation. *Geophys. Res. Lett.* **36,** doi:10.1029/2009GL038777 (2009).
11. Schweiger, A. J., Lindsay, R. W., Vavrus, S. & Francis, J. A. Relationships between Arctic sea ice and clouds during autumn. *J. Clim.* **21,** 4799–4810 (2008).
12. Francis, J. A. & Hunter, E. Changes in the fabric of the Arctic's greenhouse blanket. *Environ. Res. Lett.* **2,** doi:10.1088/1748–9326/2/4/045011 (2007).
13. Holland, M. M., Bitz, C. M. & Tremblay, B. Future abrupt reductions in the summer Arctic sea ice. *Geophys. Res. Lett.* **33,** doi:10.1029/2006GL028024 (2006).
14. Boé, J., Hall, A. & Qu, X. September sea ice cover in the Arctic Ocean projected to vanish by 2100. *Nature Geosci.* **2,** 341–343 (2009).
15. Serreze, M. C., Barrett, A. P., Stroeve, J. C., Kindig, D. N. & Holland, M. M. The emergence of surface-based Arctic amplification. *Cryosphere* **3,** 11–19 (2009).
16. Holland, M. M. & Bitz, C. M. Polar amplification of climate change in coupled models. *Clim. Dyn.* **21,** 221–232 (2003).
17. Winton, M. Amplified climate change: what does surface albedo feedback have to do with it? *Geophys. Res. Lett.* **33,** doi:10.1029/2005GL025244 (2006).
18. Lu, J. & Cai, M. Seasonality of polar surface warming amplification in climate simulations. *Geophys. Res. Lett.* **36,** doi:10.1029/2009GL040133 (2009).
19. Graversen, R. G. & Wang, M. Polar amplification in a coupled model with locked albedo. *Clim. Dyn.* **33,** 629–643 (2009).
20. Boé, J., Hall, A. & Qu, X. Current GCMs' unrealistic negative feedback in the Arctic. *J. Clim.* **22,** 4682–4695 (2009).
21. Smedsrud, L. H., Sorteberg, A. & Kloster, K. Recent and future changes of the Arctic sea-ice cover. *Geophys. Res. Lett.* **35,** doi:10.1029/2008GL034813 (2008).

22. Deser, C., Tomas, R., Alexander, M. & Lawrence, D. The seasonal atmospheric response to projected Arctic sea ice loss in the late twenty-first century. *J. Clim.* **23,** 333–351 (2010).
23. Thorne, P. W. Arctic tropospheric warming amplification? *Nature* **455,** E1–E2 (2008).
24. Grant, A. N., Brönnimann, S. & Haimberger, L. Recent Arctic warming vertical structure contested. *Nature* **455,** E2–E3 (2008).
25. Bitz, C. M. & Fu, Q. Arctic warming aloft is data set dependent. *Nature* **455,** E3–E4 (2008).
26. Dee, D. P. & Uppala, S. Variational bias correction of satellite radiance data in the ERA-Interim reanalysis. *Q. J. R. Meteorol. Soc.* **135,** 1830–1841 (2009).
27. Higgins, M. E. & Cassano, J. J. Impacts of reduced sea ice on winter Arctic atmospheric circulation, precipitation and temperature. *J. Geophys. Res.* **114,** doi:10.1029/2009JD011884 (2009).
28. Kwok, R. & Rothrock, D. A. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophys. Res. Lett.* **36,** doi:10.1029/2009GL039035 (2009).
29. Lindsay, R. W., Zhang, J., Schweiger, A., Steele, M. & Stern, H. Arctic sea ice retreat in 2007 follows thinning trend. *J. Clim.* **22,** 165–176 (2009).
30. Intrieri, J. M. *et al.* An annual cycle of Arctic surface cloud forcing at SHEBA. *J. Geophys. Res.* **107,** doi:10.1029/2000JC000439 (2002).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank N. Gillett and R. Graversen for comments on the manuscript. The ERA-Interim data were obtained from the European Centre for Medium-Range Weather Forecasts data server. Parts of this research were supported by funding from the Australian Research Council.

Author Contributions The analysis was performed and the manuscript written by J.A.S. Both authors contributed with ideas and discussions.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to J.A.S. (screenj@unimelb.edu.au).