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Increasing fall-winter energy loss from the Arctic Ocean and its role in Arctic temperature amplification

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[1] Arctic surface temperatures have risen faster than the global average in recent decades, in part due to positive feedbacks associated with the rapidly diminishing sea ice cover. Counter-intuitively, the Arctic warming has been strongest in late fall and early winter whilst sea ice reductions and the direct ice-albedo feedback have been greatest in summer and early fall. To reconcile this, previous studies have hypothesized that fall/winter Arctic warming has been enhanced by increased oceanic heat loss but have not presented quantitative evidence. Here we show increases in heat transfer from the Arctic Ocean to the overlying atmosphere during October–January, 1989–2009. The trends in surface air temperature, sea ice concentration and the surface heat fluxes display remarkable spatial correspondence. The increased oceanic heat loss is likely a combination of the direct response to fall/winter sea ice loss, and the indirect response to summer sea ice loss and increased summer ocean heating. **Citation:** Screen, J. A., and I. Simmonds (2010), Increasing fall-winter energy loss from the Arctic Ocean and its role in Arctic temperature amplification, *Geophys. Res. Lett.*, *37*, L16707, doi:10.1029/2010GL044136.

1. Introduction

[2] Dramatic changes are being observed in the Arctic. Sea ice extent and thickness are in decline [*Serreze et al.*, 2007a; *Maslanik et al.*, 2007; *Comiso et al.*, 2008; *Simmonds and Keay*, 2009] and are diminishing faster than climate models projected [*Stroeve et al.*, 2007]. The Arctic lower troposphere has been warming more than twice as fast as the global average [*Intergovernmental Panel on Climate Change*, 2007; *Screen and Simmonds*, 2010]. Such changes are already having profound climatic, ecological and socio-economic impacts in the Arctic region [*Symon et al.*, 2004], and with further ice loss projected [*Stroeve et al.*, 2007; *Boé et al.*, 2009] they may be a harbinger of more widespread impacts in the coming decades.

[3] The diminishing sea ice cover has played a key role in enhancing Arctic warming [*Serreze et al.*, 2009; *Liu et al.*, 2009; *Screen and Simmonds*, 2010]. There are a number of mechanisms by which decreasing ice cover can amplify warming in the lowermost atmosphere [*Serreze and Francis*, 2006; *Screen and Simmonds*, 2010]. The most well-known is the surface albedo feedback: surface warming enhances sea ice melt, exposing open water that is less reflective to incoming sunlight than sea ice, thereby enhancing the warming. However, the albedo feedback is only active in a direct sense when the sun is shining. Despite this, *Screen and Simmonds* [2010] show that a large part of the fall (September–November) and winter (December–February) temperature amplification is linked to sea ice reductions. This result suggests that other processes related to sea ice loss - in addition to the direct albedo feedback - have been important in amplifying recent Arctic warming. In this paper we quantify, for the first time, late fall/early winter increases in heat transfer from the Arctic Ocean to the overlying atmosphere over the last two decades. In addition, we will show the trends in surface air and lower tropospheric temperatures are intimately related to changes in these fluxes and to sea ice reductions.

2. Data and Methods

[4] We have analyzed data from meteorological stations north of 70°N which have near-complete records (at least 80%) over the period 1989–2009. Surface air temperature observations were taken from the National Aeronautic and Space Administration's (NASA) Goddard Institute for Space Studies surface temperature analysis (GISTEMP) and radiosonde upper-air temperature anomalies from the United Kingdom Meteorological Office's (UKMO) Hadley Centre atmospheric temperature analysis (HadAT2). The sixteen selected stations were Svalbard Luft, Bjornoya, Vardo, Ostrov Vize, Ostrov Dikson, Hatanga, GMO Fedorova, Tiksi, Ostrov Kotel, Chokurdah, Barrow, Resolute, Eureka, Alert, Danmarkshavn and Jan Mayen. They provide reasonable circumpolar coverage in the latitudes 70–80°N (locations in Figure 2a). Few in situ observations exist north of 80°N; for this reason results are also presented from the latest reanalysis data set, ERA-Interim [*Dee and Uppala*, 2009]. ERA-Interim provides superior spatial and temporal resolution than in situ observations alone and benefits from the assimilation of satellite-derived temperature estimates over the Arctic Ocean where in situ observations are sparse. Previous studies have shown that Arctic air temperatures and their trends in ERA-Interim are in close agreement to those in observations [*Dee and Uppala*, 2009; *Screen and Simmonds*, 2010]. We also make use of sea ice concentrations and surface heat fluxes from ERA-Interim. The sea ice area was calculated from the Hadley Centre ice and sea surface temperature analysis (HadISST). Monthly-mean sea ice concentrations (1° by 1° latitude-longitude) were used to determine the area-weighted ice covered area.

[5] Due to data availability our analysis is restricted to the 21-year period 1989–2009. Trends were calculated using linear least-squares regression and their statistical significance assessed by a two-tailed t-test. Missing data in the observations were not interpolated. Trends were only computed when a minimum of 75% of data were available. We focus on the months October to January, which correspond

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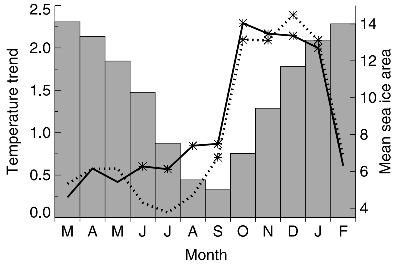

Figure 1. Annual cycle of surface temperature trends, 1989–2009. Trends (°C per decade) are shown by month and are averaged from meteorological stations north of 70°N (solid line) and from ERA-Interim averaged north of 70°N (dotted line). Asterisks show trends that are statistically significant at the 95% level or better. The gray bars show the annual cycle of mean sea ice area (10^6 km^2).

to the period of greatest Arctic-mean warming and maximum mean seasonal ice growth. When calculating October–January means all months had to be present or the entire season was considered missing.

3. Strong Arctic Surface Warming

[6] Arctic surface warming has been observed in all months over the last twenty-one years (Figure 1). Although ubiquitous, the magnitude of the warming has differed considerably from month to month. Averaged across the circumpolar stations, the greatest warming has been observed during the months October to January (all statistically significant at the 95% level or better). Weaker warming has occurred in spring and summer. We find a similar annual cycle of Arctic surface warming trends in ERA-Interim (averaged north of 70°N) as seen in the station data. Comparing the warming trends with the mean annual cycle of sea ice cover reveals that warming is amplified during the months of greatest sea ice growth. The ocean rapidly losses heat to the atmosphere at this time of year [*Serreze et al.*, 2007b]. This provides impetus to examine changes in oceanic heat loss as they may have enhanced warming in late fall and early winter. The largest differences between ERA-Interim and observations occur in summer (ERA-Interim trends are smaller than those averaged at the circumpolar stations). This may be understood by the fact that the stations are on land whereas our Arctic domain (north of 70°N) is predominantly ocean. As the following discussions will highlight, the Arctic Ocean is efficient at absorbing atmospheric heat during summer. The annual cycle of warming trends shown here is consistent with those in other reanalyses over the period 1979–2007 [*Serreze et al.*, 2009] and with the modeled response to projected sea ice loss [*Singarayer et al.*, 2006; *Deser et al.*, 2010]. The analyses presented hereafter focus on late fall/early winter (October–January) mean trends when Arctic warming is most pronounced.

[7] Figure 2a shows the spatial structure of Arctic surface temperature trends from ERA-Interim and station observations, which are in good agreement. The greatest warming has occurred in the eastern Arctic basin. There is a pronounced regional warming maximum in the northern Barents and Kara Seas (75–85°N, 39–90°E). The Russian station at Ostrov Vize (Vize Island) lies within this region and has exhibited a linear temperature increase of 4.9°C per decade since 1989. A secondary warming maximum is found in the Chukchi Sea region (70–80°N, 170–200°E).

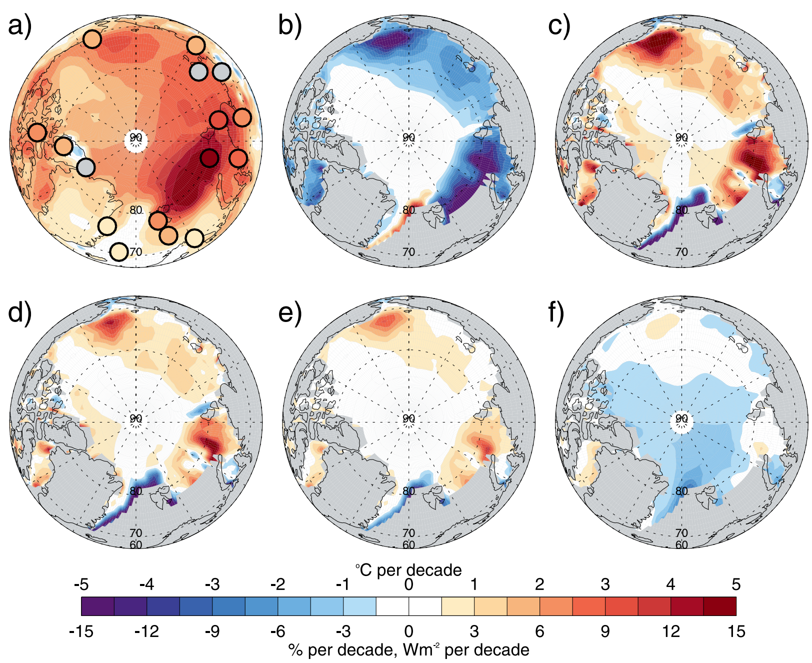

Figure 2. (a) Surface air temperature trends (°C per decade) during October–January, 1989–2009, from observations (colored dots) and from ERA-Interim (shading). Gray dots indicate insufficient data was available to calculate the trends. The corresponding trends in ERA-Interim for (b) sea ice concentration (% per decade), (c) surface turbulent heat fluxes (sensible plus latent), (d) surface sensible heat flux, (e) surface latent heat flux, and (f) net surface longwave radiation. The heat flux trends (Wm^{-2} per decade) are defined as positive in the upward direction.

Weaker warming, or modest cooling, has been observed in the North Atlantic and southern Barents Sea (60–75N°, 20°W–40°E); both of these regions lie to the south of the sea ice cover (Figure 2b).

[8] There is strong spatial coherence between the surface temperature trends and sea ice cover trends (Figures 2a and 2b). The ERA-Interim sea ice concentration trends are very similar to those apparent in satellite data (not shown). The loss of sea ice has been greatest in the northern Barents Sea, and the Kara and Chukchi Seas. In all these regions, the overlying atmosphere has strongly warmed. Sea ice increases are limited in extent to a narrow region along the ice periphery in the Greenland Sea. This is also the only ocean region that has experienced surface cooling (albeit very modest). Such striking spatial coherence between sea ice loss and warming strongly suggests the trends are intimately related.

4. Increasing Oceanic Heat Loss

[9] Previous studies have proposed that reductions in sea ice cover have enhanced recent warming in fall [*Serreze et al.*, 2009; *Liu et al.*, 2009; *Screen and Simmonds*, 2010] and winter [*Screen and Simmonds*, 2010]. We note that the associations may be two-way. Although air temperatures are well below freezing at this time of year and unlikely to cause surface melt, warmer atmospheric conditions may reduce ice growth. The thinner ice cover would then be more susceptible to melt in the following spring or summer. This pre-conditioning of the ice pack has likely played a role in the rapid recent sea ice decline [*Zhang et al.*, 2008, *Lindsay et al.*, 2009]. However, here our focus is not on the causes of sea ice loss but on the mechanisms by which the diminishing sea ice cover has amplified warming. Building on earlier studies, we hypothesize two principal ways this may have occurred. Firstly, through most of the year, the ice cover insulates the relatively warm near-surface ocean from the colder atmosphere above. Removing the ice cover allows for a greater transfer of heat to the atmosphere [*Deser et al.*, 2010]. We refer to this direct response to changes in ice cover as the "insulation" mechanism. Secondly, reductions in summer ice cover have increased the solar input to the Arctic Ocean [*Perovich et al.*, 2007]. Incoming solar radiation is taken up to melt the remaining ice and warm areas of open water. The heat stored in the ocean during the summer is given back to the atmosphere when the sea ice reforms [*Serreze et al.*, 2007b]. Thus, a greater input of solar energy in summer may have led to a greater release of heat during the following months [*Serreze and Francis*, 2006; *Serreze et al.*, 2009; *Screen and Simmonds*, 2010]. We refer to this indirect response to changes in summer ice cover as the "delayed warming" mechanism. A key consequence of both these mechanisms is an increase in oceanic heat loss during late fall and early winter; however, previous studies have not provided direct evidence of such an increase. We analyze below the October–January surface heat fluxes in ERA-Interim in search of quantitative evidence of increased oceanic heat loss.

[10] Figure 2c shows the spatial pattern of trends in the surface turbulent heat fluxes (sensible plus latent). ERA-Interim depicts increases in the transfer of heat from the ocean to the atmosphere across most of the eastern Arctic Basin. The largest upward heat flux trends are co-located with the regions of greatest sea ice reductions. In turn, the regions of largest warming are co-located with the regions of enhanced oceanic heat loss. Some of the warming adjacent to regions of sea ice loss (Figure 2a) is likely to be a consequence of horizontal temperature advection. Temperature anomalies initiated by sea ice loss in the marginal seas are transported across the Arctic Basin, primarily by synoptic weather systems [*Higgins and Cassano*, 2009]. The heat flux trends confirm that the Arctic Ocean has been losing more heat to the atmosphere during late fall and early winter. Furthermore, the close spatial correspondence between the sea ice and heat flux trends strongly suggests that the reductions in sea ice cover have facilitated the increased release of oceanic heat.

[11] Examining the ERA-Interim surface heat fluxes separately adds further insight into the mechanisms responsible for enhanced warming. Figures 2d and 2e show similar trend patterns in the sensible and latent heat fluxes, although the former are greater in magnitude (particularly in December and January (not shown)). Both show strong spatial coherence with the sea ice cover (Figure 2b) and temperature trends (Figure 2a). There is little spatial coherence between the trends in surface temperature (Figure 2a) and net longwave radiation (Figure 2f). ERA-Interim depicts increases in emitted longwave radiation in the warming regions but these are, in general, exceeded by increases in the incoming longwave radiation (not shown). The latter are poorly correlated with the patterns of warming and sea ice loss, suggesting that changes in late fall/early winter longwave radiation have not played a dominant role in recent warming. This is in contrast to results from the IPCC AR4 climate models [*Lu and Cai*, 2009]. However, our results are not in conflict with suggestions that increases in incoming longwave radiation during spring (March–May) have enhanced sea ice melt [*Francis and Hunter*, 2007] and indirectly led to late fall/early winter warming via the "delayed warming" mechanism.

[12] Our analyses of the surface heat fluxes are based solely on ERA-Interim because few direct observations exist. Whilst ERA-Interim is improved in many ways from older reanalyses [*Dee and Uppala*, 2009] and depicts realistic temperature trends (Figures 1, 2a, and 3) [*Screen and Simmonds*, 2010], the accuracy of the heat fluxes remains unclear. This places an additional degree of uncertainty on the heat flux trends identified. However, atmospheric and sea surface temperatures, and sea ice concentration are relatively well-observed climate parameters (at least during the satellite era). The heat fluxes in ERA-Interim are diagnosed using a sophisticated atmospheric model that makes use of these fundamental atmospheric and boundary parameters. Thus, the surface fluxes are indirectly constrained by observations - unlike in climate models - which gives us confidence that they are realistic and physically meaningful.

5. Vertical Structure of Warming

[13] The vertical structure of recent warming has been considered previously [*Graversen et al.*, 2008; *Serreze et al.*, 2009; *Screen and Simmonds*, 2010]. Here we add to the understanding of this issue by adopting an approach that better captures *regional* interactions and draws on in situ observations in addition to reanalysis data. *Screen and Simmonds* [2010] found that the greatest zonal-mean Arctic warming has been at and near the surface, and that the

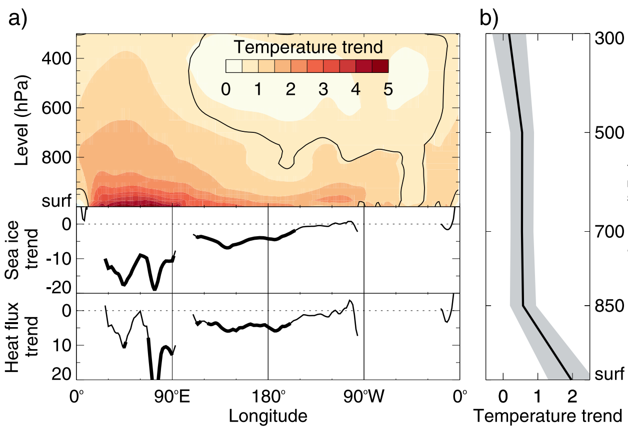

Figure 3. (a) Vertical cross section of ERA-Interim temperature trends (°C per decade) during October–January, 1989–2009, around the 79.5°N latitude circle (top). The black contour denotes the 95% significance level. Also shown for the same transect are corresponding trends in sea ice concentration (% per decade; middle) and in the surface turbulent heat fluxes (Wm^{-2} per decade; bottom; note the inverted scale). Bold lines denote trends significant at the 95% level or better. (b) Mean vertical profile of temperature trends (°C per decade) averaged at the circumpolar stations. The gray band denotes the 95% confidence intervals.

warming signal diminishes rapidly with height. This vertical structure held for all latitudes north of approximately 70°N and in all seasons except summer. The use of zonal means in the work of *Screen and Simmonds* [2010] emphasizes the amplification of recent Arctic temperature trends; however, it subsumes the longitudinal variability of temperature trends evident in Figure 2a. Here we adopt a complementary approach and show the vertical profile of October–January temperature trends around the 79.5°N latitude circle (Figure 3a). The greatest warming is indeed found in the lowermost part of the atmosphere at *all* longitudes. *Screen and Simmonds* [2010] also found strong associations between the vertical profile of warming and reductions in Arctic-wide sea ice cover. The use of an Arctic-wide sea ice index captures well the large-scale relationships but may mask regional interactions. In Figure 3a, we show the corresponding trends in sea ice cover and the surface heat flux also along the 79.5°N transect. Consistent with our earlier discussions, warming is strongly enhanced in the vicinity of the largest sea ice reductions and greatest surface heat flux trends.

[14] Figure 3b shows the mean vertical profile of temperature trends from the circumpolar stations. Averaged over the Arctic stations, there has been a mean surface warming of 2.0°C per decade (the global-mean surface warming over the period 1989–2009 has been approximately 0.25°C per decade based on all GISTEMP stations). By contrast, the Arctic warming aloft is less than 0.6°C per decade. The presence of warming aloft suggests that processes in addition to changes in the surface heat fluxes have contributed to Arctic warming [*Graversen et al.*, 2008; *Screen and Simmonds*, 2010]. However, the observed Arctic amplification is clearly strongest at the surface which is consistent with changes in the surface fluxes (due to sea ice loss) playing a central role [*Screen and Simmonds*, 2010].

6. Discussion and Conclusions

[15] A peculiarity of recent Arctic climate change is that the strongest surface warming has occurred during late fall and early winter (Figure 1) whilst the largest sea ice reductions have occurred in summer and early fall [*Serreze et al.*, 2007a]. Here we have provided the first direct quantitative evidence of an increase in late fall/early winter oceanic heat loss that helps explain the enhanced warming. This increased oceanic heat loss is closely linked to the reductions in sea ice cover. It is likely the combination of the direct response to reductions in fall/winter ice cover (the "insulation" effect), and the indirect response to the loss of summer ice cover and increased summer ocean heating (the "delayed warming" effect). The observed warming has been strongest in the lowermost part of the atmosphere where changes in the surface heat fluxes have their greatest influence. In turn, the strong warming has likely contributed to delayed refreezing and reduced ice growth [*Markus et al.*, 2009]. The thinner ice cover is more prone to melt, thereby leading to further warming.

[16] The temporal, spatial and vertical structures of recent warming all show a high level of similarity with the simulated response to reduced sea ice cover [*Singarayer et al.*, 2006; *Deser et al.*, 2010], reinforcing suggestions that the atmospheric impacts of sea ice loss are already evident [*Serreze et al.*, 2009; *Screen and Simmonds*, 2010]. With further thinning and retreat of Arctic sea ice expected, the changes shown in this study may be a precursor of more pronounced impacts over the coming decades.

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