Norrköping, 2013-04-11

We thank both referees for their comments that led to substantial improvement of the original manuscript. The entire results and discussion section is now restructured to describe results season-wise and to avoid jumping references to figures. Furthermore, all figures (except Fig. 1) are revised, rearranged, and two new figures are added.

The response to individual referee comments is given below.

Response to referee #1

We would like to thank the referee for providing constructive criticism.
The main concerns of the referee can be grouped into following three points: 1) significance of anomalies, 2) uncertainties in data sets, and 3) regional response of thermodynamics and circulation during extreme versus normal events. These points are elaborated below.

1) Significance of the anomalies

In the revised manuscript, we calculated standard deviation of temperature, humidity and cloud fraction, and masked out those anomalies that lie below one-sigma level. This should retain significant pattern showing the large-scale signal. The original figures are revised accordingly (pl. see below all revised figures). We additionally show meridional-vertical distribution of anomalies for the winter months as well. It can be clearly seen that:
a) The persistent warming observed in the Eurasian sector (over Kara Sea, Nansen Basin, Laptev Sea) during winter of 2011-12 is indeed significant (Fig. 3 below).
b) This warming pattern continued in early spring (Fig. 5). In May, Canadian archipelago was warm and continued to be warmer till July.
c) Fig. 6 further shows cold and dry air over the Atlantic sector during April, confirming our assertion (based on surface winds) that the sea-ice export out of the Arctic was unusually strong in April 2012 and continued in summer. Note that these T and q anomalies also exceed one-sigma level.

We also quantified vertically integrated moist static energy flux across 65N-85N (Fig. 7).

$$MSE = \int_{p_{100hPa}}^{p_{1000hPa}} \left[c_p T + gdz + Lq \right] \frac{dp}{g} \qquad (1)$$

Where, where c_p is the specific heat of air [1004 J kg^{-1} K^{-1}], T is temperature [K], g is the gravitational acceleration [9.81 m s^{-2}], z is height [m], L is the latent heat of vaporization [2.5x10^6 J kg^{-1}], q is the water vapor mixing ratio [kg kg^{-1}], and p is pressure [Pa]. Figure 7 shows mean meridional vertical integral from 65-85°N of MSE monthly anomalies calculated from (1) for December through May; anomalies for all years are shown in gray, while 2007 and 2012 anomalies are in blue and red, respectively. These vertical integrals of moist static energy suggest that during winter, the Eurasian sector of the

Arctic experienced positive anomalies associated with increased temperature and water vapor advection during 2012.

2) Uncertainties in the data set

The temperature and water vapour profiles from AIRS have reached validation stage 3, meaning that the uncertainties in the product well-established via independent measurements made in a systematic and statistically robust way that represents global conditions.

The stated accuracies for temperature and WV profiles are 1K/km and 15%/2km respectively (http://airs.jpl.nasa.gov/data/product_accuracies/). The Level 3 products used here have especially screened for "best" or "good" quality Level 2 retrievals, meaning that these products can be used for statistical climate studies as the one we did here. (http://disc.sci.gsfc.nasa.gov/AIRS/documentation/v5_docs/AIRS_V5_Release_User_Docs/V5-L2-Quality-Control-and-Error-Estimation.pdf)

Over the years, a number of studies have validated AIRS retrievals, including over the high latitude regions (Special issue in JGR – Divakarla et al., 2006; Fetzer, 2006; Gao et al., 2006).

3) Extreme (EX) versus non-extreme (NE) events

A lot can be gained by compositing atmospheric conditions during the EX and NE events. However, this in itself is a separate research topic (as the referee herself/himself points out), and beyond the scope of the present study. Nonetheless, based on a decade of satellite data we have at hand (i.e. 2003-2012), we investigated how the atmosphere manifests itself during the EX and NE events. We selected four years (after taking linear trend into account), namely 2007, 2008, 2011 and 2012, as EX events and the remaining six years as NE events. Then, we composited atmospheric state variables for these two cases during different seasons.

Fig. S1 below shows the composites for surface skin temperatures. It is interesting to note that the Eurasian sector shows consistent warming (cooling) during the EX (NE) events in winter and spring. The warming over the Arctic Ocean during summer in the EX events is also clearly visible (in part due to heat absorption by excessive melting water). The composites of geopotential heights at 500 hPa (Fig. S2) further show that the large-scale circulation pattern leads to advection of heat from these sectors towards central Arctic.

Please note that these results are not included in the revised manuscript, as they do not directly fit into the scope of the current investigation. These preliminary results, however, deserve separate investigations using longer data sets such as reanalyses.

Response to other specific comments:

1) The model internal variability certainly contributes to intermodel differences, but it is more likely to be important if one selects individual year or very short time scales for intercomparison. For climatological averages over 30 years or so, the differences in model physics and sensitivity to initial boundary conditions are likely to be more important.
2) By “different dynamical controls”, we are referring to the fact that the circulation dynamics is different during these two events leading to different atmospheric thermodynamics, which eventually has an influence on the rate of ice melt.
3) It would be very useful if there is commonality (or few modes of commonality) in the patterns of temperature, WV, and wind anomalies during extreme events. If so, this could be detected earlier from the satellite data and can serve as a warning signal to forecast models.
4) Description regarding correspondence of GPH and surface temperature anomalies is rephrased to improve clarity.
5) Ogi and Wallace (2012) is cited in the revised version. We thank the referee for pointing out this useful reference. Ogi and Wallace (2012) reported on the importance of near-surface wind in regulating sea-ice transport out of the Arctic via Fram Strait. They investigated wind patterns over the Arctic from May onwards. Here, we show that, in contrast to 2007, the near-surface winds were already favouring sea-ice export in April in 2012 via the Fram Strait (Fig. 8). In addition to the 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, clearly evident in meridional-vertical thermodynamic anomalies (Fig. 6) and MSE anomalies (Fig. 7), are consistent with negative surface temperature anomalies over these regions (Fig. 5). This lends further support to the case that 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. Thus, in 2012 winds played even more important role compared to the previous 2007 SIM sea-ice minimum events.

Response to referee #2

The main criticism of the referee is that "...Sea ice will fluctuate around its overall downward trend, and the community does not need a description of the atmosphere every time a negative anomaly from the trend sets a new record...."

We respectfully disagree with the opinion of the referee. We, in fact, think that we need to understand atmospheric conditions during such events more than ever. We clarify few reasons below.

1) First of all, sea-ice melting events of 2007 and 2012 are not something that "fluctuates around its trend". The ice extent was well below 2-sigma levels during 2007 and 2012 in the satellite era (i.e. from 1979). In fact, the Arctic lost about 3/4 of its normal ice extent during the summer of 2012.

2) None of the regional or global climate model could predict sea-ice loss occurred in the summer of 2007 or 2012. In a way, this is not surprising considering how little we know about the Arctic climate system, partly due to lack of adequate observations. In response to the shocking event of sea-ice minimum of summer 2007, in the framework of Study of Arctic Environmental Change (SEARCH), the international community now issues sea-ice extent forecasts (Pan-Arctic Outlook) for Sept every year from June onwards (and updating it every month). Estimates from about 23-28 models are usually issued. These models use different approaches for forecasting sea-ice extent. In spite of such an impressive array of models, none of them could forecast the sea-ice minimum in Sept 2012, even one month before (i.e. in Aug 2012) the annual minimum. For example, please see here:
http://www.arcus.org/search/seaiceoutlook/2012/august

Therefore, any knowledge that we can gather from observations regarding such extreme events will hopefully be useful to reflect back and investigate response of atmosphere in these models compared to the observations (as reported here in our study).

3) There is a consensus building in the Arctic scientific community regarding the importance of preconditioning in winter and spring seasons leading to extreme melt event in the subsequent summer. As shown in our revised results (in response to comments from Referee #1) and as argued in the original manuscript, preconditioning is indeed important. So our study provides a solid observational basis for the vital role of preconditioning.

4) By contrasting the extreme events of 2007 and 2012, we additionally show that the manifestation of preconditioning itself could be very different from one event to another, both geographically and thermodynamically. For example, while the Pacific sector of the Arctic was favouring ice melt in 2007, the Atlantic and Eurasian sectors, on the other hand, had conditions conducive for eventual sea ice melt in summer 2012. While the

advection of warm moist air from the Pacific played an important role in 2007 melt season, it was the persistent surface warming of the Eurasian sectors and efficient sea-ice export out of the Arctic since April that was mainly responsible in 2012.

These reasons undoubtedly call for better understanding of the evolution of the atmosphere and its variability during extreme events so that we can distil tell-tale signs of preconditioning to eventually use them to fine tune early detection of such events.

We kindly request the referee to further go through our reply to the referee #1 and also the revised manuscript. We would definitely be willing to work further if the referee has other concerns.

Technical corrections:

1) The method for calculating AO phase is mentioned in the revised manuscript. http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml

2) Yes. The monthly anomalies are with respect to climatology corresponding to that particular month. This is clarified in the revised text.

3) The approximate longitudes are specified in the revised text when explaining vertical cross-sections.

4) The (old) Fig. 6 is revised.

Revised figures (except Fig. 1)

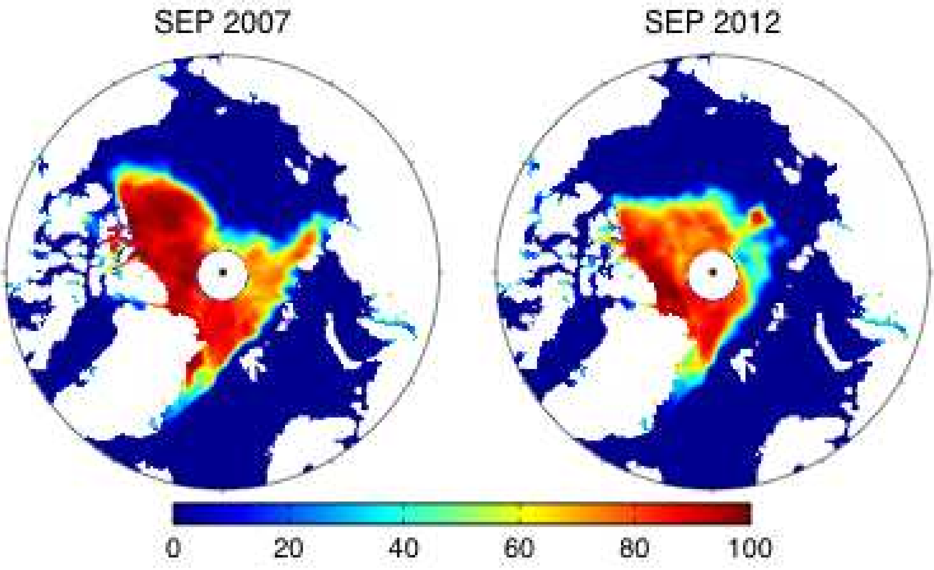


Fig. 1: Monthly mean sea ice concentration (contours [%]) for the September of 2007 and 2012. Sea ice concentration data are taken from the Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave dataset using Platform F13 and near-real time Platform F17 (Cavalieri et al. 1996).

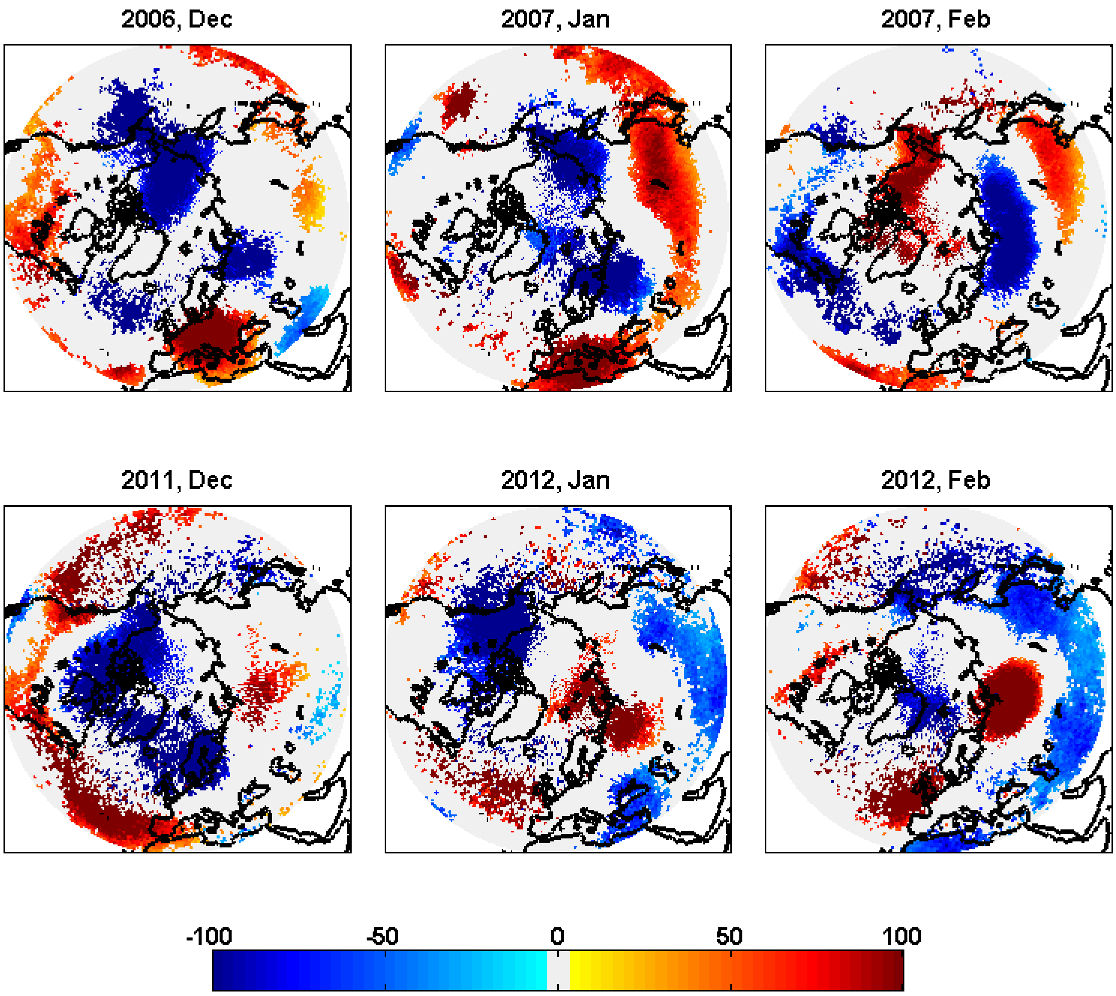


Fig. 2: Geopotential height anomalies [m] for the DJF months of 2006/07 (top row) and 2011/12 (bottom row). The regions with anomalies less than one standard deviation masked out.

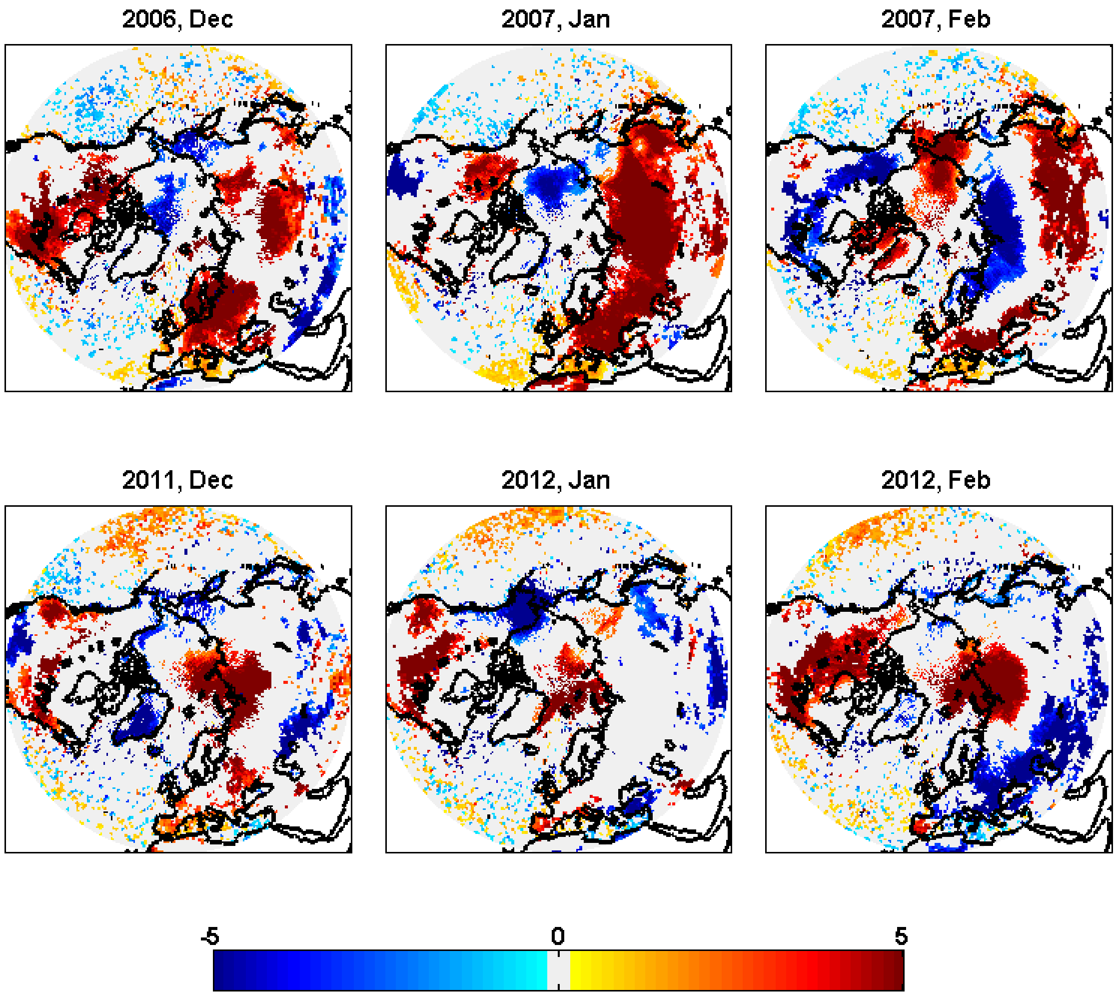


Fig. 3: Surface temperature anomalies [K] for the DJF months. The regions with anomalies less than one standard deviation masked out.

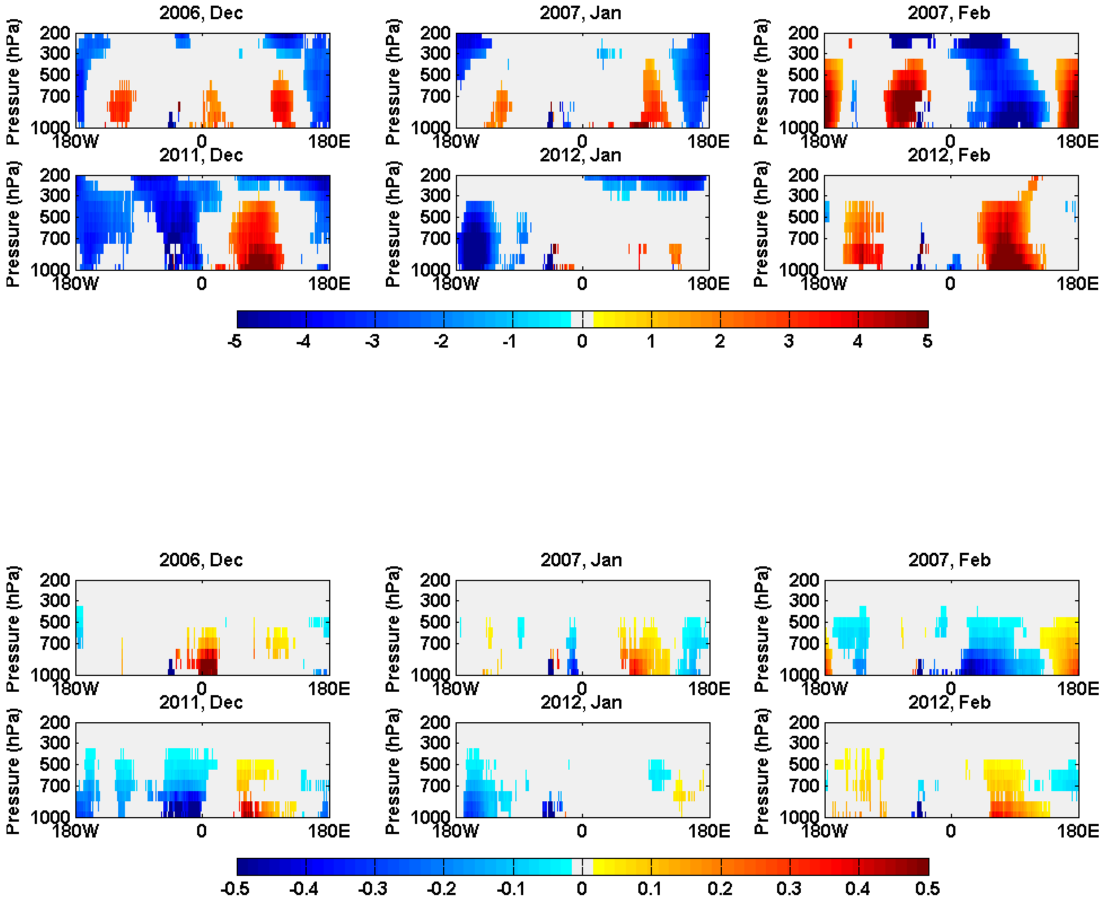


Fig. 4: Meridional-vertical distribution of 2007 and 2012 winter (DJF) temperature anomalies [K] (top two rows) and water vapor mass mixing ratio anomalies [g/kg] (bottom two rows). Temperatures and water vapor mixing ratios at each pressure level are averaged over the latitude band of 65N-75N. The anomalies that lie below one-sigma level are masked out.

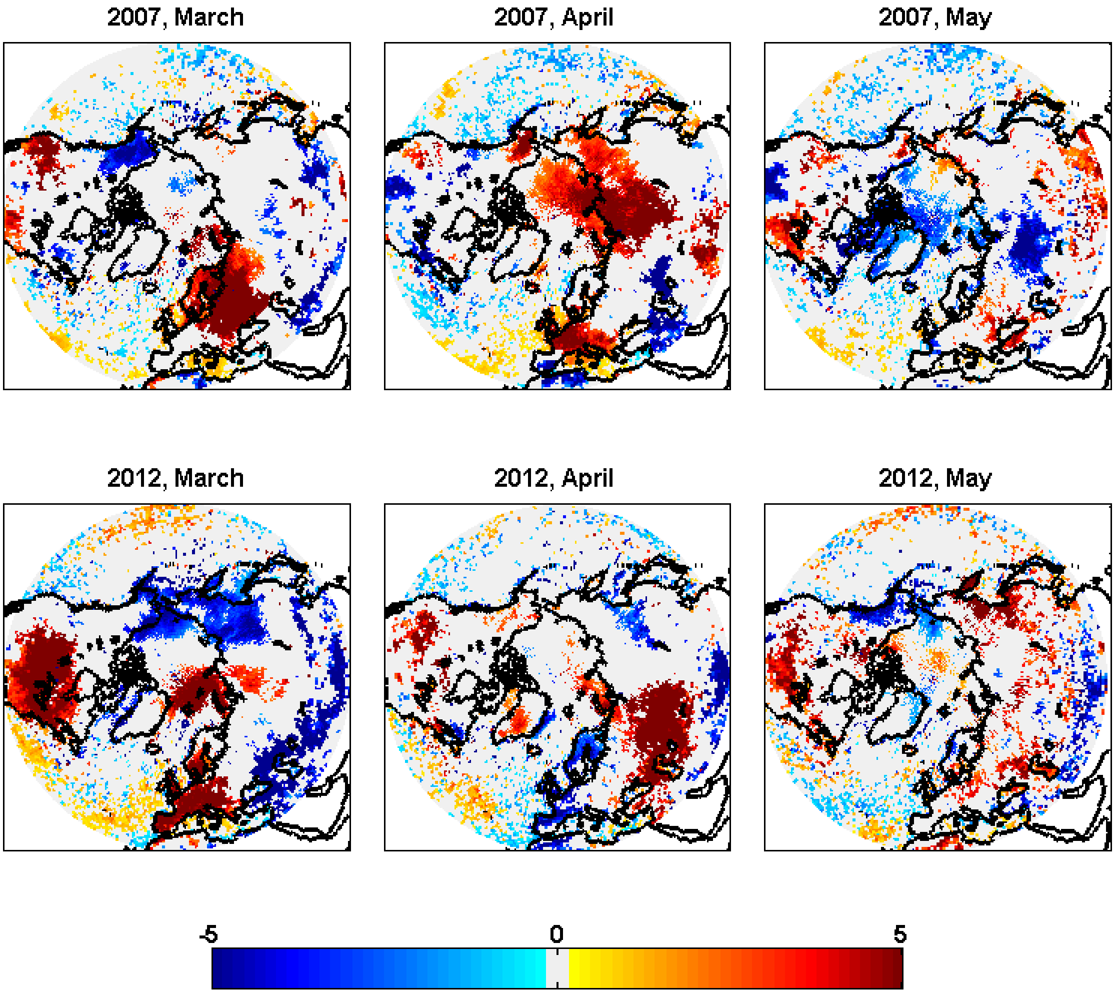


Fig. 5: Surface skin temperature [K] anomalies for the MAM months of 2007 (top row) and 2012 (bottom row).

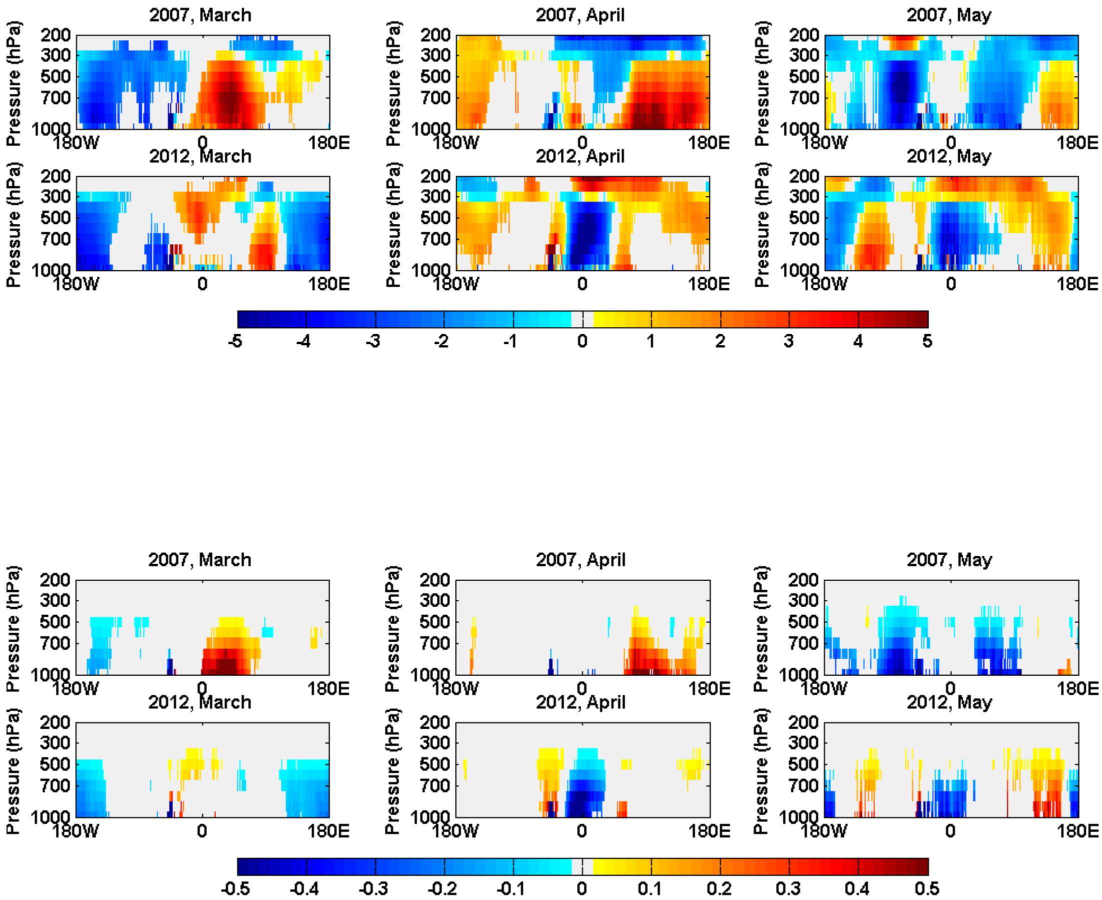


Fig. 6: Same as in Fig. 4, but for the MAM months.

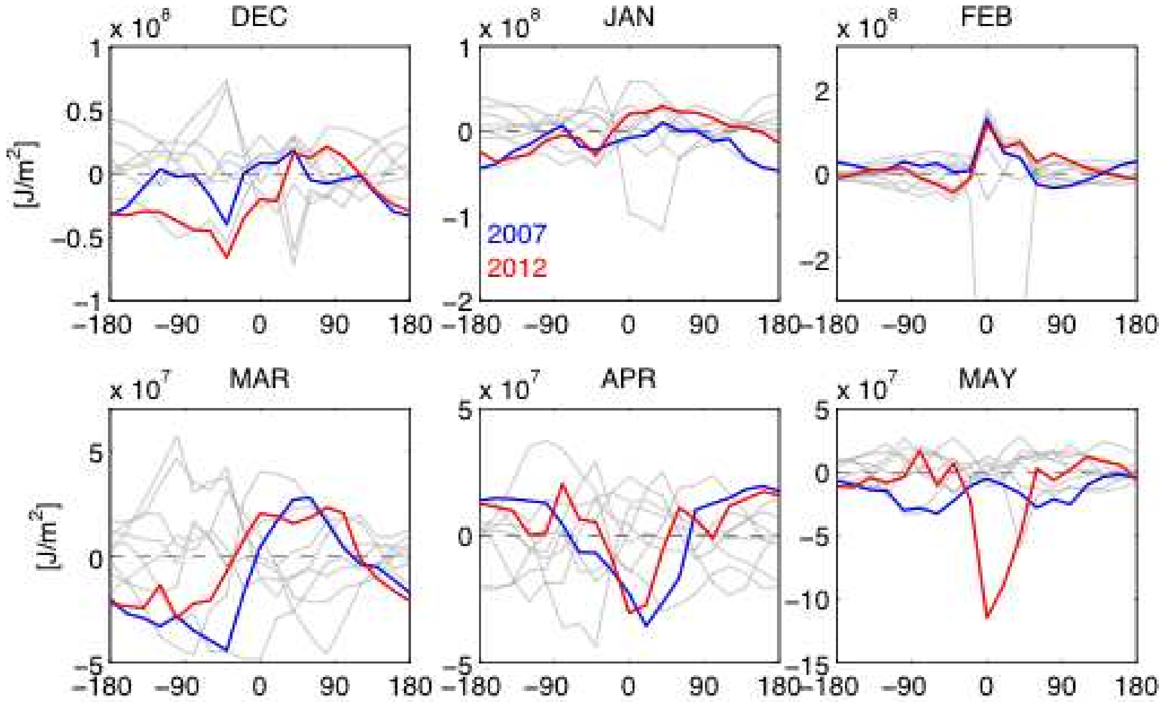


Fig. 7: Meridional means of mass-weighed vertically-integrated MSE [J m-2] monthly anomalies for the latitude band 65-85N. Monthly anomalies are estimated relative to the 2003-2012 monthly averaged vertical integrals of MSE at each AIRS grid point between 65-85N. Merdional averages are shown for 20 degree bins. Gray lines are all months (DJFMAM) for 2003-2012, with 2007 and 2012 highlighted in blue and red, respectively.

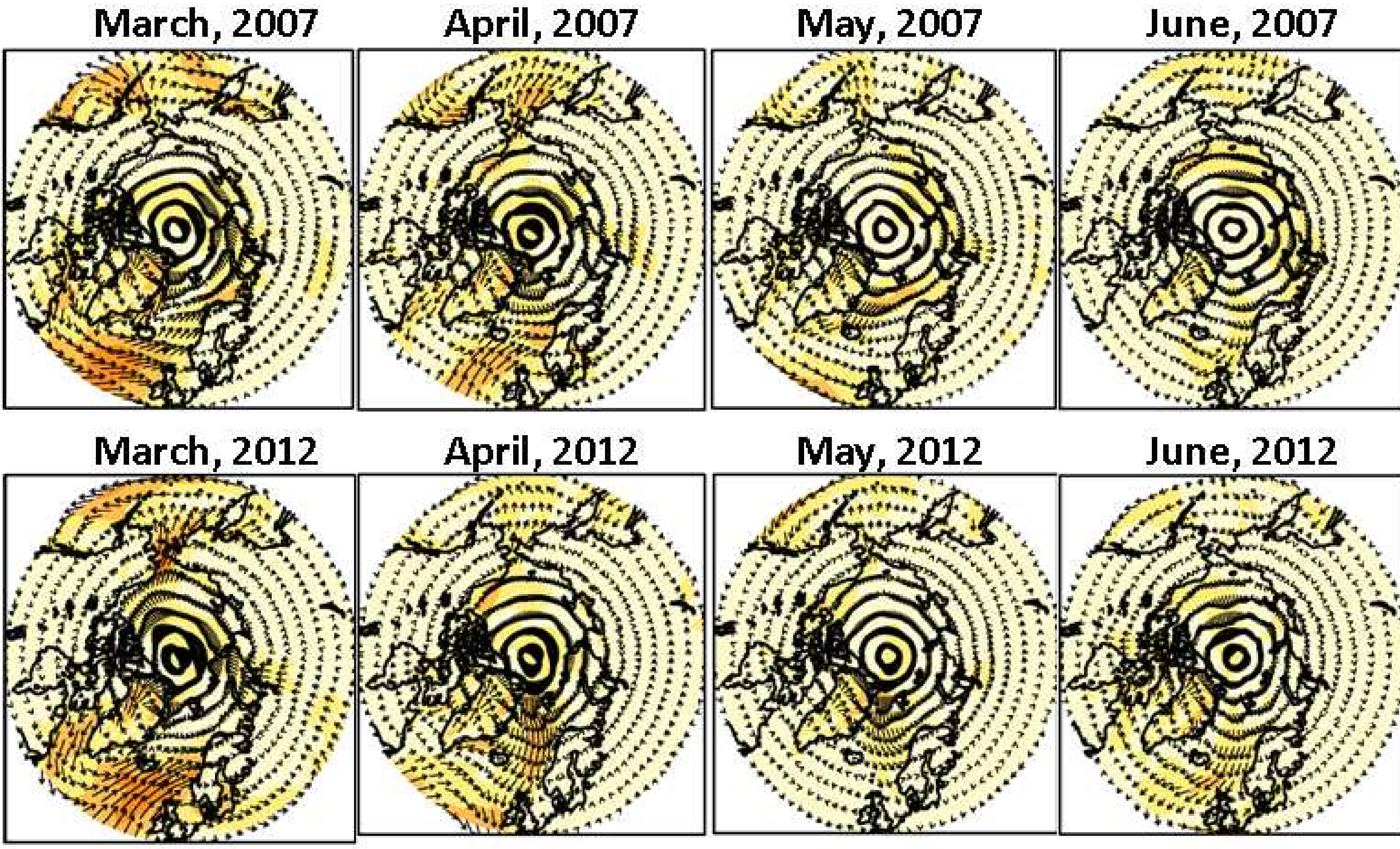


Fig. 8: Near-surface winds (1000 hPa) during spring and early summer based on ERA-Interim Reanalysis. The data for June 2012 is from the ECMWF forecasts.

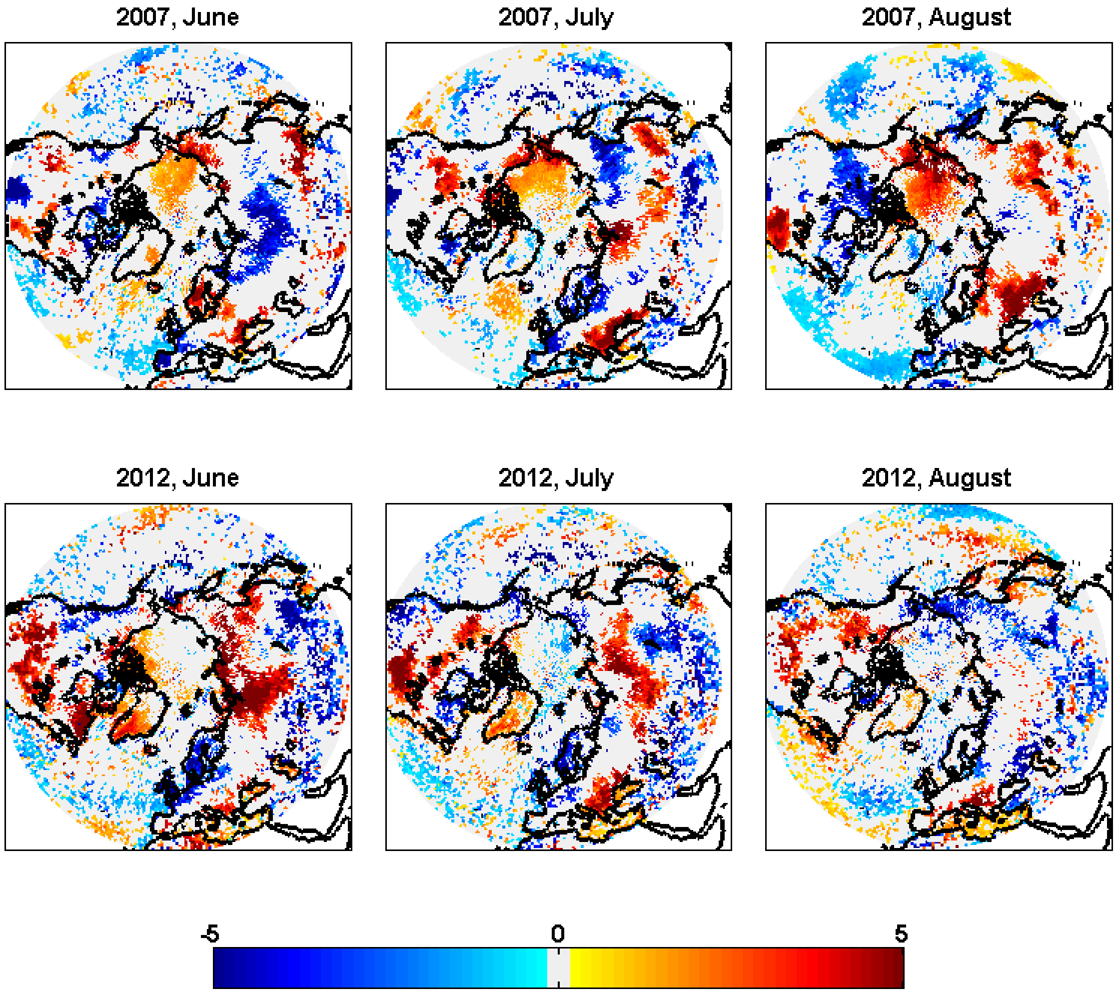


Fig. 9: Surface skin temperature [K] anomalies for the JJA months of 2007 (top row) and 2012 (bottom row).

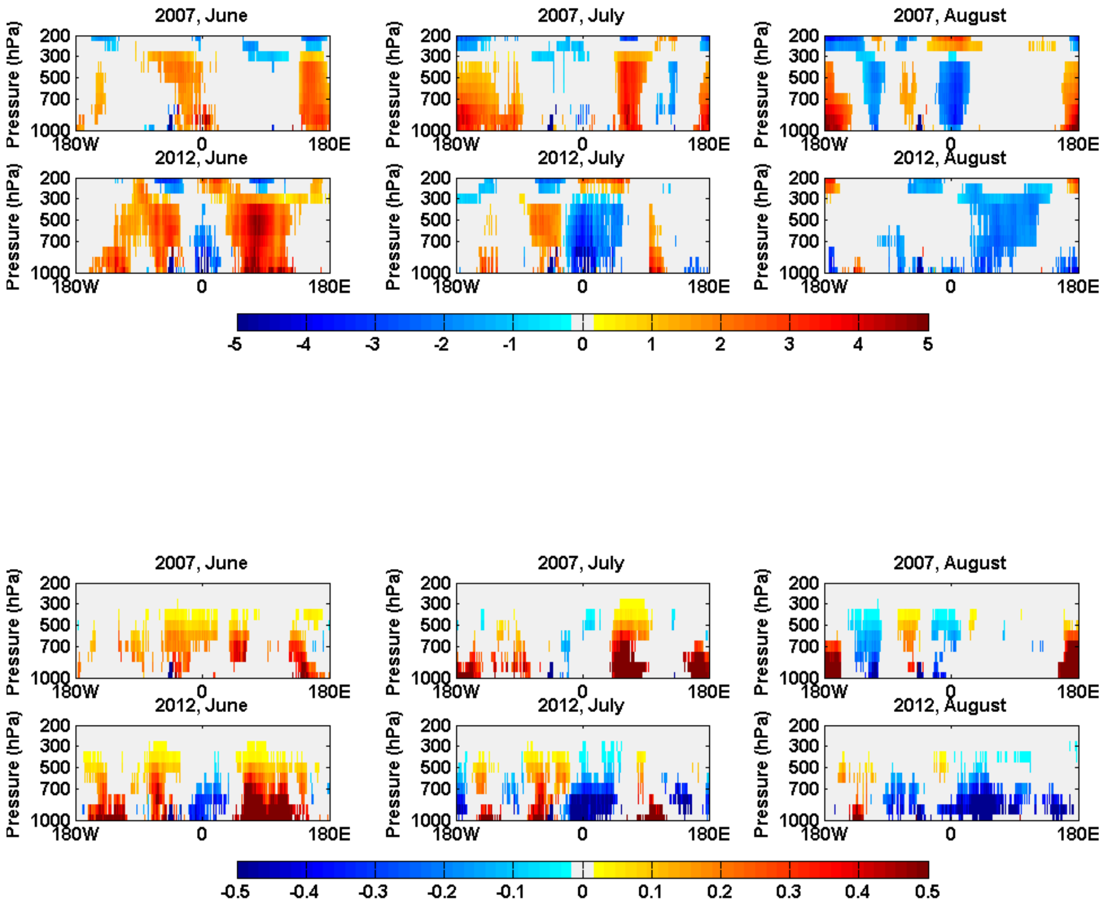


Fig. 10: Same as in Fig. 4, but for the summer months.

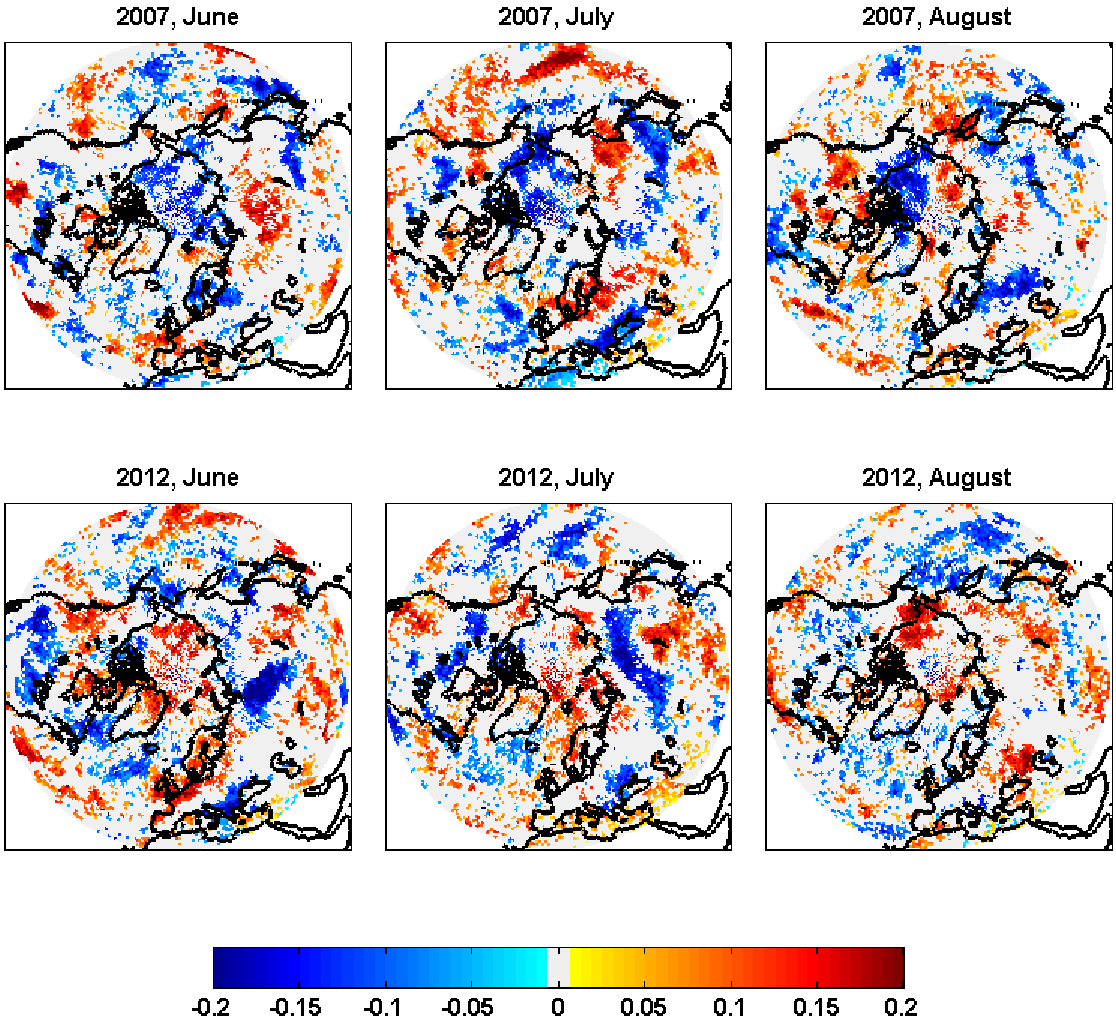


Fig. 11: Cloud fraction anomalies for the JJA months of 2007 (top row) and 2012 (bottom row).

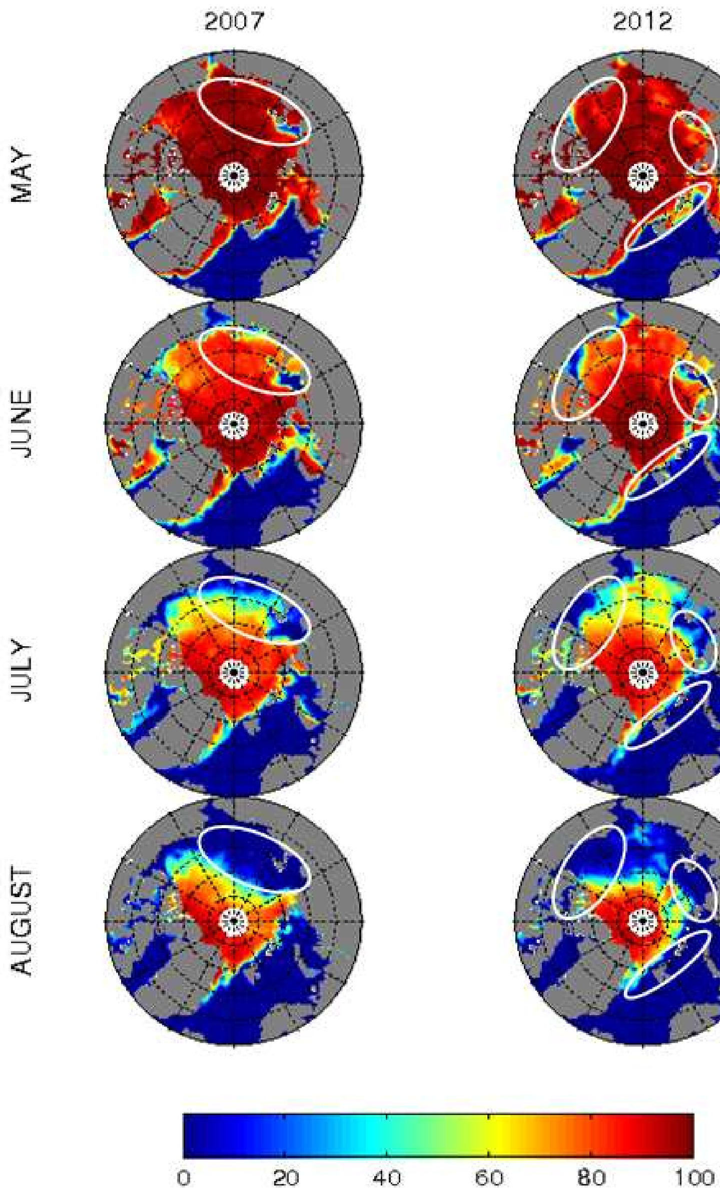
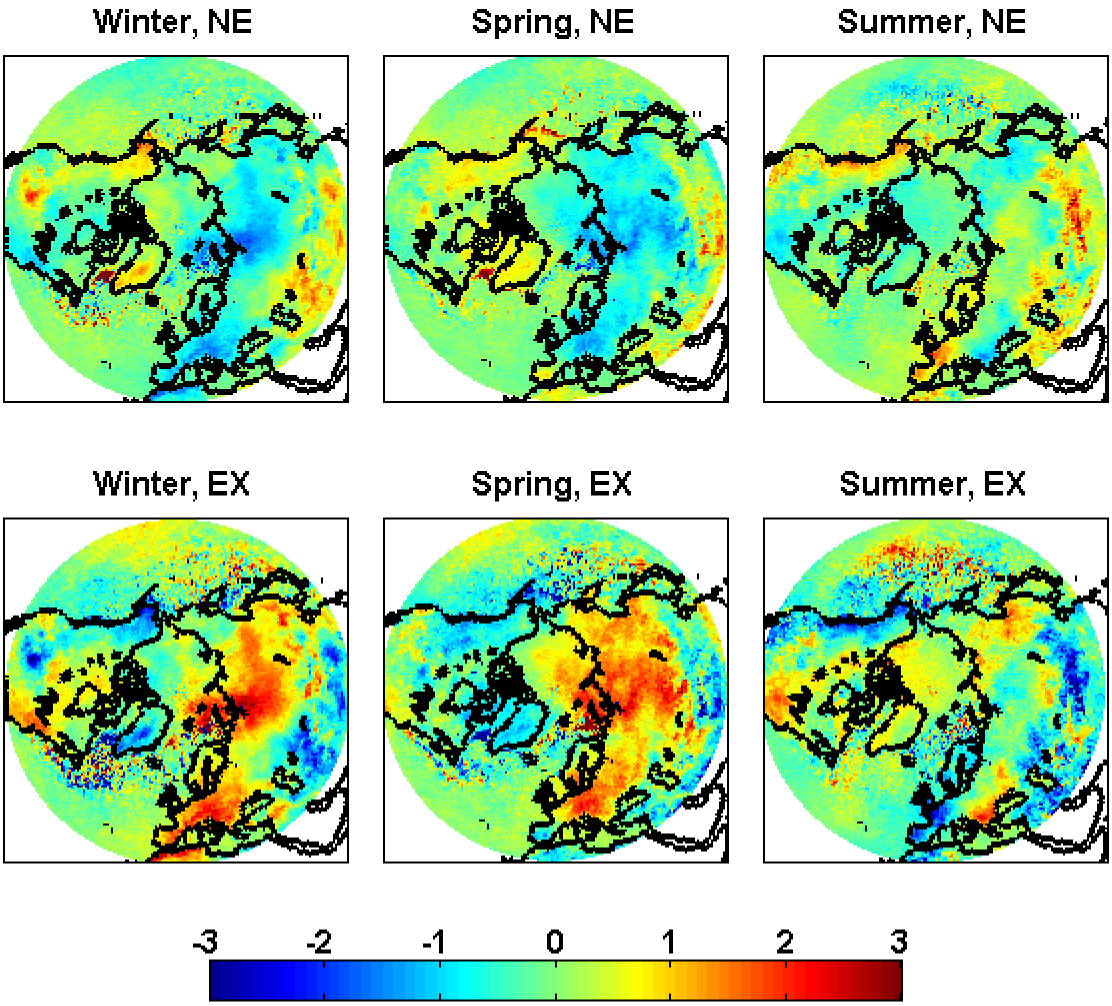
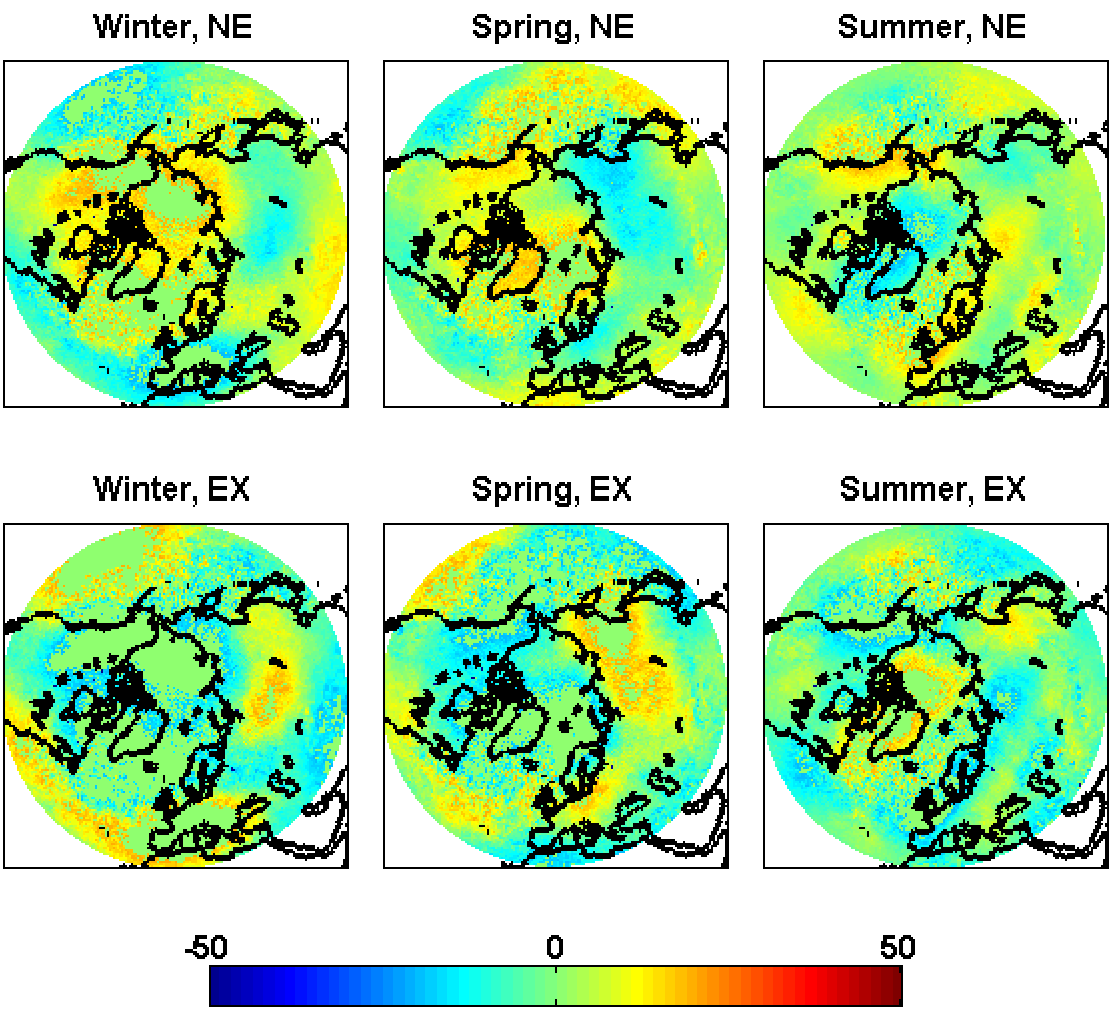


Fig. 12: Monthly mean sea-ice concentration from May through August of 2007 (left column) and 2012 (right column). The areas highlighted by white ellipses show regions that experienced accelerated sea-ice melt during these years. The same data set as in Fig. 1 is used. The disappearance of sea-ice is clearly evident in these highlighted areas.

Analysis of composites of non-extreme (NE) events and extreme (EX) events



S1: Composites of surface temperature anomalies [K] during NE and EX events.



S2: Composites of geopotential height anomalies [m] at 500 hPa for the NE and EX events.