A look at the date of snowmelt and correlations with the Arctic Oscillation

(IGS, Seasonal Snow Symposium -- Lahti, Finland, May 2012)

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submitted to Annals of Glaciology

Abstract

Spring snow cover across Arctic lands has, on average, retreated approximately five days earlier since the late 1980s compared to the previous twenty years. However, it appears that since about the late 1980s, the date the snowline first retreats north during the spring has changed only slightly -- in the last twenty years or so the date of snow disappearance has not been occurring significantly earlier. Snowmelt changes observed since the late 1980s have been step-like in nature, unlike a more continuous downward trend seen in Arctic sea ice extent. At latitude 70ºN, several longitudinal segments (of 10 degrees) show significant (negative) trends. However, only two longitudinal segments at 60ºN show significant trends, one positive and one negative. These variations appear to be related to variations in the Arctic Oscillation (AO).

When the springtime AO is strongly positive, snow will melt earlier. When the springtime AO is strongly negative, snow disappears later in the spring. The winter AO is not as straightforward, however. At higher latitudes (70ºN), a positive AO during the winter months is correlated with a later snow melt, but at lower latitudes (50ºN and 60ºN), a positive wintertime AO is correlated with an earlier snow melt. If the AO during the winter months is negative, though, the reverse is true. Similar step-wise changes (since the late 1980s) have been noted in sea surface temperatures and in phytoplankton abundance as well as in snow cover.

Introduction

Both empirical and modeling studies have illustrated the influential role that snow cover plays within the global heat budget (Walsh and Chapman, 1990). Because of the importance of snow cover as a climate variable and as a component in the Earth's energy budget, various components of the cryosphere, including seasonal snow cover and sea ice, have been analyzed to identify changes that may be correlated with each other as well as with other climate indicators, particularly surface air temperature. The timing of snowmelt is impacted by whether a region is dominated by continental or maritime climatic influences, by whether the snow pack faces north or south and whether it sits at a higher elevation Moreover, percent of sunshine, the position of storm tracks and the thickness of the snow pack all affect the interannual variability (Foster et al., 2008)

In the late 1980s, Foster et al. (1989) examined the date of snow disappearance as measured at meteorological stations in the tundra of Eurasia and North America. The date of snowmelt was found to be occurring earlier in the spring since the late 1960s over much of the North American tundra. In Barrow, Alaska, a trend toward earlier snowmelt was evident after about 1950. Nevertheless, running means of the date of snow disappearance across much of northern Russia (north of 70ºN) displayed no such trend. In the early 1990s, satellite observations confirmed the earlier date of snow disappearance poleward of 70ºN as compared to visible satellite observations at the start of the satellite record -- 1970s (Foster et al., 1992).

Robinson and Dewey (1990) also observed declines in snow cover extent (SCE) in the mid to late 1980s. By the mid and late 1990s, it had become more obvious that the spring SCE changes identified in the 1980s represented more of a stepwise change, and not a steady drop in snow extent (Robinson et al., 1995; Robinson and Frei, 2000). The step like change in Northern Hemisphere SCE during 1986-87 was first identified in the publication by Robinson, D.A. (1996). The time period studied in this paper uses observations from January 1972 to September 1996, with the earlier period running from 1972-1985 and the later period 1986-1996. The 12-month running means of these two periods (25.9 million sq. km and 24.2 million sq. km, respectively) are significantly different (T test, $p < 0.01$).

Annual averages of SCE since the mid 1980s have remained approximately 2 million square kilometers (about 8%) lower than averages in the period from the late 1960s to the late 1980s – the first 20 years of the satellite era. For more on this see Foster et al. (2008). This paper examines snow disappearance data through 2004.

In recent years, the Arctic Oscillation (AO) has been linked to fluctuations in certain climate parameters and to changes in snow/ice features. The surface AO can be traced back in time to originate in the middle stratosphere and propagates through the lower stratosphere and then through the entire troposphere on a time scale of one to two weeks (Cohen et al., 2010). The influence of the winter AO on spring snow cover has been discussed previously in Bamzai (2003). Additionally, Saito and Cohen (2003) looked at the potential role of snow cover in forcing interannual variability, and Saito et al. (2004) have studied changes in the sub-decadal co-variability between Northern Hemisphere snow cover and the general circulation of the atmosphere. They found that decadal changes in the date of snowmelt correlate in some degree to the position of atmospheric pressure patterns, including the AO. According to their results, a shift in the storm track could result in snowfall being less frequent in boreal forests, for instance, in more recent years compared to earlier in the satellite era. Therefore, the spring snow pack would be thinner and likely melt away more readily.

The Arctic atmosphere has been warming for more than two decades now and sea ice extent regularly falls below previously observed minima (Comiso and Parkinson, 2004; Parkinson, 2006; Serreze and Barry, 2011). We believe an investigation is warranted that examines recent trends in the character of spring snowmelt over the mid and high latitudes of the Northern Hemisphere, during the period from 1967-2011. Our intent is to both further extend our earlier results by using satellite- derived snow maps to evaluate the timing of the retreat of spring snow cover in the Arctic and subarctic, and to see if there is a meaningful correlation between the date snow disappears from these latitudinal bands and the strength and direction of the winter AO (January, February, March and the spring AO (March, April, May). The thrust of the paper is then to determine if the date of snow disappearance from specified latitudinal boundaries (the week when the snowline first retreats north of the boundary), is significantly related to fluctuations of the AO (also known as the Northern Annular Mode (NAM), which is the dominant mode of Northern Hemisphere, extratropical climate variability (*Thompson and Wallace*, 1998).

Methodology

In earlier investigations, the authors examined weekly maps of continental SCE produced by the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Data and Information Service (NESDIS) (Matson et al., 1986; Robinson et al., 1993; Ramsay, 1998). These maps are the crux of the longest satellite-derived environmental dataset available and have long been the premier dataset used to evaluate large-scale NOAA/NESDIS snow maps dating back to late 1966. Polar stereographic snow maps have been digitized using a hemispheric 128 x 128 cell (half mesh) grid. The temporal resolution of this dataset is weekly. For more details regarding how snow is mapped and the quality of the NOAA satellite interpretations of snow, see - http://climate.rutgers.edu/snowcover, and also Foster et al. (2008) and Wang et al. (2005).

For this study, the years 1967 to 2011 were examined. As was the case in the 2008 study (Foster et al., 2008), at 60ºN, 16 longitudinal segments were selected for study. The final week of snow cover is the last week during which snow cover was observable from visible/infrared satellite imagery for those locations where a snow pack was established – snow covered the ground for more than one week. Thus the week (end of 7-day period) when the snowline first retreats north of 70º N (and 60º N) is determined to be the date of snow disappearance.

At 70ºN, predominantly land-covered cells were identified. All cells at 70ºN are considered maritime with tundra vegetation most prevalent (Foster et al., 2008). In contrast, a number of the longitudinal segments at 60ºN have a high degree of climatic continentality, particularly in Eurasia. These segments reside mostly within the boreal forest zone. Note that the segments at 60º N are grouped by longitude. However, the individual grid cells at 70º N do not necessarily correspond with lines of longitude. The decision to use individual grid cells at 70º N was made considering the coarse resolution of the Northern Hemisphere weekly snow product...

Snow covered areas within mountain shadows may sometimes be mapped as snow free, and large water bodies can influence the timing of melt. We therefore decided that predominantly mountainous segments or segments that included a substantial amount of water would not be evaluated.

The days/decade change for individual longitudinal segments at 60° and individual cells at 70° determined the annual snow disappearance date, using linear regression. The mean day of snow disappearance for the period before the previously mentioned stepwise change (1967-86) and after this change (1987-2011) was calculated for comparison purposes.

For values of the AO, we used NOAA monthly derived values. Monthly values were averaged to produce seasonal means. To compute the linear relationship between the monthly/seasonal AO values and the date of snow disappearance, we computed the correlation coefficient between the AO values and the calendar week that snow cover was last observed.

Arctic Oscillation and Relation to Seasonal Snow Cover

The AO, the first leading mode of sea level pressure, is strongly correlated with tropospheric climate fields in the boreal extratropics. It is a dipole pattern with one anomaly covering much of the Arctic and a second anomaly stretching across the mid-latitudes but focused in the ocean basins, peaking in strength during the coldest months. The AO's early-season onset is not well understood, however, it is postulated that an atmospheric teleconnection pathway, with origins at the surface over northern Eurasia, may be involved (Cohen et al., 2010). Anomalies of early season surface diabatic heating across Eurasia are believed to result from seasonal variations in snow extent (Saito et al. 2001; Saito and Cohen, 2003). It appears to take approximately 4-weeks for such anomalies to propagate from the troposphere to the stratosphere (Cohen and Barlow, 2003). The stratosphere-to-troposphere downward propagation of associated AO anomalies, as the snow season progresses, has been well documented (Saito and Cohen, 2003; Saito et al., 2004; Cohen et al., 2007).

Regime shifts in the AO were computed following the methodology of Rodionov (2004). We found one robust regime shift associated with the AO positive/negative phase of 1988/89 (see Figure 1) that is concomitant with the step-like changes noted in date of snow disappearance. The positive phase of the AO brings lower-than-normal pressure over the polar region – higher pressure accompanies the negative phase. According to Thompson and Wallace (2000), the positive phase of the AO accounts for more than half of the surface air temperature trends over Alaska, Eurasia, and the eastern Arctic Ocean but less than half in the western Arctic Ocean.

It was reported in Cohen et al. (2010) and Foster et al. (2012) among others that one of the biggest contributing factors to the unusually severe winter weather in 2009/10, in both Europe and eastern North America, was a persistent exchange of mass from north to south, with unusually high pressure at high latitudes and low pressure at mid-latitudes. A back and forth or seesaw pattern is a classic signature of the AO index. The AO of 2009/10 was the most negative observed since at least 1950 (Figure 1). Empirical orthogonal function analysis of sea level pressure poleward of 20ºN resulted in a standard deviation of -2.5 (Cohen et al., 2010). Using a skillful winter temperature forecast, it was shown by Cohen et al. (2010) that the AO explained a greater variance of the observed temperature pattern across the extratropical landmasses of the Northern Hemisphere than did El Nino Southern Oscillation (ENSO), (Foster et al., 2012).

Results

North of 60º N, snow begins to retreat between mid April and mid May, while north of 70ºN, the pack may melt out in late May or last until early July. The present study has shown that date of snow disappearance in the spring continues to occur earlier now than in the late 1960s/1970s over much of the Northern Hemisphere. At 60ºN, snowmelt has occurred 1.77 days/decade earlier in the last decade (2000-2010) than in the 1970s for most latitudinal segments (see Figure 2). At 70ºN, snow is melting out even earlier -–– 3.10 days/ decade earlier in the 2000s than in the 1970s (see Figure 4 and 5). Note that days/decade (a trend value) is used in Figures 2 and 4 rather than snow free date. Days/decade simply refers to how much earlier (or later) snow melted out in each decade over the data record.

As was the case in the Foster et al. (2008) investigation, an examination including the additional data (more recent years) shows that a noteworthy shift or step-wise change in snowmelt occurred in the mid to late 1980s. For instance, the average date of snow disappearance at 60º N was nearly 6 days earlier averaged over the 1987-2011 period as compared to the years from 1967-1986. Not all segments showed tendencies toward earlier snowmelt over time. Segment 14 (Figure 3), from 100º to 110º west longitude, actually shows the date of snow disappearance from 1987-2011 occurring 8 days later than from 1967-1986.

A similar shift toward earlier snowmelt was observed at 70ºN -- study cells showed an average melt out occurring nearly 7 days earlier from the period 1987-2011 compared to the period from 1967-1986. See Figure 5 – cell 18, from 100º-110º west longitude. For this cell, on Victoria Island, the snow has disappeared 8-days earlier during the period 1987-2011 than during 1967-1986.

Moreover, as was the case with the earlier investigation (Foster et al., 2008), at latitude 70ºN, eight cells showed significant (negative) trends. However, at 60ºN only two longitudinal segments showed significant trends; one was positive and the other negative.

Shifts in snow cover extent during the spring season in the middle latitudes of the NorthernHemisphere are similar to those reported at the 60º and 70º bands. For example, the decrease in SCE during the month of May has continued in recent years (Figure 6). In May 2010 the SCE was approximately 6 million km^2 less than in May 1970. From 1967-1986, the snow extent was on average more than 2 million km^2 greater than during the period from 1987-2011. The snow has melted out on average 3-days earlier during the second half of the period than during the first half (Fig. 6).

The AO was strongly positive from the late 1980s through about the mid 1990s (Fig. 1). This matches the step-like changes in dates of snow disappearance quite well. From the mid 1990s to about 2009, the trend was neither strongly positive nor negative, which is consistent with the tendencies in spring snowmelt during this period (Cohen and Barlow, 2005). In 2010 and 2011, however, the AO was strongly negative. See also Rigor et al., 2002; Bamzai, 2003; Gong et al., 2003; and Saunders et al., 2003.

Figure 7 shows the correlation coefficient for the date of the final week (end of week) of snow cover versus the strength and direction (positive or negative) of the A O during the winter season (December-February). It should be mentioned that the correlations include all grid boxes that had observed snow cover for every year of the record. The greatest areas of positive correlations (averaging about 0.4) in Figure 7 occur between the December AO and the date of snowmelt in north central Siberia as well as between the February AO and the date when snow melts in the Great Plains of southern Canada and the northern U.S. Note that positive correlations are associated with later snow melt or disappearance when the winter AO is positive. In regards to negative correlations (later snowmelt is associated with a negative winter AO), r values are fairly strong (0.6) between both the January and February AO indices and the western steppes and the taiga regions of Russia, stretching from west of the Ural Mountains to the Pacific Ocean. Additionally, similar values (negative) exist across much of central and northern Canada, in both months, and for Alaska during January. Examining the entire winter season (top left panel), negative correlations prevail; particularly across central Russia and northern Canada.

Figure 8 is similar to Figure 7 but for springtime AO conditions. The most significant area of positive correlations (again averaging about 0.4) is evident between the March AO and the date when snow disappears across much of Canada. Negative correlations are widespread in all three spring months but especially in March and April throughout Russia– r values average approximately 0.45 with maximum values reaching 0.6. In May, areas of negative r values (averaging about 0.4) are quite obvious in the northern U.S., whereas in March and April the areas where negative r values occur are considerably smaller. For the entire spring season (March-May), negative correlations dominate across much of Russia while in North America comparatively small areas of both negative and positive correlations are found. For both Fig. 7 and Fig. 8, the 95% level of significance is contoured in black. Table 1 gives the mean correlations for the DJF (and monthly) AO and the MAM (and monthly) AO and date of snow disappearance for every 5 degrees latitude.

Discussion

There is an implicit relationship between the phase and amplitude of the AO (springtime AO) and the date of snow disappearance (Fig. 8). For example, regarding the spring AO and Eurasian snow cover, it can be inferred that the more strongly positive the AO, the earlier snowmelt will occur; whereas, the more strongly negative the AO, the later melt will occur. However, the winter AO is more complex. At higher latitudes, a positive AO is associated with a later snow melt, and at lower latitudes a positive AO is associated with an earlier snow melt -- the reverse is true for a negative AO (see Fig.7).

In general, the AO-date of snowmelt relationship during both winter and spring is relatively strong in Eurasia compared to North America, primarily because of Eurasia's greater continentality. Eurasia makes up approximately 37% of the Earth's land surface compared to about 16% for North America. Snow is a more constant feature in Eurasia. Incursions of air from non polar sources (marine and tropical air masses) have a greater likelihood of reaching interior regions of North America than interior Eurasia. Moreover, Eurasia is positioned much closer to the Arctic than is North America – considerably more of its land mass is located above the Arctic Circle. Thus there is nearly always snow cover present in the northern tier of Eurasia during the winter and spring seasons (December-May), which may act to increase the correlation coefficient between AO and date of snowmelt.

The negative AO is associated with colder temperatures across the Northern Hemisphere continents and the positive AO with warmer temperatures (Thompson and Wallace 1998).

Therefore, in general it is reasonable to expect that the negative AO is associated with later snow melt and the positive AO with earlier snow melt. From Fig. 7 and Fig. 8, it can be seen that this relationship usually holds, especially between the spring AO and Eurasian snow cover.

The negative winter AO is associated with later snowmelt across southern latitudes of snow covered regions but also with earlier snowmelt across more northern latitudes (Fig. 7). The winter AO is also correlated with the latitudinal extent of storm tracks across Eurasia (Hurrell 1995), where the storm track is shifted south during the negative phase of the AO and shifted north during the positive phase. Thus, when the winter AO is negative with a more southerly storm track, a deeper snow pack is established along the southern periphery of the SCE. Then, during the spring snowmelt season, the deeper snowpack results in a later snowmelt further south, but snowmelt occurs earlier further north with a thinner snow cover. In contrast, when the winter AO is positive, the storm track is shifted north resulting in a deeper snowpack along the northern periphery of the SCE. In this case, during the spring snowmelt season, the deeper snowpack results in a later snowmelt further north but an earlier snowmelt further south, where a thinner snow cover was established during the winter. A similar explanation is likely true across North America in March, which though considered here to be a spring month, often behaves as a winter month.

Step like changes in date of snow disappearance (in the 1980s) were not just observed in the snow record; they were also noted in sea surface temperatures and in phytoplankton. Reida et al. (1998) observed significant positive and negative linear trends from 1948 to 1995 in phytoplankton as measured by the Continuous Plankton Recorder survey in the northeast

Atlantic and the North Sea. These trends seem to reflect a response to changing climate on a timescale of decades. Spreading of anomalously cold water from the Arctic may have contributed to the decline in phytoplankton north of 59 degrees north latitude. According to Reida et. al. (1998 and 2001), there is evidence for a stepwise phytoplankton increase after the mid-1980s. Higher sea surface temperatures were also measured after 1987 then prior to this year, particularly during the spring and summer. It is though these biological and physical events may be a response to observed changes in pressure distribution over the North Atlantic. From 1988 onwards, the North Atlantic Oscillation (NAO) index increased to the highest positive level observed in decades. The NAO and AO are closely linked (Ambaum et al., 2001). The positive NAO anomalies are associated with stronger and more southerly tracks of the prevailing westerlies and higher temperatures in western Europe (Reida, et al., 1998; Reida et al., 2001).

The synchronicity of the above mentioned changes in northern seas and land surfaces is perhaps forced by a threshold increase in temperature, the source of which could be higher temperatures in ocean water linked to the NAO. It may be that over land areas, at 70º north, for instance, and for areas adjacent to the Arctic Ocean, maritime air has taken up heat from the ocean (Reida, personal communication). Over northern land areas adjacent to the Arctic Ocean, maritime air incursions appear to be linked to observed changes in the date of snow cover disappearance. Observed changes in SCE and snow disappearance at the more northerly latitudes, in the late 1980s, is likely not a coincidence.

Changes in the date of disappearance of spring snow cover, especially at high latitudes, found in this study as well as previous studies (Foster, 1989; Foster et al., 1992; Foster et al., 2008) coincide with the observed increasing spring warmth of recent decades. However, the earlier snowmelt dates do not correlate particularly well with the diminution of Arctic Ocean sea ice, for instance (Comiso and Parkinson, 2004).

Conclusions

This current investigation, with 7-more years of additional data available than in the Foster et al., 2008 study, has found that the poleward retreat of spring snow cover has continued to occur approximately 4-7 days earlier, at most latitudinal segments at 60ºN and 70ºN, than in the first half of the satellite era (1966-1988). Snowmelt along coastal areas of the Arctic Ocean (70ºN) continues to be slightly greater than further inland (60ºN).

In regards to the AO, when the springtime AO is strongly positive, snow will melt earlier. When the springtime AO is strongly negative, snow disappears later in the spring. The winter AO is not as straightforward, however as the results are more mixed. At higher latitudes (70ºN, for example in December across Eurasia), a positive AO during the winter month(s) is correlated with a later snow melt, but at lower latitudes (60ºN, for example in January across Eurasia), a positive wintertime AO is correlated with an earlier snow melt. If the AO during the winter months is negative, though, the reverse is true.

Acknowledgements:

Judah Cohen is supported by the National Science Foundation grants ARC-0909459, ARC-0909457 and BCS-1060323 and NOAA grant NA10OAR4310163. Justin Jones and Jason Furtado assisted with some of the figures and computations for the manuscript.

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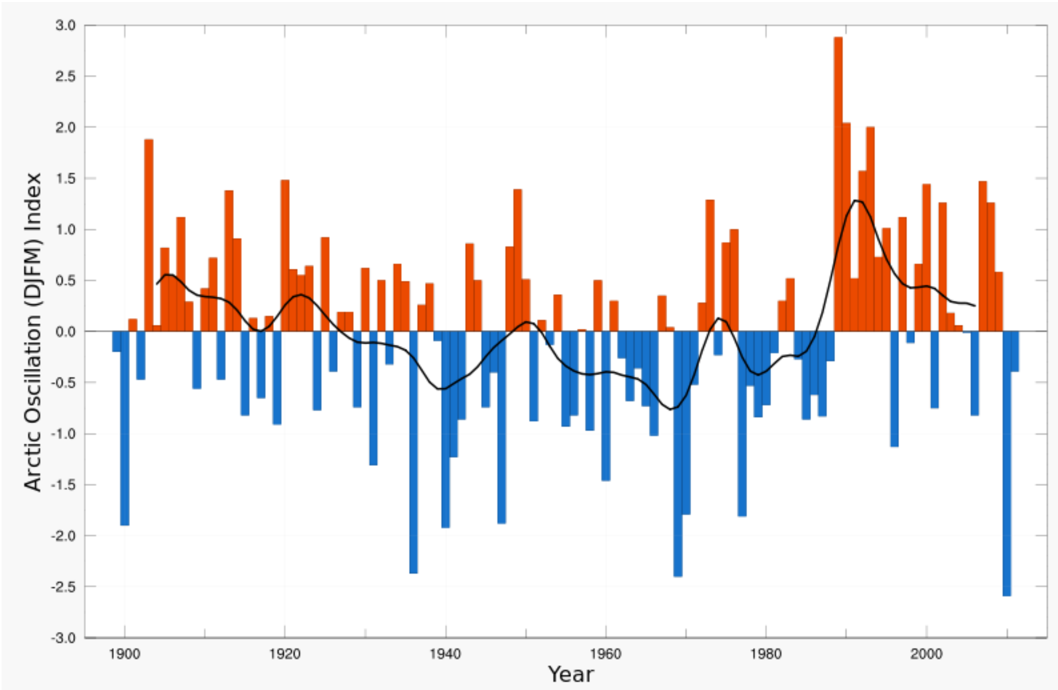

Arctic Oscillation values (December-March) from 1900-2011 (From NOAA)
Figure 1

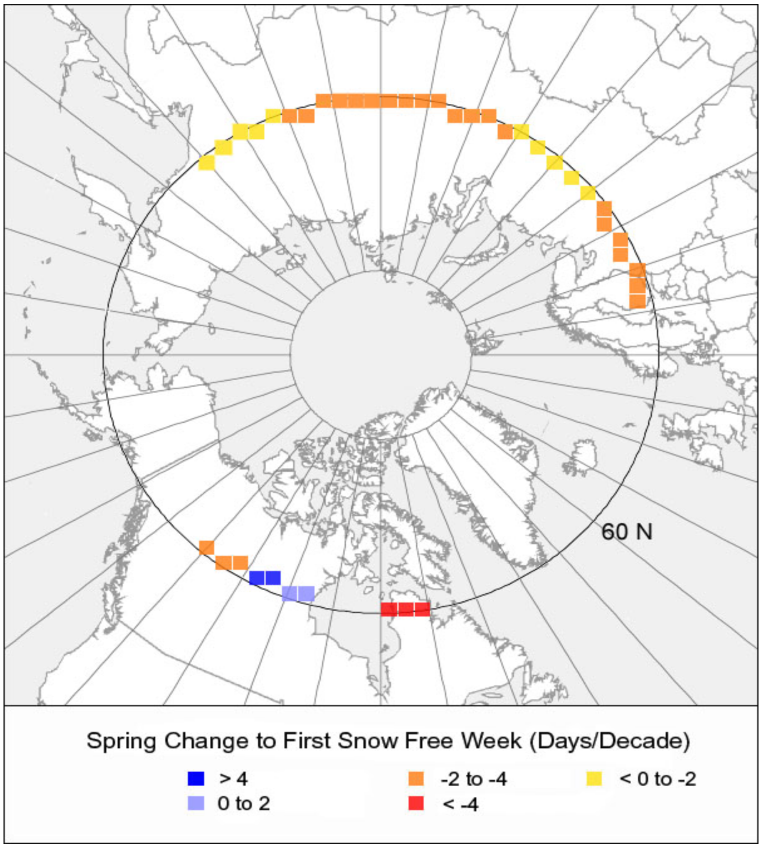

Figure 2
Change in the timing of spring snowmelt at 60ºN from 1967-2011 as expressed in days of change/decade

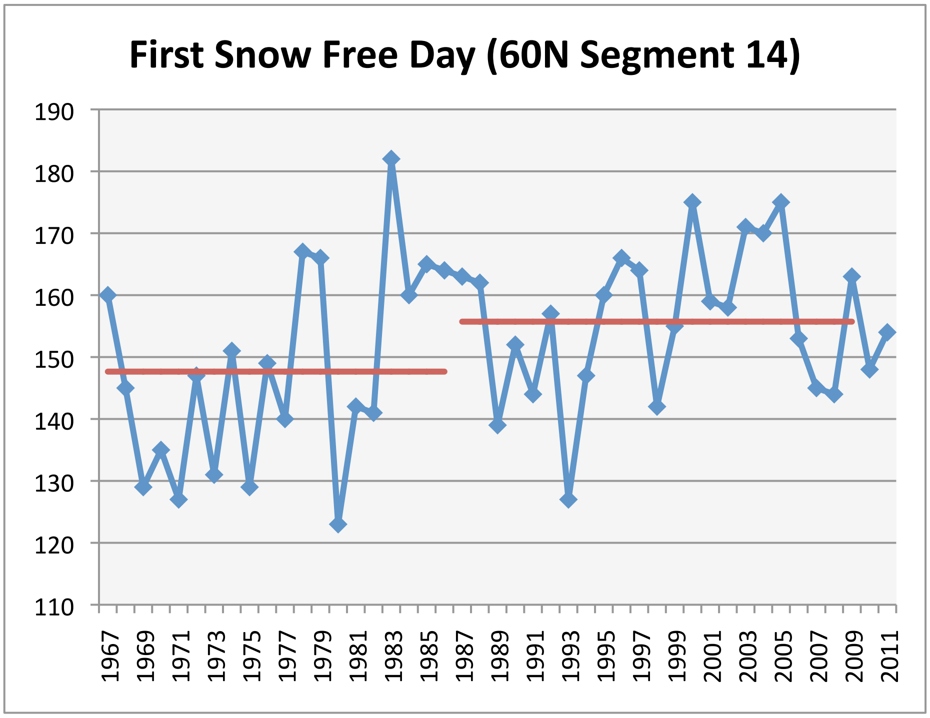

Figure 3

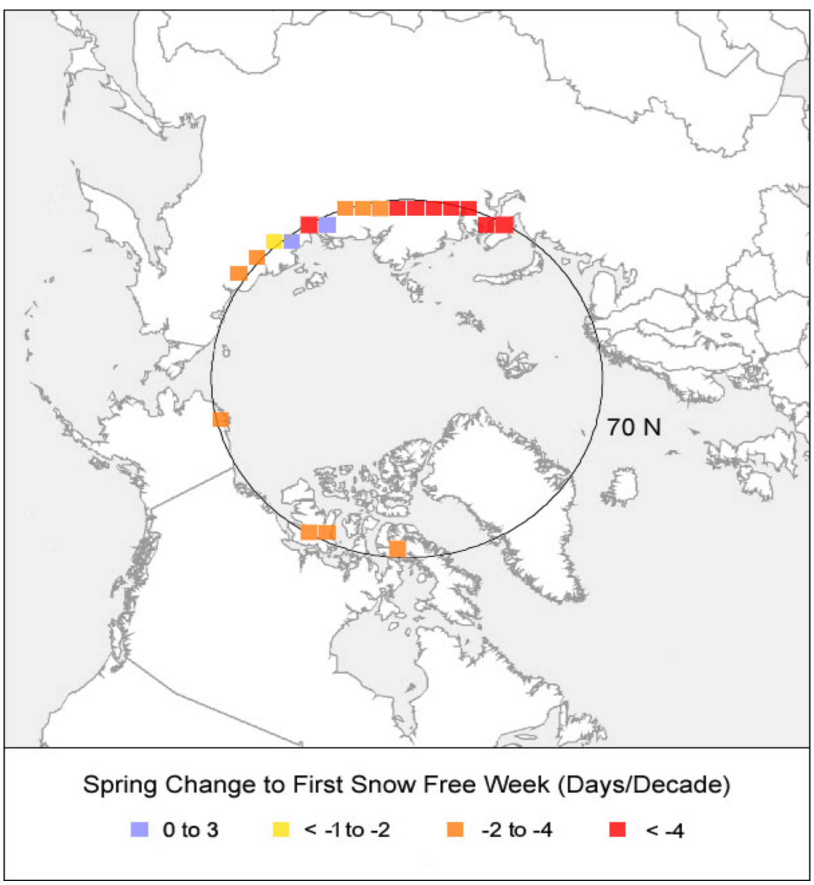

Figure 4 - Change in the timing of spring snowmelt at 70ºN from 1967-2011 as expressed in days of change/decade

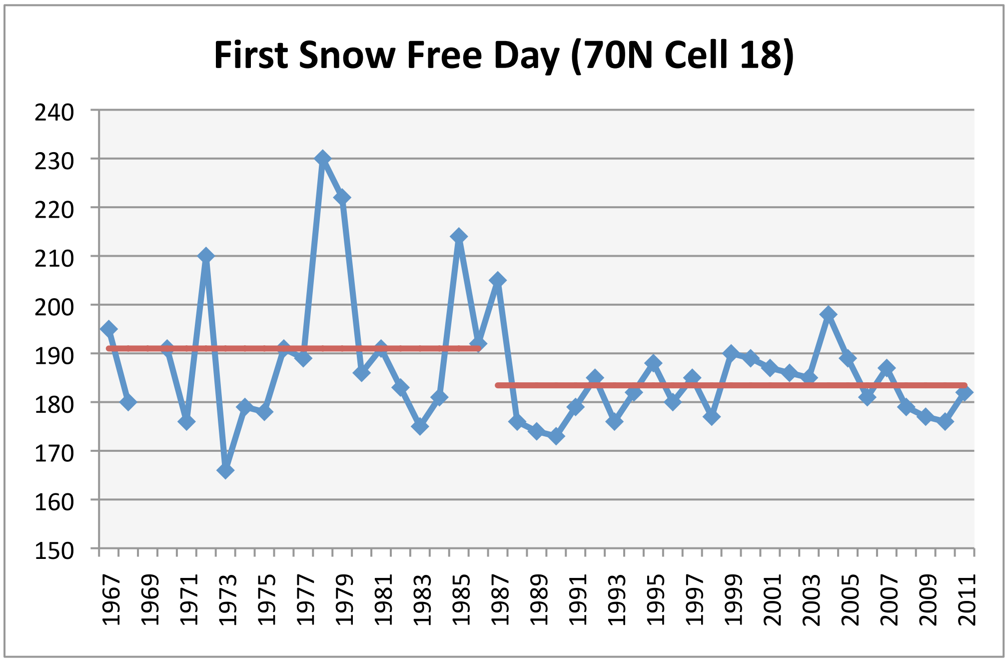

Figure 5

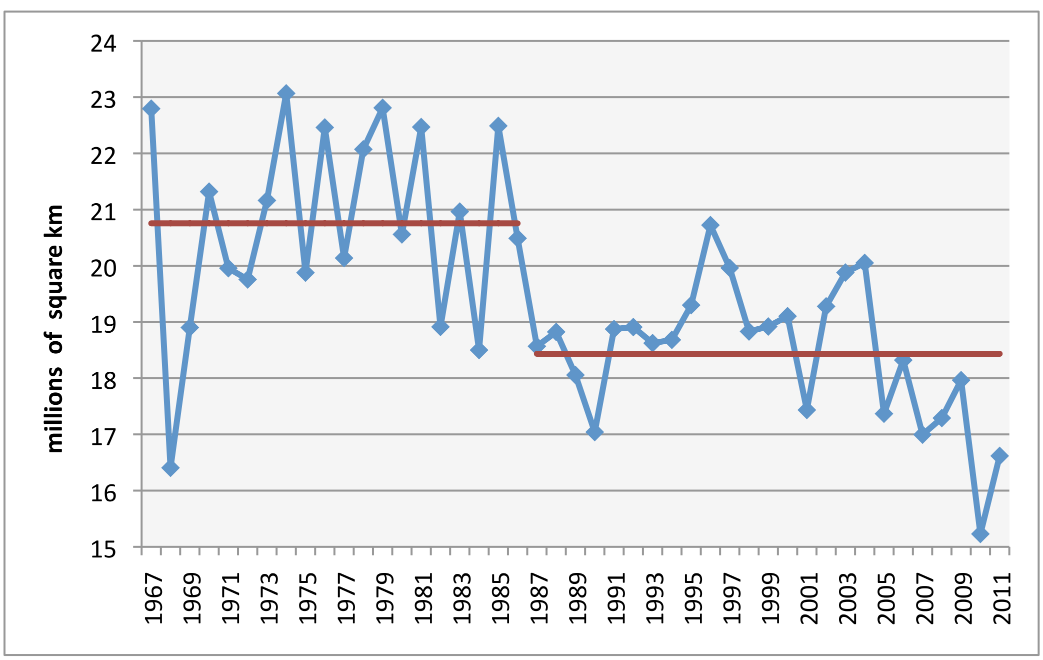

Figure 6

528 Snow cover extent of Northern Hemisphere in May (1967 - 2011)

Correlation of final week of snow cover with AO

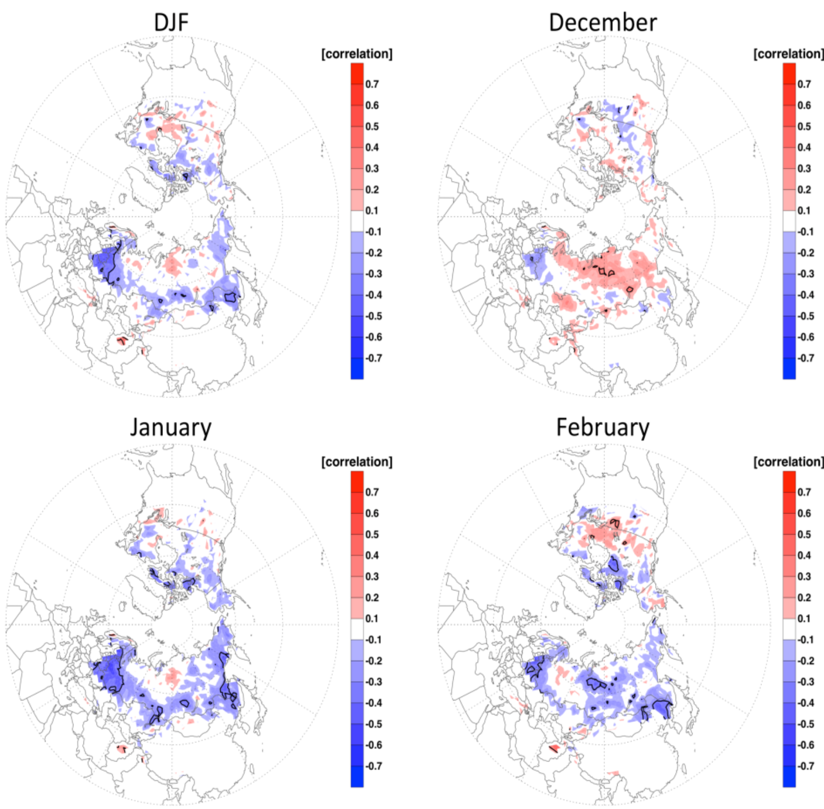

Figure 7

Correlation of final week of snow cover with AO

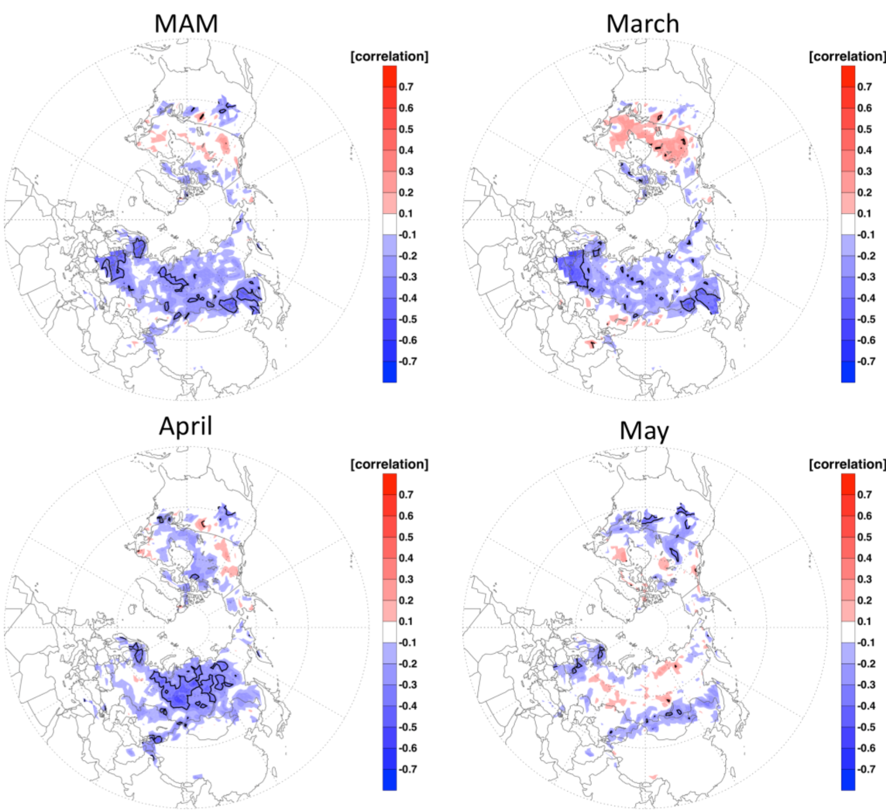

Figure 8

Table 1

Mean correlations for every 5 degrees latitude

Latitude	DJF	MAM
75-80	-0.0005	-0.0119
70-75	-0.0376	-0.0813
65-70	-0.0737	-0.2340
60-65	-0.1266	-0.2257
55-60	-0.1538	-0.1655
50-55	-0.1955	-0.3035
45-50	-0.1206	-0.2172
40-45	-0.0187	-0.1472