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

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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 atmospheric greenhouse gas concentrations have driven Arctic and global average warming[1,4]. However, the underlying causes of Arctic amplification remain uncertain. The roles played by reductions in snow and sea ice cover[5-7], changes in atmospheric and oceanic circulation[8-10], cloud cover and water vapour[11,12] are still a matter of scientific 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 primarily consistent with reductions in sea ice cover. In contrast, changes in cloud cover have not contributed strongly to recent warming. Increases in atmospheric water vapour content, partially 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 played 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 with likely impacts on 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], due to positive feedbacks in 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 well 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 due to 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 1980's[21], a period of rapid sea ice declines[5,7]. Changes in Arctic storm behavior[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]. Graversen *et al.*[8], using the ERA-40 reanalysis, found that Arctic warming trends aloft were of equal or greater magnitude than 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 Graversen *et al.*[7] have been contested[15,23-25] and concerns 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 from the older ERA-40 data set include higher resolution, improved model physics, a better hydrological cycle, 4DVAR assimilation and variational bias correction of satellite radiance data[26]. The latter is of particular relevance for this study as 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 due to changes in the observing network or drift of satellite orbits. ERA-Interim depicts more realistic Arctic tropospheric temperatures and likely suffers less from spurious trends than any previous reanalysis data set[26] (see Supplementary Discussion). Furthermore, we build on the results of Graversen *et al.*[8] by including the post-2001 period, during which time 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 Graversen *et al.*[8] in finding that the maximum Arctic warming is at the surface and 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 near-surface (herein levels 950-1000 hPa) trends 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 which 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 approximately 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 played 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 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 the total trends are 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). Undoubtedly the interaction is two-way as 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 partially offset, or exceeded, by a compensating increase in incoming long-wave radiation. In the Arctic, this latter greenhouse effect dominates outside of summer (Fig. 3), in agreement with in situ observations[30]. In summer, the shading effect dominates in the lower latitude regions of the Arctic basin whilst the two competing effects approximately cancel out north of 80°N (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 Discussion]). Rather than contribute to the warming, decreased cloud cover would be expected to promote surface cooling as 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 to compensating changes in the temperature and humidity profiles associated with varying ice conditions[11]. We find the large majority of spring warming 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 that suggest 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 likely enhanced warming in summer and early autumn. It is of further interest to ascertain whether these increases in humidity are locally driven or 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 the total humidity trends are linked to changes in sea ice (Fig. 4b) and further to significant increases in the surface latent heat flux (i.e. evaporation) in the Arctic basin (Fig. 4a). The humidity increases at latitudes 50-65°N show weaker links to sea ice and are likely influenced by other processes. However, within the Arctic these lines of evidence support the notion that a fraction of the humidity increases are driven by enhanced surface moisture fluxes associated with sea ice reductions.

The evidence from the last two decades, based on ERA-Interim, reveals that recent reductions in sea ice cover and thickness have been sufficiently great to strongly enhance Arctic warming 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.

METHODS SUMMARY

The raw data 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 Discussion. These data were averaged around latitude circles (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-to-October means in Fig. 4. Trends were estimated using least-squares linear regression. The statistical significance 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 Figure 2, the temperature field was regressed 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 on to 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. The same procedure was used for specific humidity data (Fig. 4b). We note that 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 based on 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 are physically meaningful.

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

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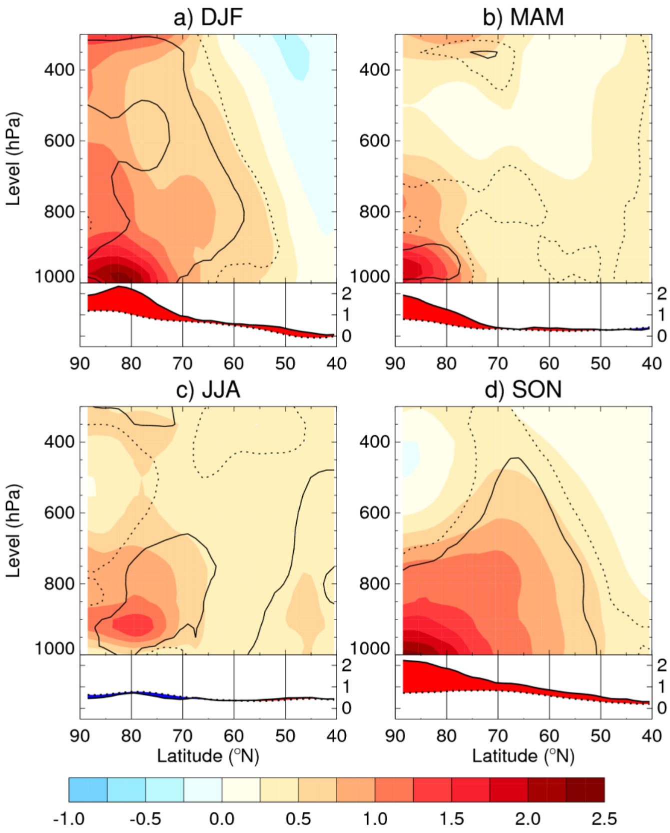

Figure 1. Surface amplification of temperature trends, 1989-2008. Temperature trends (°C per decade) are averaged around latitude circles and are shown for winter (**a**, December-February), spring (**b**, March-May), summer (**c**, June-August) and autumn (**d**, September-November). The black contours denote where trends differ significantly from zero at the 99% (solid lines) and 95% (dotted lines) levels. The line graphs show trends averaged over the lower part of the atmosphere (solid lines; 950-1000 hPa) and averaged over the entire atmospheric column (dotted lines; 300-1000 hPa). 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.

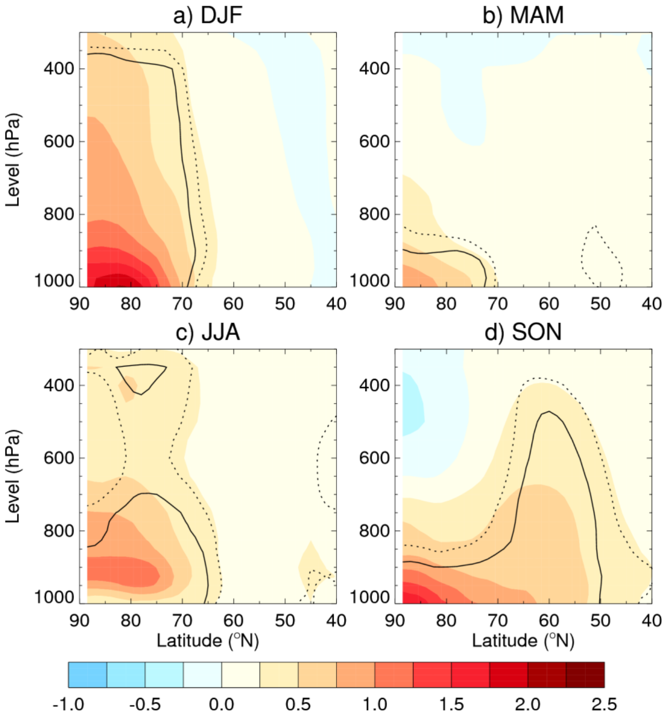

Figure 2. Temperature trends that are linked to changes in sea ice. Temperature trends (^{o}C per decade) over the 1989-2008 period are averaged around latitude circles and are shown for winter (**a**, December-February), spring (**b**, March-May), summer (**c**, June-August) and autumn (**d**, September-November). The trends are derived from projections of the temperature field on the sea ice time series (see Methods). The black contours denote where the temperature-ice regressions differ significantly from zero at the 99% (solid lines) and 95% (dotted lines) levels.

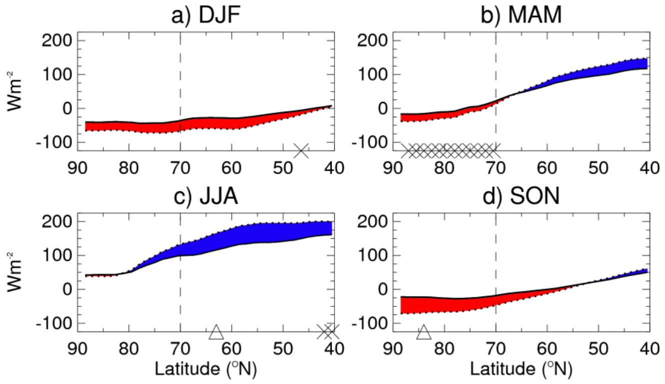

Figure 3. Impacts of cloud cover changes on the net surface radiation. Mean net surface radiation (Wm^{-2}; short-wave plus long-wave) over the 1989-2008 period under cloudy-sky (solid lines) and clear-sky (dotted lines) conditions. Means are averaged around latitude circles and shown for winter (**a**, December-February), spring (**b**, March-May), summer (**c**, June-August) and autumn (**d**, September-November). 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 along the x-axes show latitudes where significant (at the 99% level) increases (triangles) and decreases (crosses) in total cloud cover are found.

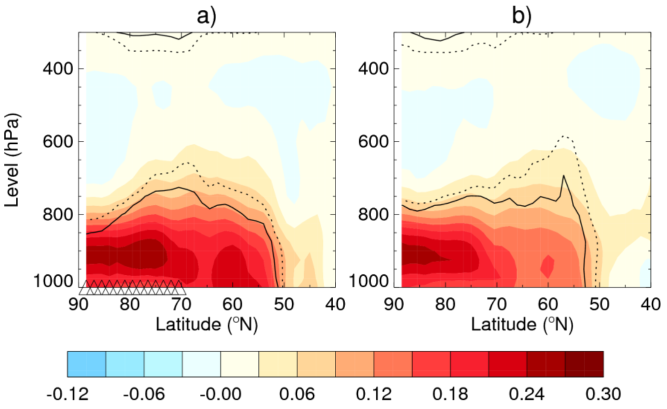

Figure 4. Atmospheric moisture trends, 1989-2008. Specific humidity trends (g kg^{-1} per decade) are averaged around latitude circles and are shown for June-October. **a**, total trends; **b**, trends that are linked to changes in sea ice. The black contours denote where trends (in **a**) or humidity-ice regressions (in **b**) differ significantly from zero at the 99% (solid lines) and 95% (dotted lines) levels. In **a**, triangles along the x-axis show latitudes where significant (at the 99% level) increases in the surface latent heat flux are found.