Spring snow melt timing and changes over Arctic lands

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Abstract

Spring snow cover over Arctic lands has, on average, melted approximately 4-7 days earlier since the late 1980s compared to the previous 20 years. The earlier disappearance of snow has been identified in non-mountainous regions at the 60º and 70ºN parallels over Eurasia and North America using visible satellite observations of continental snow cover extent (SCE) mapped by the National Oceanic and Atmospheric Administration. The change was greater in the farthest north continental locations. Northern hemisphere SCE declined by almost 10% (May) to 20% (June) between the two intervals. At latitude 70ºN, eight segments of longitude (each 10º in width) show significant (negative) trends. However, only two longitudinal segments at 60ºN show significant trends, one positive and one negative). SCE changes coincide with increasing spring warmth and the earlier diminution of sea ice in the last several decades. However, while sea ice has continued to decrease during this recent interval, snowmelt dates in the Arctic changed in a step-like fashion during the mid to late 1980s and have remained much the same since that time.

Introduction

Climate models indicate that the Arctic will provide the earliest indication of an incontrovertible global warming, in part as a result of feedback effects associated with the high albedo of snow and ice (Budyko 1966; Manabe et al., 1992). Both empirical and modeling studies have illustrated the influential role snow cover plays within the global heat budget (Walsh and Chapman, 1990). In the last two decades, various components of the cryosphere, including snow cover, permanent ice over land, sea ice, and permafrost, have been analyzed to identify changes in these features that may be correlated with each other, as well as with other climate variables, including surface air temperature.

Foster et al. (1989) examined the date of snow disappearance as measured at meteorological stations in the tundra of Eurasia and North America. For much of the North American tundra, the date of snow disappearance was found to be occurring earlier in the spring since the late 1960s, and in Barrow, Alaska, there was a trend toward earlier snowmelt since about 1950. However, running means of the date of snow disappearance across much of northern Russia (north of 70ºN) showed no discernible trend toward earlier melting. Subsequently, satellite observations confirmed the earlier date of snow disappearance poleward of 70ºN in the late 1980s and early 1990s compared to the 1970s and 1980s (Foster et al., 1992). These observations agreed with a 1990 satellite study that first identified the mid to late 1980s decline in snow cover extent (SCE) throughout the Northern Hemisphere (Robinson and Dewey, 1990). By the mid and late 1990s, it became clear that the spring SCE changes identified in the 1980s represented more of a stepwise change, rather than a continuous decline in extent (Robinson et al., 1995; Robinson and Frei, 2000). For the most part, due to a late winter through early summer decrease in SCE, annual averages of SCE since the mid 1980s have remained approximately 2 million square kilometers (approximately 8%) lower than averages in the first 20 years of the satellite era. SCE strongly influences temperature, especially during spring snow melt, through various feedback mechanisms and has been shown to be inversely related to hemispheric surface air temperatures (Groisman et al., 1994).

Observations of Arctic sea ice extent similarly show significant changes during the satellite era. In the summer of 2002, the sea ice cover in the central Arctic reached a new low for the satellite era (since 1978). However, this was surpassed in 2005, when September sea ice extent was 5.31 million square kilometers. This may be the smallest summer extent in at least a century. Over the 27-year satellite record (using passive microwave data,1978-2005), there has been an estimated 8.5% decline in Northern Hemisphere sea ice extent per decade (Comiso, personal communication). Comiso and Parkinson (2004) report that the Arctic has warmed by about 1ºC in the past two decades.

As the Arctic atmosphere warms and sea ice extent continues to fall below previously observed minima, it is worth taking a closer look at the character of spring snow cover across Eurasia and North America. Here, we extend our earlier work by using visible satellite derived snow maps to evaluate the timing of spring snow cover retreat poleward of 60ºN and 70ºN. The purpose of this paper is to assess whether the date of snow disappearance from these latitudinal boundaries is similar to what was previously observed as well as to compare the date of disappearance to SCE in order to gain a more complete understanding of spring snow cover behavior in Arctic lands.

Data and Methodology

Weekly maps of continental SCE produced by the National Oceanic and Atmospheric Administration’s (NOAA) National Environmental Data and Information Service (NESDIS) are the source of the snow information used in this study (Matson et al., 1986; Robinson et al., 1993; Ramsay, 1998). To date, these maps constitute the longest satellite-derived environmental dataset available and have long been the premier dataset used to evaluate large-scale snow extent NOAA/NESDIS snow maps date back to late 1966, with trained meteorologists producing the weekly maps from manual analyses of visible satellite imagery. The polar stereographic snow maps are subsequently digitized using a hemispheric 128 x 128 cell (half mesh) grid. Maps produced between 1966 and 1971 were later reanalyzed at the Rutgers Global Snow Lab to better conform to the quality of later maps. Since June 1999, maps have been produced on a daily basis and at a higher spatial resolution. However for the purpose of consistency, in the present study a weekly product at the half mesh resolution derived from the new higher resolution maps is employed.

There has been some concern about the quality of NOAA satellite interpretations of snowmelt in the Canadian Arctic (Wang et al., 2005). Wang and colleagues claim that the NOAA maps show a later melt than observed from station data and case studies employing high-resolution visible imagery. It is true that the actual day snow disappears is difficult to ascertain. Clouds are prevalent in the Arctic during the spring and may persist over a given area for days at a time. Thus, visible satellite images and lower resolution snow maps derived from these images cannot provide definitive results on a local or annual basis. Nonetheless, given the 38-year study interval and the rather broad 10º longitudinal segments studied, we are confident that credible results at days to a week or more temporal resolution are attainable. It is also interesting to note that Wang et al.'s study area to the immediate west of Hudson's Bay is one of the few areas where our study results suggest a trend toward later snow melt during the satellite era. Clearly this region, as well as others, warrants further investigation. However, any procedural and technological changes are such that they should not have a significant impact on study results.

As in the Foster et al. (1992) study, in a given year, the weeks when the NOAA maps no longer show snow along the 60º and later the 70ºN parallels are considered the dates of snow disappearance. At both 60º and 70ºN, the NOAA map grid cells straddling these parallels were divided into 10º longitudinal segments; approximately 557 km wide at 60ºN and approximately 190 km wide at 70ºN. The middle day of the map week that first showed all cells to be snow free was determined and placed in a database that includes year, date, parallel, and segment/cell.

For this study, the years 1967 to 2004 were examined. At 60ºN, 16 longitudinal segments were selected for study (figure 1). At 70ºN, 20 predominantly land-covered cells were identified (figure 2). Only those segments that included a substantial amount of water or were predominantly mountainous were not evaluated. Many of the longitudinal segments at 60ºN have a high degree of climatic continentality and are within the boreal forest zone. This is particularly evident in central Eurasia. The extreme eastern and western segments at 60N, for both North America and Eurasia, are of course much more subject to maritime influences. In particular, the segments on either side of Hudson's Bay are quite maritime in nature and have tundra vegetation. All cells at 70ºN are maritime, especially in North America, with tundra vegetation dominating.

Results

Typically, snow retreats north of 60ºN between mid April and mid May and north of 70ºN between mid May and early July (Tables 1 and 2) (cf. **http://climate.rutgers.edu/snowcover** for maps depicting mean snow cover).

Climatological timing of snowmelt is affected by whether a region is dominated by continental (early) or maritime (late) climatic influences and whether it sits at a higher elevation (late). Variables such as cloudiness, storm tracks and snow depth also affect the interannual variability within each region.

An examination of spring snow retreat at 60ºN shows a marked advance of the snowmelt season since 1967 (Table 1). Linear regression analysis indicates that this occurred in 13 of the 16 latitudinal study segments, with a trend of more than 2 days/decade earlier in 5 of those 13 (figure 3). Melt has occurred more than 2 days/decade later in one of the three segments showing a trend toward delayed melt. Averaged together, the retreat of snow at this latitude has occurred 0.8 days per decade earlier. While not the focus of this study, the first occurrence of snow in the fall shows little change at 60ºN, thus the length of the snow season has changed in each segment by roughly the spring value.

There is considerable scatter in the time series of melt dates for each segment, as shown in figure 4 for region 13 (110-120ºW). The regression analysis indicates an advance of the melt season of 2.4 days/decade between 1967 and 2004. However, an examination of this scatter plot and those for nearly all of the other segments suggests that the major change during the almost four decades took place in the mid to late 1980s. Thus it is also worth discussing this as a stepwise change. Figure 4 shows that the average date of melt was 7.1 days earlier averaged over the 1987-2004 interval compared to the 1967-1986 period. Whether one depicts change in linear or step terms, snow melt has generally occurred earlier in the spring along the vast majority of this parallel over the past two decades when compared to the previous two.

A similar shift to an earlier end to the snow season is evident at 70ºN (figure 5). The 22 study cells showed an average trend to earlier melt of an average of 3.1 days/decade. As at 60ºN, the timing of fall snow occurrence at 70ºN has changed minimally during the satellite era, though several Siberian segments suggest an earlier advance of autumnal cover. Looking more closely at the cell located on Banks Island, in the far western Canadian Archipelago, regression analysis indicates that the melt season advanced 1.6 days/decade between 1967 and 2004 (figure 6). As at 60ºN, a stepwise change was noted at this and other 70ºN cells. The Banks Island cell lost snow cover 7.5 days earlier averaged over the 1987-2004 interval compared to the 1967-1986 period, despite the fact that melt has actually occurred later in the 2000s than in the 1990s.

The trends were tested by regressing the date of snow melt against time, as suggested by Kendall and Ord (1990). The significance of the trend is tested by examining the significance of the regression coefficient. P-values for the regression coefficients were computed for all the segments at both 60N and 70N. Because in some years some of the segment data were not available (e.g. 1969), the trend significance was computed with only available data. Since this is a two-sided test, p-values less than 0.025 are significant at the 95% level. At latitude 70ºN, segments 1-7 and 19 and 20 show significant (negative) trends. However, only two segments at 60ºN show significant trends, segment 14 (positive) and 16 (negative) trends. Refer to figures 4 and 6.

A non-parametric Kendall's Tau test as suggested by Kendall and Ord (1990) was also used to bypass the assumption of normality of the data. All trends remain significant except trends in segments 6, 7, and 19 at 70N. See also Gough et al. (2004).

Arctic spring snow cover extent over the Northern Hemisphere continents shows variations similar to those noted at the two study parallels (figure 7). A decrease in SCE is noted in May and June between the early and later portions of the satellite era. This amounts to a difference in area between the 1967-1986 and 1987-2004 periods of 2.0 million square kilometers in May and 2.5 million square kilometers in June, or an almost 10% (May) to 20% (June) decrease in SCE. The magnitude of the monthly step change in spring is considerably larger than the 1.1 million square kilometers averaged over the entire year. Also evident in each time series is the rather stable May and June SCE throughout the recent interval compared to the first half of the satellite record. This is similar to that observed at the 60ºN and 70ºN parallels.

Discussion

While there is indeed an interest in assigning “cause and effect” to the results obtained in this investigation, such attribution is, of course, not always straightforward. We offer here plausible scenarios to explain what has been observed; namely, the long-term tendency toward earlier melt dates and the more recent interval of melt stability. Although each has its own merits, likely an amalgam of the following contributes to the observed spring snow melt behavior.

Variations in the observed interannual variability and decadal changes in snowmelt behavior over the study period correspond in some degree to the position of atmospheric pressure patterns such as the Arctic Oscillation (AO) and the polar vortex, with their associated fluctuations in storm tracks and air masses. For instance, if due to a shift in the storm track, winter snowfalls were less frequent in recent decades compared to earlier in the satellite era, the spring snow pack would be shallower, and thus possibly melt out more quickly. Similarly, the extended spring snow cover season at several Arctic locations in the 2000s might also be evidence for a pattern shift.

The AO, the first leading mode of sea level pressure, is the dominant mode of the Northern Hemisphere winter atmospheric variability and has a considerable influence on tropospheric climate fields. It is hemispheric in nature (dipole pattern about the North Pole) and peaks in January, February and March. The initiation of this dominant mode and its early-season onset are not clearly understood, but it is believed that there may be an atmospheric teleconnection pathway involved, with origins at the surface over northern Eurasia. Analysis of satellite observations and numerical modeling experiments has been used to substantiate the role of early-season, surface diabatic heating anomalies across Eurasia. These anomalies are thought to result from seasonal variations in snow cover (Saito et al. 2001; Saito and Cohen, 2003). It seems to take about 2 weeks for the anomalies to propagate from the troposphere to the stratosphere. Late in the snow season, well-established evidence exists for stratosphere-to-troposphere downward propagation of associated AO anomalies (Saito and Cohen, 2003; Saito et al., 2004).

Regime shifts associated with the AO positive/negative phase of 1988/89 coincide quite well with the step-like changes noted in this study (Figure 8). The negative phase of the AO brings higher-than-normal pressure over the polar region, while the opposite conditions accompany the positive phase. Beginning in the 1970s, the AO has tended to remain in the positive phase, facilitating above-normal temperatures in much of the United States and across northern Eurasia, though, winters across areas such as Greenland and Newfoundland were colder than normal. It has been reported that 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 (Thompson and Wallace, 2000).

The January, February, March phase of the AO has typically alternated between positive and negative years for much of the last century; generally positive from 1899-1939 and negative from 1940-1988 (Figure 8). Interestingly, the AO was strongly positive from the late 1980s through about the mid 1990s, which matches the step-like changes described earlier in dates of snow disappearance. Since this time, the trend has been neither strongly positive nor negative and is consistent with the spring snowmelt tendencies observed in Figures 5 and 6 (Cohen, J., and M. Barlow, 2005). For more on the details of the AO see Rigor et al., 2002; Bamzai, 2003; Gong et al., 2003; Saunders et al., 2003; Brown et al., in press.

In addition, the Arctic is known to be a sink for atmospheric pollutants, such as industrial particulates from sources in Eastern Europe and Russia. In addition, soot from wildfires in the boreal forests of both North America and Eurasia is often transported across the Arctic (Foster et al., 1989; Hansen and Nazarenko, 2005). Furthermore, in late spring, when the polar jet stream moves northward and low-level winds increase due to daily heating differences, dust from natural sources sullies the retreating snowpack. Increases in any of these contaminants in recent decades would dampen the albedo of the spring snow pack, thus accelerating melt (Clarke and Noone, 1985).

Another area that warrants more attention is cold season precipitation. If more snow falls during this time of the year (October-May), which appears to be the case at least in some locations, snow melt would require more energy, and thus this could compensate for the greater availability of energy (sensible heat) that would otherwise act to melt the snow sooner. This needs to be further explored. Also, the role if any that thermal inertia plays should be further evaluated as well. Since the snow extent was smaller in the 1980s than in the 1970s, the snow free surface was greater, and therefore the surface temperatures were warmer. Could this have affected the near surface permafrost? For example, was there a longer active layer melt season (thinner permafrost) in the late 1980s? If so, once a cooler or snowier regime was initiated in the 1990s, heat in the active layer may have gradually been released. As the heat dissipated, it would likely have a less compensatory impact on the new climate regime (AO positive). The result would be that the snow cover melt dates occur later in the season.

An underlying question is if the recent (1987-2004) dominance of early melt can be at least partially explained by human-induced warming? However, because satellite technology emerged only in the second half of the twentieth century, the data record is perhaps still too short for climate studies. Though obvious changes in the cryosphere can be detected, there exists a fair amount of uncertainty in regards to how much of the recent changes can be attributed to natural variability and how much results from human-induced influences.

Conclusions

The availability of well over a decade of additional snow cover data has warranted an update of the earlier observations on the date of snow disappearance during spring in the Arctic. Previous investigations identified an earlier Arctic snow melt in the late 1980s and early 1990s compared to that observed from the advent of the satellite snow cover monitoring era in the late 1960s. The current study has found that the poleward retreat of spring snow cover at 60ºN and 70ºN has, at most locations, continued to occur approximately 4-7 days earlier than in the first half of the satellite era. With the additional years of data, it is also quite evident that the snowmelt change observed in the 1980s was step-like in nature, unlike a more continuous downward trend seen in Arctic sea ice extent. Northern Hemisphere continental snow cover extent declined by almost 10% (May) to 20% (June) between the two intervals (1967-1986 and 1987-2004). The additional data have also shown that the snowmelt is somewhat greater near the Arctic coast than inland. At latitude 70ºN, segments 1-7 and 19 and 20 show significant (negative) trends. However, only two segments at 60ºN show significant trends, segment 14 (positive) and 16 (negative).

A satisfying understanding for the variations in the dates of snow disappearance has thus far proven to be elusive. This is likely due to multiple factors being at play, ranging from the impact of pollutants on snow albedo, to natural variations in oscillations and storm tracks, to human-enhanced global warming. Further observational and modeling investigations are needed to better explain past and present spring melt characteristics and peculiarities.

Acknowledgements

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Comment [JC1]: I think it makes more sense to talk about the influence of the winter AO on spring snow cover. Three papers that do that are the Bamzai paper you already reference and: Saito, K. and J. Cohen, 2003: The potential role of snow cover in forcing interannual variability of the major Northern Hemisphere mode, *Geophys. Res. Lett.*, 30(6), 1302, doi:10.1029/2002GL016341 and Saito, K., T. Yasunari and J. Cohen, 2004: Changes in the sub-decadal co-variability between Northern Hemisphere snow cover and the general circulation of the atmosphere, *Int. J. Climatol.*, 24, 33-44.

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Table 1. Characteristics of spring snow melt within 60ºN segments. Included are segment numbers and coordinates (cf. figure 1 for a map of locations), along with a) changes in timing as determined by linear regression expressed in days per decade, and b) mean dates when snow disappeared, averaged for intervals between 1967-1986 and 1987-2004 (day 121 = May 1).

		Change in first snow-free week (1967-2004)	Mean day of snow disappearance	
Segment (60N)	Location	Days/Decade	1967-1986	1987-2004
1	20-30 E	-3.7	118	106
2	30-40 E	-0.4	124	118
3	40-50 E	-1.0	125	121
4	50-60 E	-0.5	128	125
5	60-70 E	-0.5	125	122
6	70-80 E	-1.5	135	129
7	80-90 E	-2.4	140	133
8	90-100 E	-2.5	142	133
9	100-110 E	-0.3	137	135
10	110-120 E	-1.9	142	136
11	120-130 E	-0.7	136	135
12	130-140 E	1.7	159	160
13	110-120 W	-2.4	137	130
14	100-110 W	5.8	148	155
15	90-100 W	1.5	168	167
16	70-80 W	-4.5	184	174
Mean		-0.9	134	136

Table 2. Same as Table 1, except for 70ºN cells (day 152 = June 1). Coordinates denote the center point of a cell.

			Change in first snow-free week (1967-2004)	Mean day of snow disappearance	
Cell (70N)	Latitude	Longitude	Days/Decade	1967-1986	1987-2004

1	70.1 N	70.0 E	-3.7	182	174
2	70.9 N	74.7 E	-4.6	187	178
3	69.9 N	81.7 E	-5.5	183	174
4	70.4 N	86.7 E	-4.7	182	176
5	70.7 N	92.0 E	-4.8	182	176
6	70.9 N	97.4 E	-4.8	181	176
7	70.9 N	102.9 E	-4.5	181	174
8	70.7 N	108.3 E	-1.1	177	176
9	70.4 N	113.5 E	-1.0	168	166
10	69.9 N	118.5 E	-1.5	163	162
11	70.9 N	125.4 E	-0.5	174	172
12	70.0 N	130.1 E	-3.5	174	167
13	70.5 N	137.4 E	-1.3	175	169
14	69.4 N	141.4 E	-0.6	163	159
15	69.4 N	148.6 E	-2.3	169	162
16	69.1 N	155.6 E	-2.8	172	164
17	70.4 N	156.7 W	-2.5	172	164
18	70.1 N	110.0 W	-1.6	192	184
19	70.9 N	105.3 W	-3.6	195	187
20	70.9 N	82.6 W	-6.7	201	187
Mean			-3.1	179	172

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Figure 1. Latitudinal segments evaluated at 60ºN. Numbers correspond to segments in Table 1.

Figure 2. Latitudinal cells evaluated at 70ºN. Numbers correspond to cells in Table 2.

Figure 3. Change in the timing of spring snowmelt at 60ºN from 1967-2004 as expressed in days of change/decade.

Figure 4. Dates of snow melt from 1967-2004 at 60ºN between 110-120ºW (segment 14 on Figure 1). Individual years, a linear regression and means from 1967-1986 and 1987-2004 are plotted.

Figure 5. Change in the timing of spring snowmelt at 70ºN from 1967-2004 as expressed in days of change/decade.

Figure 6. Dates of snow melt from 1967-2004 at 70ºN for the cell centered at 110ºW (cell 5 on Figure 2). Individual years, a linear regression and means from 1967-1986 and 1987-2004 are plotted.

Figure 7. Northern Hemisphere continental snow cover extent during the months of May (top) and June (bottom) from 1967-2004. Individual years and means from 1967-1986 and 1987-2004 are plotted.

Figure 8. Chart showing January- February-March means of the Arctic Oscillation time series for 1950-2002 (from Dave Thompson AO Web page http://www.atmos.colostate.edu/ao/Data/ao_index.html).

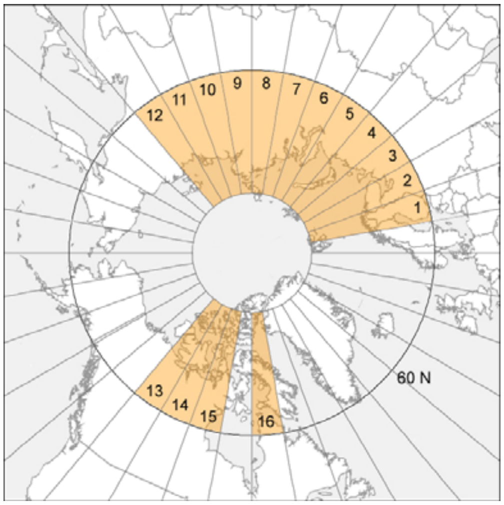


Figure 1

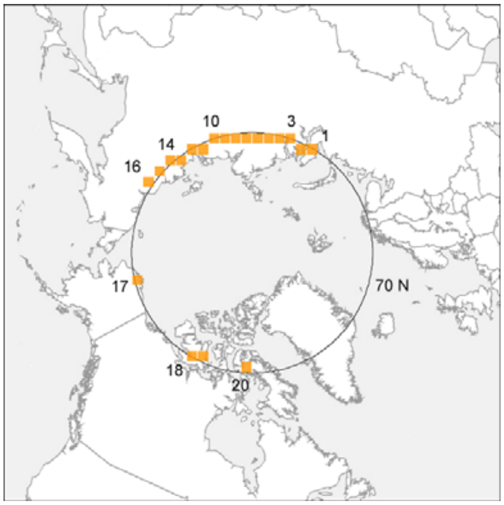


Figure 2

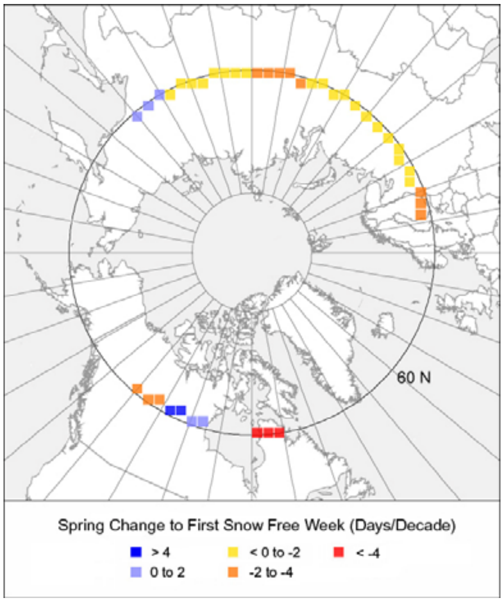

60 N
Spring Change to First Snow Free Week (Days/Decade)
> 4
0 to 2
< 0 to -2
-2 to -4
< -4

Figure 3

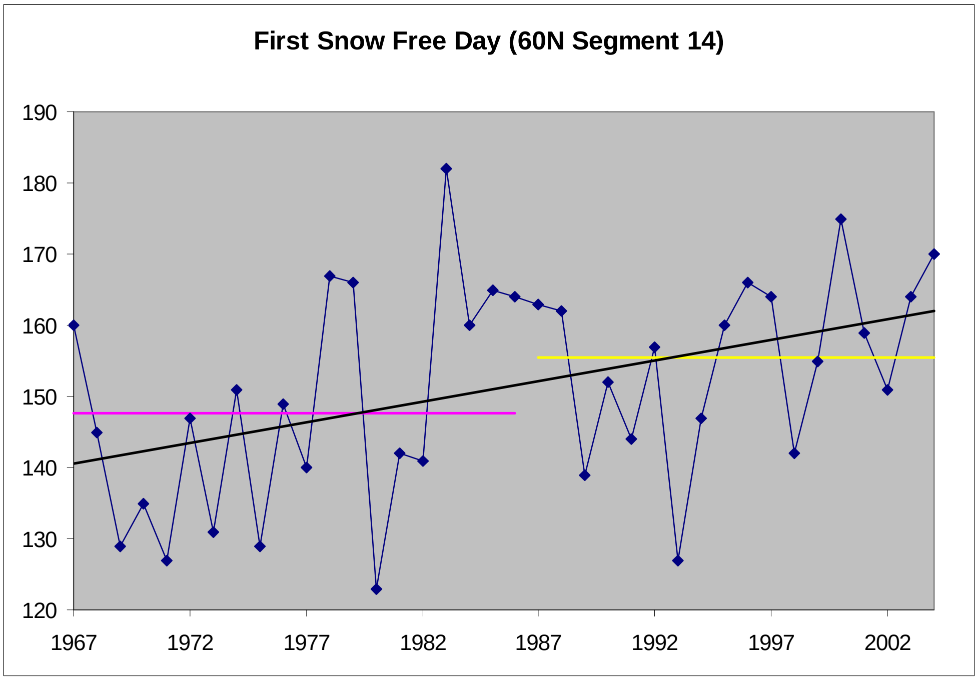


Figure 4 (y = 0.5788x -999.97, p = 0.007)

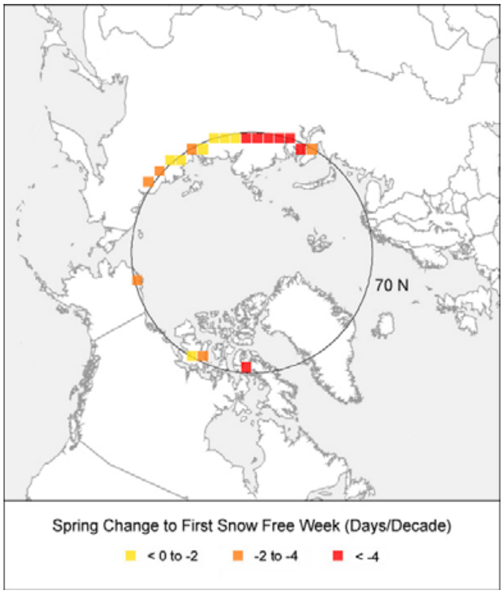

70 N
Spring Change to First Snow Free Week (Days/Decade)
< 0 to -2
-2 to -4
< -4

Figure 5

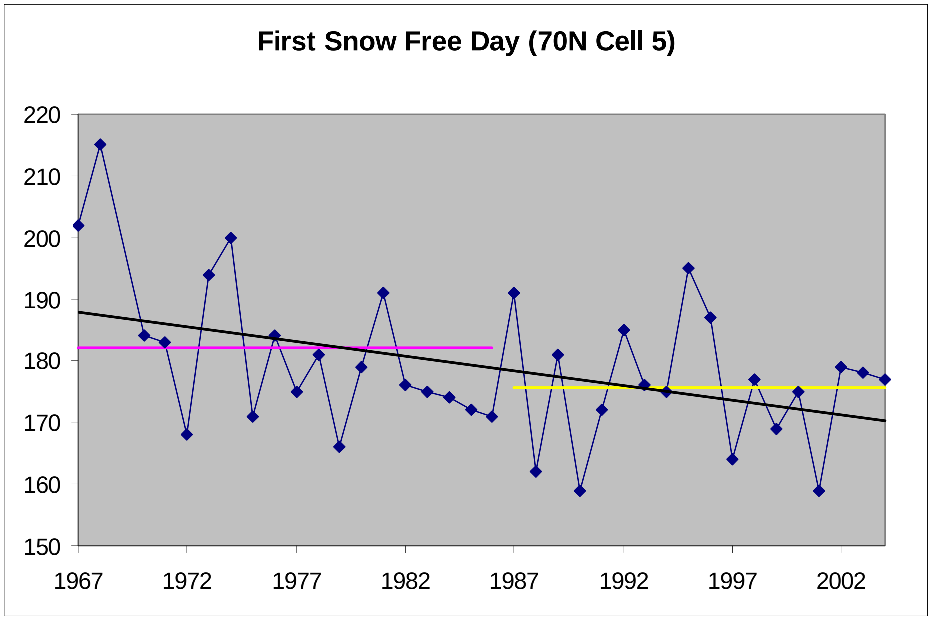
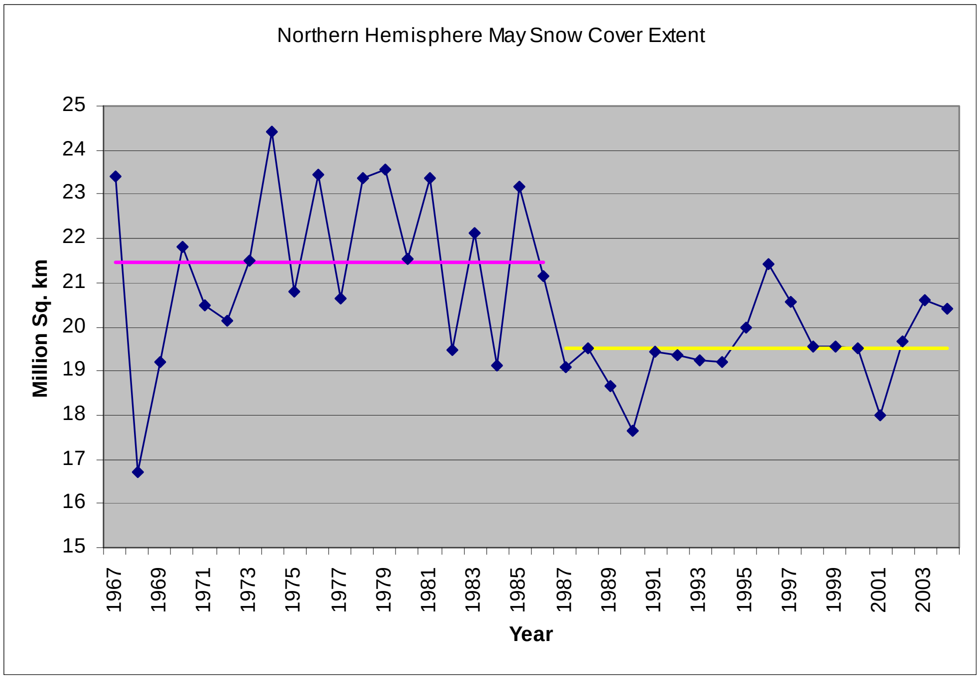


Figure 6 (y = -0.4755x +1123.4, p = 0.006)


Northern Hemisphere May Snow Cover Extent
Million Sq. km
25
24
23
22
21
20
19
18
17
16
15
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
Year

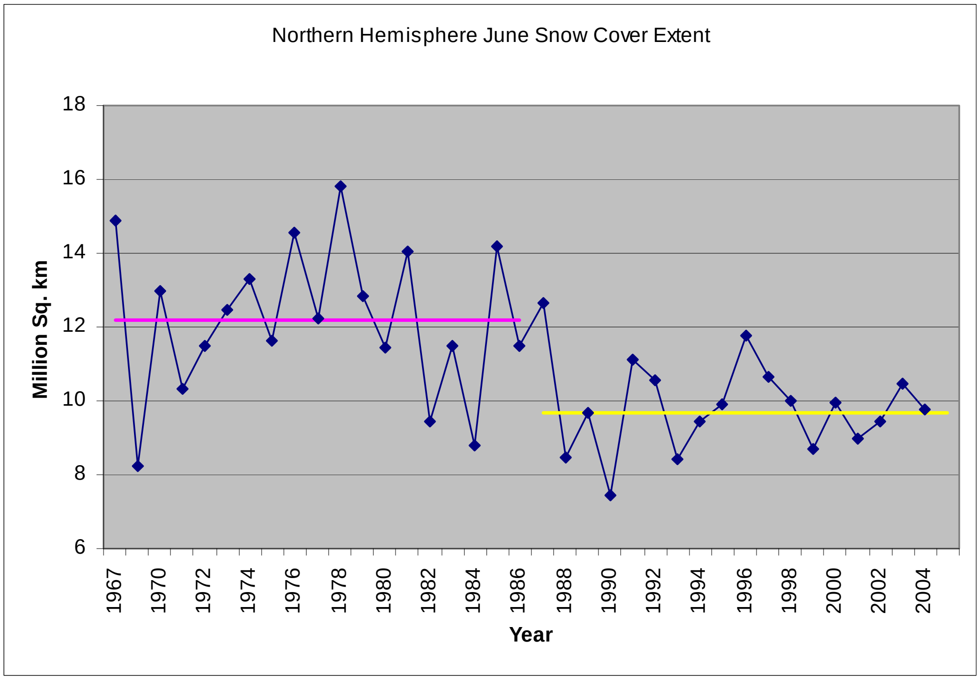

Northern Hemisphere June Snow Cover Extent
Million Sq. km
18
16
14
12
10
8
6
1967
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
Year

Figure 7

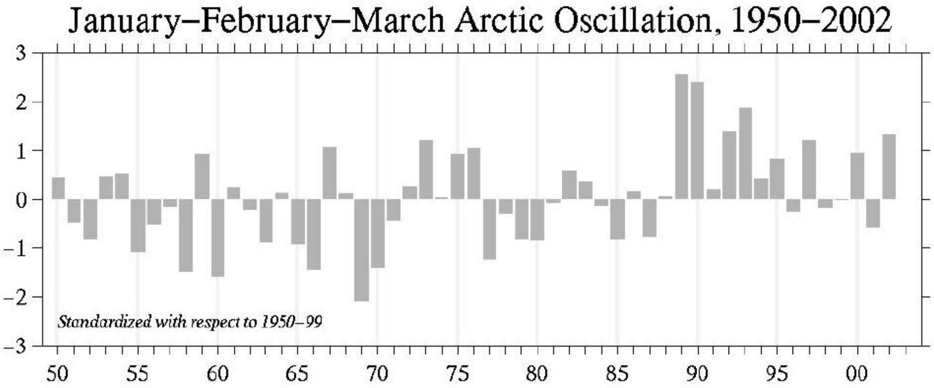
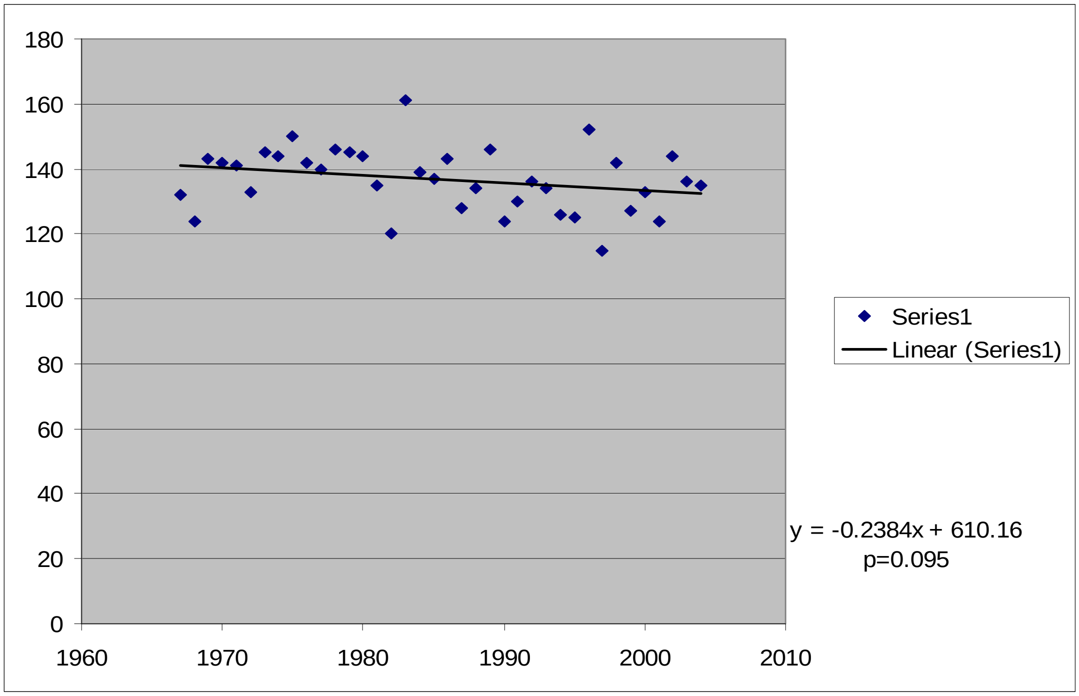

January–February–March Arctic Oscillation, 1950–2002
3
2
1
0
–1
–2
–3
Standardized with respect to 1950–99
50
55
60
65
70
75
80
85
90
95
00

Figure 8


180
160
140
120
100
80
60
40
20
0
1960
1970
1980
1990
2000
2010
◆ Series1
Linear (Series1)
y = -0.2384x + 610.16
p=0.095