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LETTER

A link between Arctic sea ice and recent cooling trends over Eurasia

S. D. Outten · I. Esau

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Abstract A band of cooling that extends across mid-latitude Eurasia is identified in the wintertime surface air temperatures of the latest ECMWF reanalysis. This cooling is related to extreme warming around the Kara Sea through changes in the meridional temperature gradient. Surface temperatures in the Arctic have risen faster than those at lower latitudes, and as the Arctic warming increases, this north–south temperature gradient is weakened. This change in the meridional temperature gradient causes a decrease in the westerly winds that help maintain the mild European climate by transporting heat from the Atlantic. Since decreasing sea ice concentrations have been shown to be a driving factor in Arctic amplification, a singular value decomposition analysis is used to confirm the co-variability of the Arctic sea ice, including the Kara Sea, and the temperatures over the mid-latitude Eurasia. These findings suggest that decreasing sea ice concentrations can change the meridional temperature gradient and hence the large-scale atmospheric flow of the Northern Hemisphere.

1 Introduction

The meridional temperature gradient (MTG) is a primary indicator of the Earth's climate system; determining mean zonal flow at large scales, while at small scales providing the energy for the baroclinic cyclones that dominate the mid-latitude weather (Holton 2004). While in early global warming studies the MTG was not considered to be important since temperatures were expected to rise evenly across the globe (Hoffert and Covey 1992), it has become clear that temperatures are rising faster at high latitudes (Solomon et al. 2007; ACIA 2004), causing the MTG to steadily weakened for the past 50 years (Braganza et al. 2004).

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S. D. Outten (✉) · I. Esau
G. C. Rieber Climate Institute, Nansen Environmental and Remote Sensing Center, Thormhlensgt. 47, 5006 Bergen, Norway
e-mail: stephen.outten@nersc.no

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Between 1875 and 2008, the mean trend over the Arctic was 0.136 K dec^{-1}, while over the last decade the trend was 1.35 K dec^{-1} (Bekryaev et al. 2010). While this Arctic amplification is largely driven by strong heat transfer from the ocean as sea ice retreats (Serreze et al. 2009), many other processes are also important. The loss of sea ice causes a deepening of the boundary layer and a shift from low-level to mid-level cloud cover in the Arctic, thus changing the radiation balance (Schweiger et al. 2008). Overland et al. (2008) identified a shift in the winds, from a mostly zonal pattern seen last century to a more meridional pattern in the last decade. This allows more heat to be transferred between the mid-latitudes and the Arctic, resulting in both Arctic warming and mid-latitude cooling, both of which accelerates the weakening of the MTG. Further research has shown that these changes of large-scale wind patterns are directly connected to changes in sea ice in the Arctic (Overland and Wang 2010).

Recent work has focused on the regional effects of sea ice loss over the Barents and Kara Seas, which has been shown to cause cooling as far away as Southeast Asia (Honda et al. 2009). The Kara Sea has also become a region of great interest due to extensive plans for oil and gas exploration, but such long term economic plans require a clear understanding of the driving mechanism behind the observed sea ice changes. A debate is currently ongoing in the literature as to whether the driving mechanism is dynamically based, suggesting high variability in the Kara Sea ice cover in future decades, or anthropogenically based, suggesting a steady decline in sea ice cover.

It has also been suggested that changes in sea ice concentrations over the Barents-Kara Seas cause warming in the lower troposphere that could change the MTG and thus weaken the zonal winds in the mid-latitudes (Petoukhov and Semenov 2010). These westerly winds transport heat from the Atlantic to the interior of the continent and help maintain a warmer climate, thus a decrease in these winds would result in cooling over mid-latitude Eurasia.

This work identifies wintertime negative temperature trends over Eurasia and investigates how this cooling is related to changes in sea ice concentration over the Kara Sea through the meridional temperature gradient. Sections 2 will discuss the data sources used, section 3 examines the derived temperature trends, and section 4 investigates the effects of changing sea ice concentrations.

2 Data sources

The ERA-Interim reanalysis was used in this work, and covers the period from 1989 until the present (Simmons et al. 2006; Uppala et al. 2008). For this study it was used on a grid of 0.5° in both longitude and latitude, with daily outputs at 00, 06, 12, and 18 UTC. The meteorological parameters used in this work were the 2-metre temperature, the sea ice concentration, and the zonal wind component at 850 hPa. For the SVD analysis, these fields were de-trended, and covariance matrices were calculated.

ERA-Interim was selected for this work due to its high spatial resolution and because the period it covers includes the most recent decade. It also has the advantage of not including the 1950's or 1970's, when major changes were made to the global observing system. The inclusion of these years is often a problem when deriving long-term trends from reanalysis data (Screen and Simmonds 2011).

This work also made use of the temperature observations from various ground stations. The stations were selected so as to provide a good sample of different regions and climates.

3 Temperature trends in ERA-interim

Temperature trends for the 21 years of the ERA-Interim reanalysis were calculated using a linear fit to the mean January temperatures. These calculations were limited to the grid points over land, and the resulting temperature trends are shown in Fig. 1.

The most striking feature of this plot is the strong warming trends over Northern Eurasia and Northern Canada, with values peaking in excess of 5.86 K dec^{-1} near the Kara Sea. However, there is also a large area of negative temperature trends over the Eastern U.S. and, more notably, extending zonally across mid-latitude Eurasia. The overall distribution of warming and cooling over high and mid-latitude Eurasia respectively is similar to the winter seasonal trends observed by Zhang et al. (2008). This region of cooling over Eurasia reaches a minimum trend of −3.18 K dec^{-1} at 83E. This is approximately the same location as the negative temperature anomalies observed in 2006 and 2007 by Overland et al. (2008), while Comiso (2003) also found a minimum in temperature trends from satellite data at around 85E that reached −3.2 K dec^{-1}.

The January temperature trends shown here support the findings of these and many other studies which suggest that Arctic warming during the wintertime can be accompanied by cooling in the mid-latitudes (Overland et al. 2008; Zhang et al. 2008; Honda et al. 2009; Petoukhov and Semenov 2010). Studies using temperatures derived from satellite data have also shown similar negative trends over Eurasia during the winter (Liu et al. 2009; Comiso 2003). However, the trends in ERA-Interim are larger in

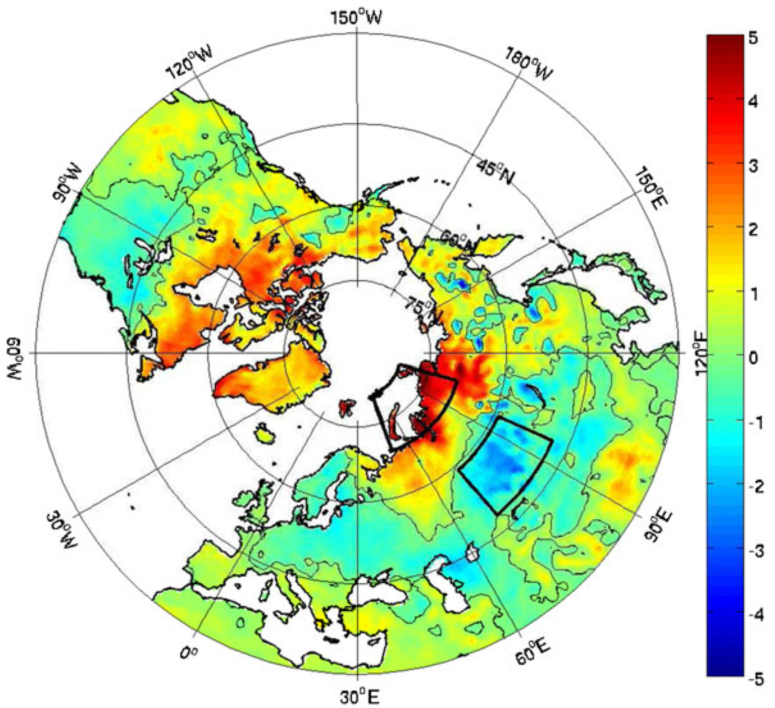

Fig. 1 Temperature trends [K/dec] for mean January SAT from 1989 to 2009, from ERA-Interim. A *black* contour is shown for 0 K/dec. The two outlined segments are the Northern domain over the Kara Sea and the Southern domain located over the region of maximum cooling in the mid laltitudes

magnitude in some regions. This is because ERA-Interim includes the most recent years, which have been some of the warmest on record and which were not covered by the previous studies. In order to investigate whether or not the temperature trends from ERA-Interim are realistic, they were compared to observations from selected weather stations (see supplementary material) and showed differences from the observed January trends of between 0.1 and 0.6 K dec^{-1}.

4 The role of sea ice

Two approaches were used to investigate the role of high latitude sea ice in determining the temperatures at mid-latitudes over the continent. The first examines the correlations of various diagnostics in a high latitude domain and a mid-latitude domain, while the second approach uses singular value decompositions (SVD) to investigate the co-variability of sea ice, 2-metre temperatures, and zonal winds over the Northern Hemisphere.

The two domains used in this work are shown in Fig. 1. The Northern domain over the Kara Sea was chosen because it covers a region of both high warming and high sea ice concentration change, while the Southern domain in the mid-latitudes was selected so as to cover the region of maximum cooling over Eurasia. Three diagnostics from ERA-Interim were examined over the two domains: the 2-metre air temperature, the sea ice concentrations, and the zonal wind speed at 850 hPa. Mean monthly values for January, averaged over each of the domains, were found for all three diagnostics. Individual MTGs were calculated along each of the meridians between the northern edge of the Northern domain and the southern edge of the Southern domain. These were calculated using a linear fit to the temperatures, and were then averaged to produce a mean MTG between the two domains.

Figure 2 shows the normalized variations of the relevant diagnostics over the 21 years of ERA-Interim data. The first plot shows that many of the years with low sea ice concentrations in the Northern domain are accompanied by high 2-metre temperatures, as heat is released from the exposed sea. This is especially clear after 2005 where there is a steep drop in the sea ice concentrations and a steep rise in the air temperatures. The correlation between the sea ice concentration and the 2-metre temperature is −0.83. All the correlations in this work were found at the 99% significance level. A strong correlation of 0.64 is also found between the sea ice concentration and the MTG, highlighting how warming (cooling) in the Northern domain resulting from changing sea ice concentrations causes the MTG between the two domains to decrease (increase).

The second plot in Fig. 2 shows how the variations in the MTG relate to the variations in the zonal wind in the Southern domain. As the MTG decreases, due partly to warming in the Northern domain, the zonal wind in the Southern domain also decreases. The correlation between the MTG and zonal wind is 0.77. The zonal wind is also highly correlated, 0.72, to the 2-metre temperature in the Southern domain, as decreased westerly winds result in cooler air temperatures over the interior of the continent.

The second approach to establish the relationship between the sea ice concentrations and the air temperatures over Northern Eurasia was to examine their co-variability using SVD analysis. The primary mode of co-variability is shown in Fig. 3. It shows a strong region of negative correlation between 20 E and 160 E in the sea ice concentration. This overlaps a region of positive correlation in the 2-metre temperature, which is centered over the Arctic, north of the Kara Sea. There is also a region of negative correlation over mid-latitude

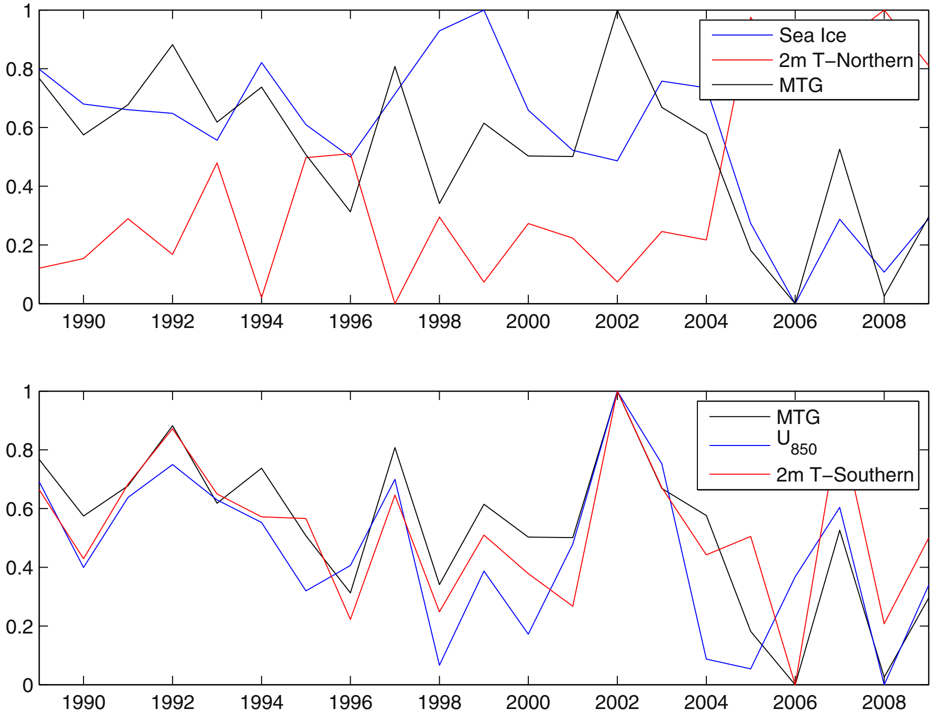

Fig. 2 The first plot shows the mean January 2-metre temperature (*red*) and the sea ice concentration (*blue*) in the Northern domain. The second plot shows the mean zonal wind (*blue*) and 2-metre temperature (*red*) in the Southern domain. The MTG between the two domains is shown in both plots (*black*)

Eurasia that is co-located with the negative temperature trends shown in Fig. 1. These two diagnostics are strongly related to one another in this first mode, as indicated by their coupling correlation coefficient of 0.68. The amount of co-variance explained by this mode is approximately 59%.

This analysis suggests that as the sea ice concentration to the north of central Eurasia (including the Kara Sea) decreases, not only does the temperature over the same region rise, but that the temperatures over the continent to the south decrease. It is also interesting to note that while the southern centre of action for this mode is located where the maximum cooling occurs, there is also a weak band of negative correlation extending zonally across mid-latitude Eurasia that is similar to the zonal band of weaker cooler seen in the temperature trends in Fig. 1. This analysis does not explain all of the observed trends in the Northern Hemisphere; e.g. cooling over the mid-latitudes of North America, hence further investigation is required.

A similar SVD analysis was done to investigate the covariance between zonal wind and the sea ice concentration (see supplementary material). The coupling correlation coefficient was 0.57 and the covariance explained by the first mode was around 47%. This first mode showed that when the sea ice concentration decreased, there was a region of decreased zonal wind centered over the region of maximum cooling shown in Fig. 1. This supports the idea that changes in the large scale circulation and the zonal wind are the linking factor between the decrease in sea ice concentrations and the cooling over the continent, as proposed by Petoukhov and Semenov (2010).

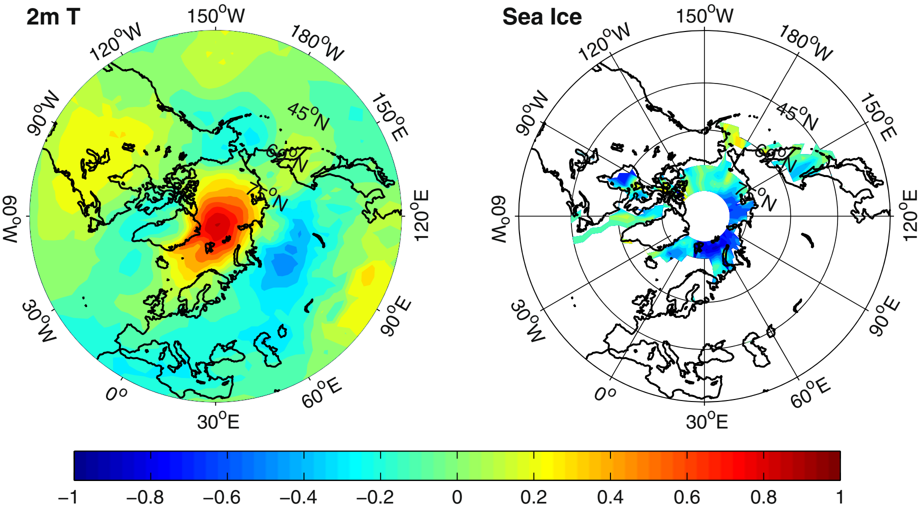

Fig. 3 Spatial patterns of the first SVD mode presented as homogeneous correlation maps of 2-metre temperature (*left*) and sea ice concentration (*right*). Contour interval is 0.1

5 Discussion and summary

The relationship between the winter temperature trends over Eurasia and sea ice concentrations over the Kara Sea was investigated. The trends were derived from ERA-Interim reanalysis and covered the period from 1989 to 2009. They showed strong warming over Northern Eurasia and North-Western Canada, peaking at around 5.8 K dec^{-1} near the Kara Sea. They also showed a band of cooling extending zonally across Eurasia and reaching −3.1 K dec^{-1}. While these trends are slightly larger than those found in other studies, they include the last decade, which has been the warmest on record. The mean monthly temperatures, on which these trends are based, do compare well with observations from various weather stations, lending confidence to the derived trends.

The high temperature trends over the Kara Sea were found to be highly correlated to the sea ice in that region. This supports the idea that sea ice cover is responding to increased temperatures caused by increased GHG concentrations (Stroeve et al. 2007; Serreze et al. 2009; Solomon et al. 2007), however this analysis does not provide enough evidence to be conclusive. The variations in sea ice were also correlated to the MTG. In the region of cooling over the interior of the continent, strong correlations were found between the MTG and the zonal wind, and between the zonal wind and the local 2-metre temperature. Taken together, these correlations support the idea proposed by Petoukhov and Semenov (2010) that a decrease in the sea ice concentrations can cause a decrease in the zonal wind over the continent, by altering the MTG through local heating. The decreased zonal wind allows the interior of the continent to cool, as seen in the derived temperature trends. This idea is further supported by an SVD analysis that showed how the sea ice in the Arctic co-varied with the local air temperature and inversely varied with the air temperature over mid-latitude Eurasia. An important implication of these results, and numerous other studies, is that decreasing sea ice concentrations can change the MTG and the large-scale atmospheric flow of the Northern Hemisphere.

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