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The thermodynamic state of the Arctic atmosphere observed by AIRS: comparisons during the record minimum sea-ice extents of 2007 and 2012

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Abstract

The record sea-ice minimum (SIM) extents observed during the summers of 2007 and 2012 in the Arctic are stark evidence of accelerated sea ice loss during the last decade. Improving our understanding of the Arctic atmosphere and accurate quantification of its characteristics becomes ever more crucial, not least to improve predictions of such extreme events in the future. In this context, the Atmospheric Infrared Sounder (AIRS) instrument onboard NASA's Aqua satellite provides crucial insights due to its ability to provide 3-D information on atmospheric thermodynamics.

Here, we facilitate comparisons in the evolution of the thermodynamic state of the Arctic atmosphere during these two SIM events using a decade long AIRS observational record (2003–2012). It is shown that the meteorological conditions during 2012 were not extreme but three factors in preconditioning from winter through early summer probably played an important role in accelerating sea-ice melt. First, the marginal sea-ice zones along the central Eurasian and North Atlantic sectors remained warm throughout winter and early spring in 2012 preventing thicker ice build-up. Second, the circulation pattern favoured efficient sea-ice transport out of the Arctic in the Atlantic sector during late spring and early summer in 2012 compared to 2007. Third, additional warming over the Canadian Archipelago and southeast Beaufort Sea from May onward further contributed to accelerated sea-ice melt. All these factors may have lead already thin and declining sea-ice cover to pass below the previous sea-ice extent minimum of 2007. In sharp contrast to 2007, negative surface temperature anomalies and increased cloudiness were observed over the East Siberian and Chukchi Seas in the summer of 2012. The results suggest that satellite-based monitoring of atmospheric preconditioning could be a critical source of information in predicting extreme sea-ice melting events in the Arctic.

1 Introduction and perspectives from the summer of 2007

The record Arctic sea-ice minimum (SIM) extent during summer 2007 (Stroeve et al., 2008) was the most palpable manifestation of accelerated climate change and of the so-called Arctic amplification during recent decades. Although the declining trend in sea-ice extent had been well known prior to the 2007 SIM, the magnitude and timing of such a decline was not foreseen. The 2007 SIM event challenged our already limited understanding (reflected in the large inter-model differences) of the processes influencing sea-ice variability and atmosphere-ocean-cryosphere interactions.

A number of studies have shed light on the role of various drivers of 2007 sea-ice melt and a lot can be learned these research works. Kay et al. (2008) showed that the effect of warm air advection, reduced cloudiness, and increased shortwave surface flux over the Beaufort high region may have contributed to the observed sharp decline in sea-ice. Over this region, the lower troposphere warmed by 2–3 K, while more persistent and stronger temperature inversions were observed (Devasthale et al., 2009). However, the role of reduced cloudiness and increased downwelling shortwave radiation was questioned by Schweiger et al. (2008) using an ocean-ice model. Subsequent discussions were then focused on the processes that occur at shorter time scales versus those occurring at longer, synoptic scales. For example, L'Heureux et al. (2008) argued for the role of an anomalously strong Pacific-North American (PNA) pattern in influencing the unusual atmospheric circulation during 2007. The preconditioning of winds, thermodynamic and surface parameters before the melt season were also argued to be important factors (Sedlar and Devasthale, 2012; Graversen et al., 2011; Vihma et al., 2008; Zhang et al., 2008). Using ice mass balance observations, Perovich et al. (2008) further suggested that the additional solar heating of the upper layers of ocean was a primary cause of Beaufort sea-ice bottom melting. The continued decrease in sea-ice extent during the recent years could be due to recent large-scale changes in atmospheric circulation, trends in cloudiness, or continuous thinning of the sea-ice (Comiso, 2012; Deser and Teng, 2008; Kay and Gettelman, 2009; Kwok et al.,

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2009; Kwok and Rothrock, 2009; Lindsay et al., 2009; Liu et al., 2009, 2012; Maslanik et al., 2007a, b; Ogi and Wallace, 2007; Overland and Wang, 2010). Apart from the processes mentioned above, it must be noted that increased greenhouse gas forcing is actually the primary driver for the rapid onset of the sea-ice decline (Notz and Marotzke, 2012).

Already in August 2012, ice extent in the Arctic was below the previous record minimum of September 2007. Figure 1 shows an overview of 2007 and 2012 sea ice concentration during September, the month when minimum occurs. The spatial pattern and magnitude of sea ice concentration is different during these two months, likely a result of different dynamical controls. From a scientific point of view, the SIM event in 2007 provided an unsolicited opportunity to gain insights into these different influences concerning sea-ice spatio-temporal variability, partly because modern satellite observations contain detailed 3-D information about the state of the atmosphere. It is important to investigate the comparative evolution of the state of the atmosphere during these two SIM events. Atmospheric information can be exploited (a) to seek commonalities, which can further be used to improve prediction skills and (b) to provide useful information to understand processes that drive such extreme events. In this context, in the present study, we examine similarities and differences in the state of the Arctic atmosphere during 2007 and 2012 leading up to the corresponding SIM events. We exploit data observed from the Atmospheric Infrared Sounder (AIRS) instrument that is flying onboard NASA's Aqua satellite since 2002 and providing 3-D information on atmospheric thermodynamics at unprecedented resolutions and accuracy.

2 AIRS data

For the present study, we use data from the Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit (AMSU) instrument suite (Chahine et al., 2006). The AIRS grating spectrometer has a total of 2378 infrared channels, with a spectral coverage between 3.7 and 15.4 µm, and the temperature and water vapor

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profiles are calculated at approximately 40 km spatial resolution at nadir view. As AIRS scans in both directions to 49.5° off nadir, this provides near-global coverage on a daily basis. Here, the AIRS Daily L3 Version 5 (V5) Standard Product is used. In this study, we analyse the retrievals of temperature, water vapour, geopotential height and clouds from December 2002 through August 2012. Over the years, AIRS data sets have matured considerably and a wealth of literature on the validation of AIRS retrievals is now available (e.g. Divakarla et al., 2006; Fetzer, 2006; Gettelman et al., 2006; Kahn et al., 2008; to name a few). The L3 standard product has previously been used for studying large-scale climatic features over the high latitudes (Devasthale et al., 2010, 2011, 2012; Sedlar and Devasthale, 2012).

3 Similarities and differences between 2007 and 2012 SIM events

In the winter of 2006–2007, the Arctic Oscillation, the most dominant mode of variability over the Arctic, was in the positive phase during December, January and March and was in the negative phase during February 2007. In the winter of 2011–2012, positive phase was observed during December and March and negative during January and February. The corresponding geopotential height anomalies at 500 hPa for 2007 and 2012 are shown in Fig. 2. The marginal sea-ice zones along East Siberian, Laptev and Kara Seas experienced anomalously large geopotential heights resulting in a relatively warmer atmospheric column throughout the winter in 2011–2012; the warming also extended well into the Central Arctic (Nansen Basin). Additionally, a distinct positive geopotential anomaly over west-central Eurasia and neighboring seas was persistent during winter 2011–2012, opposite to the generally negative anomalies in the same regions and season during 2006–2007. The surface skin temperature anomalies shown in Fig. 3 reflect the large-scale circulation differences for winter. While a general warming ranging from 2–5 K was observed over the majority of the Arctic during 2011–2012, in contrast, the strong warming was only observed during February and from the Pacific sector in the winter of 2006–2007, in accordance with the different circulation patterns.

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The warming pattern continued in March 2012 and the surface temperature anomalies were close to, or exceeded, 5 K north of the Greenland, Barents and Kara Seas (Fig. 4). Advection of warm and humid air, consistent with the geopotential height anomalies in Fig. 2, from the northeast Atlantic lead to corresponding anomalies in water vapour (WV) mixing ratios (Figs. 7–8). Despite temperature and WV anomalies upwards of 6 K and 0.5 $\mathrm{g\,kg^{-1}}$ from the northeast Atlantic, March 2007 advective anomalies did not extend much beyond the Barents and Kara Seas into the Central Arctic. Instead, colder air advection dominated from near surface through much of the troposphere resulted in negative anomalies in temperature and WV over Alaska, eastern Siberia and neighbouring sea areas. A distinct difference in thermodynamics between the SIMs for April is clearly evident over, and north of, Eurasia and Siberia (Figs. 7–8). Large warm and moist anomalies were found during 2007, directly leading to positive skin temperature anomalies larger than 4 K (Fig. 4). Additionally, a surface and mid-tropospheric warming was observed north of the Canadian archipelago and the Beaufort Sea during May 2012, a feature that was clearly opposite to that observed during May 2007. The center of action of the Arctic Oscillation was clearly shifted from the Central Arctic in 2007 to further southwest over the Greenland and Barents Seas in 2012, as visible in the geopotential height anomalies.

This warm air preconditioning in winter and early spring was followed by persistent northerly near-surface winds in subsequent months in the Fram Strait, Greenland Sea and Norwegian Sea, with a difference that these winds were stronger in 2012 compared to 2007 and persisted throughout late spring and summer (Fig. 6). In 2007, the southerly and southwesterly winds blowing over the northern Northeast Atlantic, to some extent, did not provide favourable conditions for efficient sea-ice transport out of the Arctic (via Atlantic sector), especially in April and May. In contrast, in 2012, northerly winds were not only stronger, but also extended toward more southerly latitudes (up to $\sim$55 N). Therefore, favourable conditions prevailed over the entire Fram Strait and Greenland Seas for increased sea-ice transport out of the Arctic in late spring and early summer in 2012.

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In addition to Fig. 6 showing surface wind patterns, the cold and dry air advection from the Central Arctic over Fram Strait and Norwegian and Greenland Seas in the late spring and early summer of 2012 is clearly evident in Figs. 4, 7 and 8 showing negative surface temperature anomalies and lower tropospheric water vapour anomalies over these regions, further supporting the case that the outward sea-ice transport may have been efficient. It is also to be noted that in 2007 these anomalies were in fact mostly positive over southern Greenland and Norwegian Seas.

From May 2012 onward, a noticeable surface warming (up to 3 K) was observed over the Canadian Basin (especially along the coast) and Victoria and Banks islands (Figs. 4 and 5). This warming pattern persisted throughout early summer (Fig. 4). In sharp contrast to 2007, cooling was observed over the East Siberian Sea in 2012 during summer. Warm and humid air advection over the East Siberian Sea region, which was mostly blamed for accelerating sea-ice melt in summer 2007, was in fact very weak in summer 2012. This is evident in Fig. 8 showing either negative or very weakly positive water vapour anomalies over this region.

Cloud cover plays an important role in seasonal sea-ice growth and melt. For example, increased longwave surface forcing due to an increased cloud greenhouse effect in winter may inhibit the build-up of sea-ice. However, in summer, increased cloud cover tends to reflect solar radiation that would have reached the surface, thus cooling it and possibly retarding sea-ice melt. The transition from positive to negative surface radiative forcing of clouds occurs roughly during the late spring in April–May, and vice-versa in August–September, depending on latitude, surface albedo and cloud microphysical characteristics (Walsh and Chapman, 1998; Shupe and Intrieri, 2004; Sedlar et al., 2011; Persson, 2012). While the summer of 2007 was characterized by reduced cloudiness over the Beaufort and East Siberian Seas (Pacific sector of the Arctic) and north of Greenland (Fig. 9), in the summer of 2012 cloudiness actually increased over these regions, especially over the East Siberian Sea. Reduced cloudiness was instead observed over the Southeastern Canadian Basin and Victoria and Banks islands (Fig. 9). As a result of these summer cloud cover anomalies, the surface warming was observed

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over Southeastern Canadian Basin and around Victoria and Banks islands, and cooling over East Siberian Sea, as mentioned above.

Figure 10 shows the state of the sea-ice concentration on 31 July 2007 and 2012. Based on the previous literature and the analysis of the anomalies of different geophysical variables described above, the regions that were most sensitive to accelerated sea-ice melt during 2007 and 2012 are marked in Fig. 10. While the East Siberian Sea (or the Pacific sector in general) experienced advection of heat and moisture and subsequent rapid melting in 2007, there were three hot spots in 2012 that experienced above or below normal anomalies in temperature, water vapour and clouds. Therefore, the sea-ice melt from these three sides of the marginal sea-ice zone was as a result more efficient in 2012.

4 Discussions and conclusions

As a result of increased greenhouse gas forcing and associated feedbacks, Arctic sea-ice during the last decade is rapidly melting. The sea-ice is continually thinning making the Arctic cryosphere sensitive to small- and short-scale changes in the state of the atmosphere, which can either retard or accelerate this already declining trend in sea-ice extent and thickness. Therefore, it is important to investigate how the atmosphere manifests itself during record minimum events so as to understand commonalities and differences, which can further be exploited to improve prediction skills of such events and to study and model relevant processes.

Here, an overview of the thermodynamic state of the Arctic atmosphere during two recent record minimum sea-ice extent events (2007 and 2012) is presented using data from the Atmospheric Infrared Sounder (AIRS) instrument onboard Aqua satellite, which has the capability to provide full-scale 3-D information on thermodynamics. Winter and spring atmospheric preconditioning of sea ice growth and retardation are concluded as a common, important contributor to the subsequent ice extent minima observed during record sea ice loss years. Based on the analysis presented here, we conclude that the preconditioning of the Arctic atmosphere, especially over three geographical hot-spots (Fig. 10), may have lead to favourable conditions for sea-ice melt and its faster transport out of the Arctic in 2012. First, already thinning sea-ice, especially from the last few years, was subjected to warming throughout the winter of 2011–2012 over the Fram Strait, Kara, Barents and Greenland Seas as well as over the Nansen Basin extending into the Central Arctic. This may have prevented sufficient ice thickening over these areas during winter. Second, stronger and persistent northerly winds over these regions from April 2012 onward facilitated efficient transport of sea-ice out of the Arctic. Third, additional warming over the Canadian Basin and around Victoria and Banks Islands from May onward further accelerated sea-ice melt from the North American sector. During winter and spring of 2007, northward advection of heat and moisture in the north Atlantic sector were large, but the majority of the central Arctic basin was under the influence of a synoptic circulation pattern that promoted cold air advection into the Arctic. Not until late spring did the circulation change, allowing a strong predconditioning warming from the Eurasian and Siberian sectors of the Arctic – which appears to have contributed largely to the ice extent mimima in the East Siberian and Laptev Seas (Sedlar and Devasthale, 2012; Graversen et al., 2011). The Arctic sea-ice was instead warmed from three critical sides (Northern Atlantic, north central Russian and North American sectors) in 2011–2012. These areas played a critical role in 2012, in contrast to the contributions from the Pacific Sector in 2007, where warm and humid air advection over East Siberian and Chukchi Seas were mostly blamed for accelerating sea-ice melt (Graversen et al., 2011). In addition to the three hot spots discussed in this article, a strong cyclone entered the Arctic in August 2012. More detailed studies are necessary to analyze the impact of this storm on sea ice reduction, if any. However, it is worth mentioning that the rate of sea ice melt was already higher since June 2012, long before the occurrence of this particular storm.

All geophysical variables studied here (temperature, water vapour, cloud fraction, geopotential height), wind patterns from ERA-Interim Reanalysis and the spatio-temporal progression of sea-ice melt are consistent with the interpretations mentioned

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above. It is interesting to note that the anomalies observed in geophysical variables are not extreme in 2011–2012 compared to climatology. However, since the last decade, the sea-ice system is transforming into such a delicate state that even weak but persistent changes in these variables are sufficient to alter the progression of sea-ice melt. The satellite-based monitoring could provide critical information regarding atmospheric preconditioning, thus helping in predicting such extreme melting events in the Arctic.

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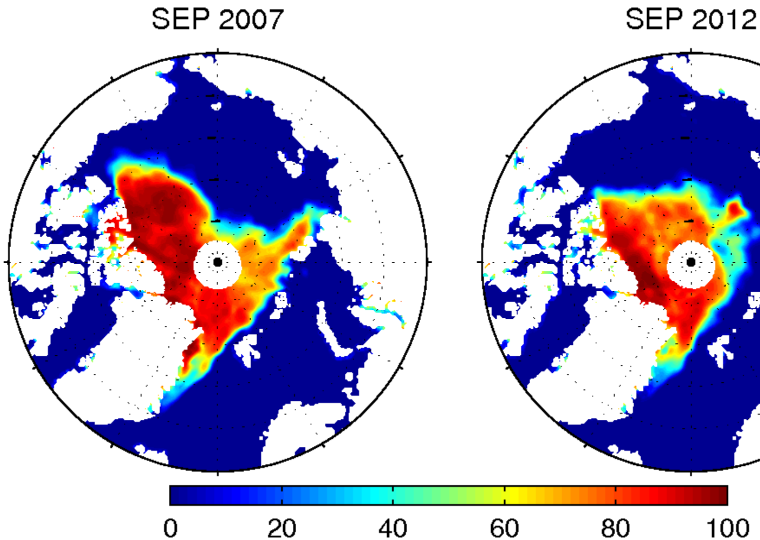

Fig. 1. Monthly mean sea ice concentration (contours [%]) for the September of 2007 and 2012. Sea ice concentration data are taken from the Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave dataset using Platform F13 and near-real time Platform F17 (Cavalieri, D., Parkinson, C., Gloersen, P., and Zwally, H. J., 1996, updated yearly. Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data. Boulder, Colorado, USA: National Snow and Ice Data Center).

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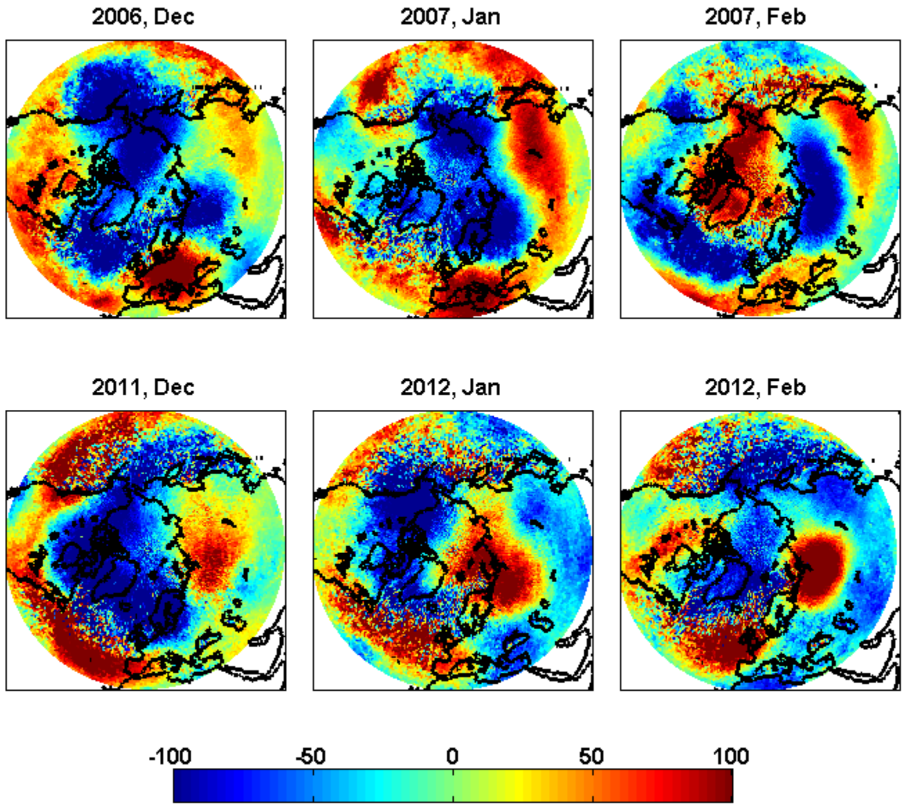

Fig. 2. AIRS derived 500 hPa geopotential height [m] anomalies during the winters of 2006–2007 (top row) and 2011–12 (bottom row). Note that all AIRS derived anomalies shown in the present study are with respect to the 10-yr period of 2003–2012.

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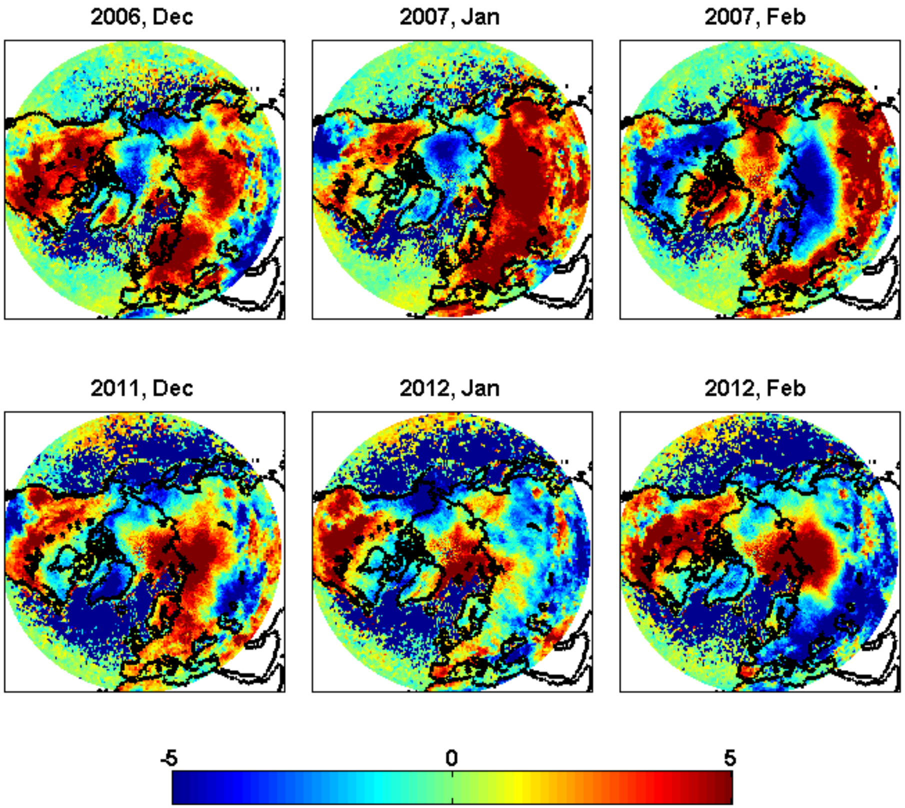

Fig. 3. Surface skin temperature [K] anomalies for the winter months of 2007 (top row) and 2012 (bottom row).

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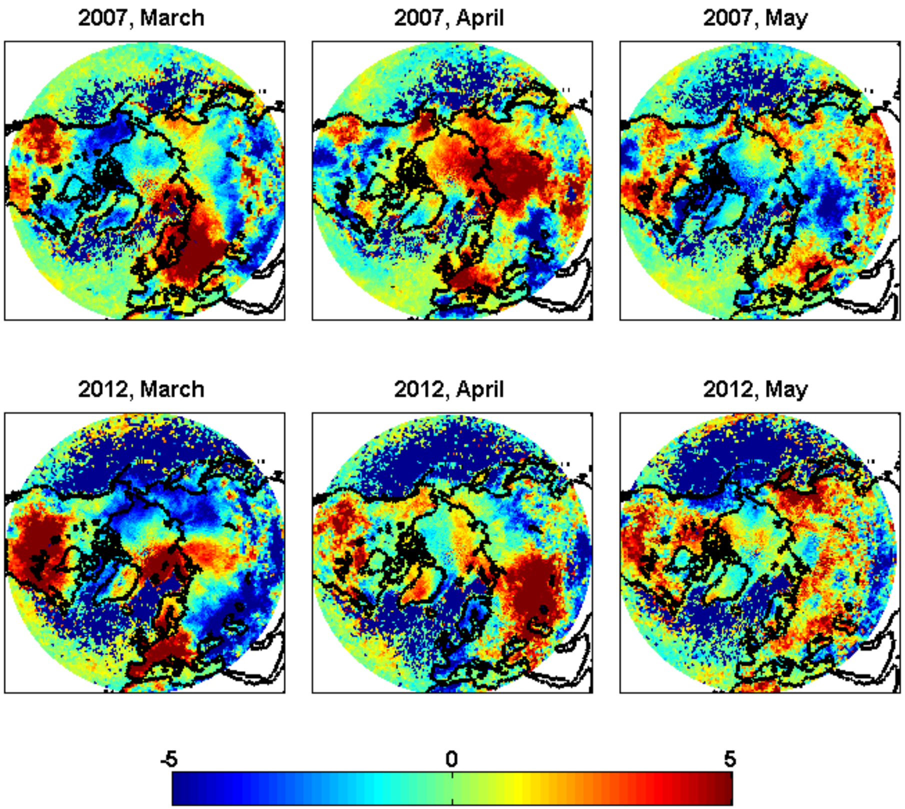

Fig. 4. Surface skin temperature [K] anomalies for the spring months of 2007 (top row) and 2012 (bottom row).

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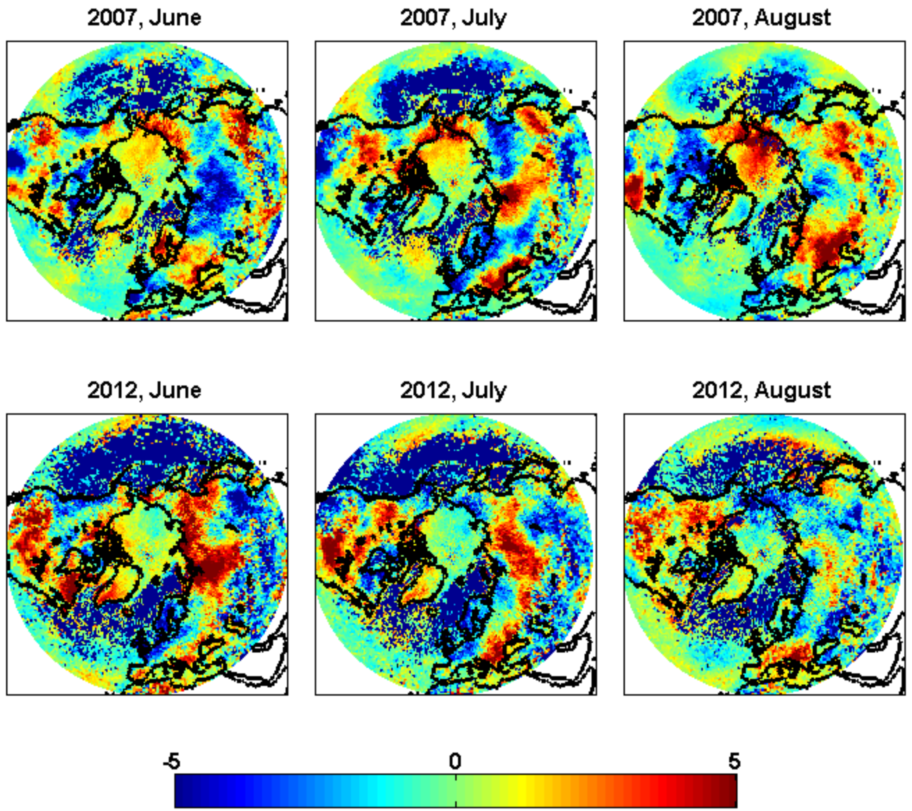

Fig. 5. Surface skin temperature [K] anomalies for the summer months of 2007 (top row) and 2012 (bottom row).

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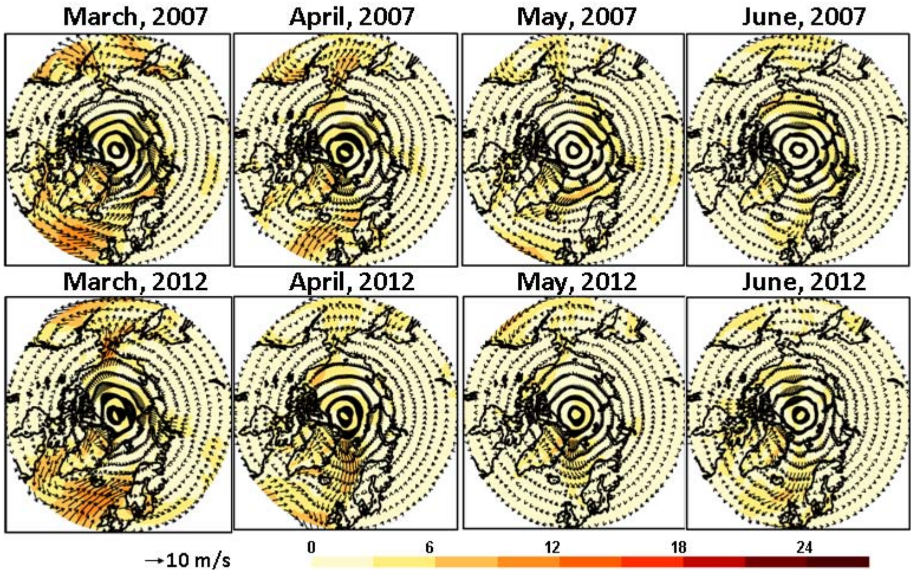

Fig. 6. Near-surface winds (1000 hPa) during spring and early summer based on ERA-Interim Reanalysis. The data for June 2012 is from the ECMWF forecasts.

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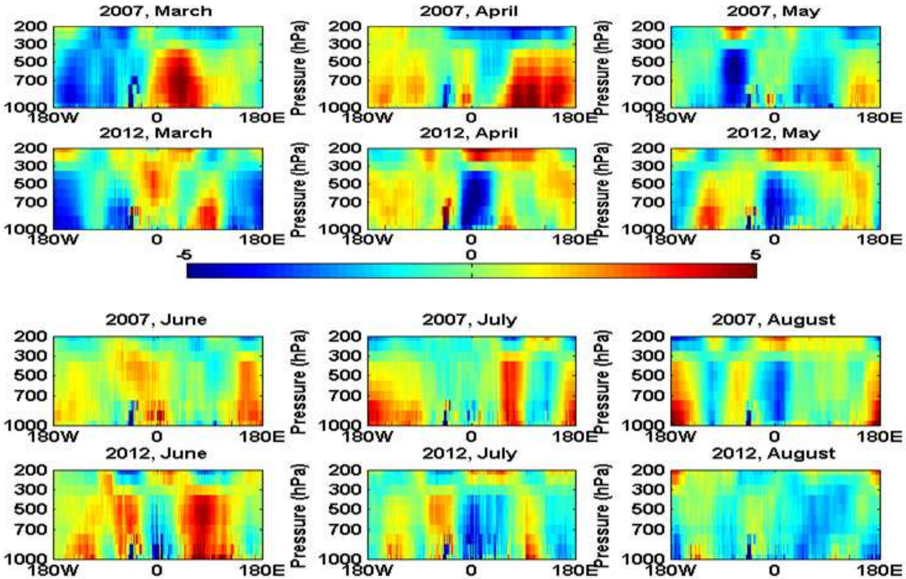

Fig. 7. Meridional-vertical distribution of temperature anomalies [K] for the spring (top twp rows) and summer (bottom two rows) seasons. Temperatures at each pressure level are averaged over the latitude band of 65° N–75° N.

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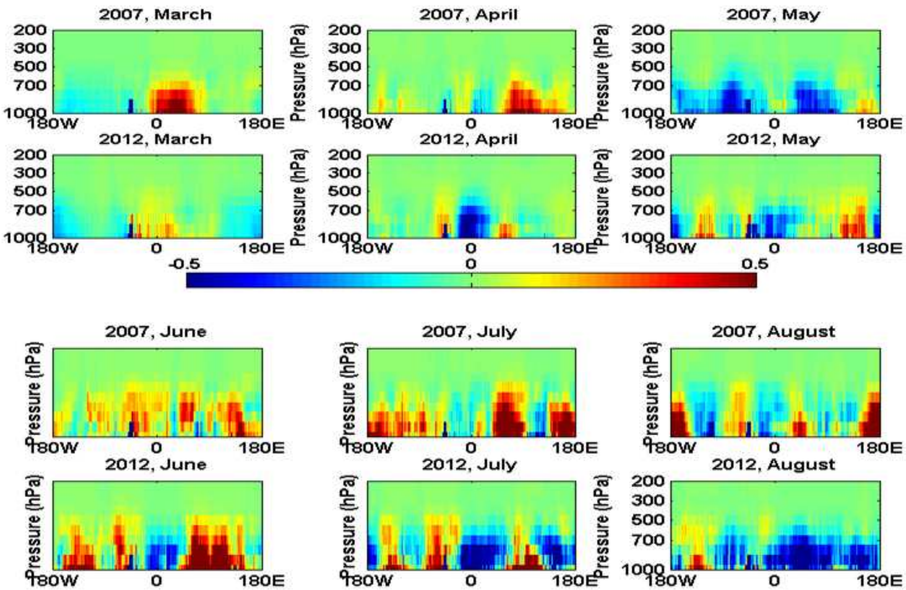

Fig. 8. Meridional-vertical distribution of water vapour mass mixing ratio anomalies [$g\,kg^{-1}$] for the spring (top two rows) and summer (bottom two rows) seasons. Mixing ratios at each pressure level are averaged over the latitude band of 65° N–75° N.

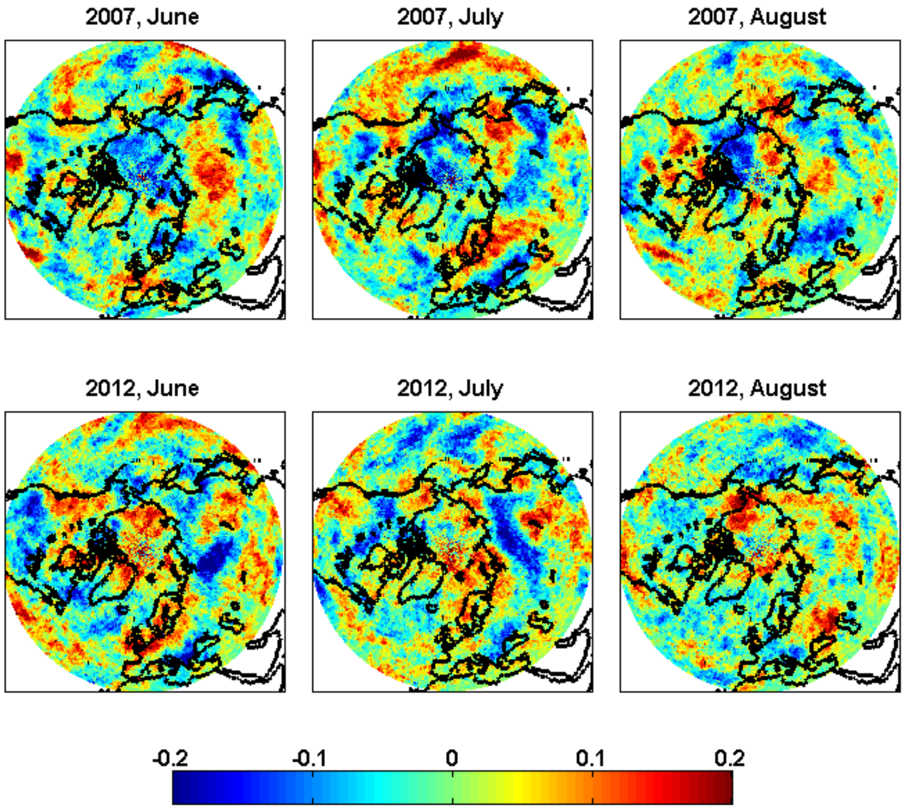

Fig. 9. Total cloud fraction anomalies for the summer months of 2007 (top row) and 2012 (bottom row).

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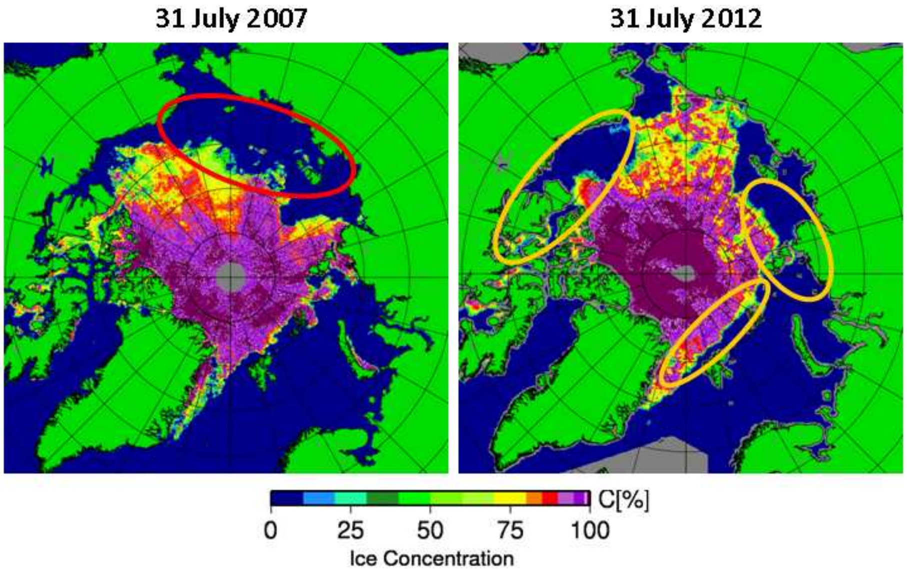

Fig. 10. Sea-ice concentration over the Arctic as observed on the 31 July 2007 and 2012. The ellipses marked in red and yellow colours show the regions that experienced accelerated melting in 2007 and 2012 respectively. The sea-ice concentration data was obtained from the University of Bremen website providing near-real time information (Spreen et al., 2008).

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