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Long-term variability in Northern Hemisphere snow cover and associations with warmer winters

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Abstract A monthly snow accumulation and melt model is used with gridded monthly temperature and precipitation data for the Northern Hemisphere to generate time series of March snow-covered area (SCA) for the period 1905 through 2002. The time series of estimated SCA for March is verified by comparison with previously published time series of SCA for the Northern Hemisphere. The time series of estimated Northern Hemisphere March SCA shows a substantial decrease since about 1970, and this decrease corresponds to an increase in mean winter Northern Hemisphere temperature. The increase in winter temperature has caused a decrease in the fraction of precipitation that occurs as snow and an increase in snowmelt for some parts of the Northern Hemisphere, particularly the mid-latitudes, thus reducing snow packs and March SCA. In addition, the increase in winter temperature and the decreases in SCA appear to be associated with a contraction of the circumpolar vortex and a poleward movement of storm tracks, resulting in decreased precipitation (and snow) in the low- to mid-latitudes and an increase in precipitation (and snow) in high latitudes. If Northern Hemisphere winter temperatures continue to warm as they have since the 1970s, then March SCA will likely continue to decrease.

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1 Introduction

Snow is an important hydrologic variable because it serves as an important water source in many regions, and it also has a significant effect on regional radiative and thermal energy budgets, atmospheric circulation, and thermal conditions of soils (Groisman et al. 1994; Frei and Robinson 1999). Thus, changes in snow cover have important hydrologic and climatic implications. In addition, snow cover is a climatically sensitive hydrologic variable and may be a useful indicator of climatic changes (Frei et al. 1999; Frei and Robinson 1999; Brown 2000).

In a study of Northern Hemisphere SCA for the 1972–1992 period, Groisman et al. (1994) found a substantial retreat of SCA during the second half of the hydrologic year (April through September). Groisman et al. (1994) also suggest that the retreat of the SCA during spring (April through May) has contributed to increases in air temperature during the spring months through positive radiative feedbacks.

Snow extent of the Northern Hemisphere also was studied by Frei and Robinson (1999). They identified connections between regional SCA and atmospheric circulation during 1972 through 1994. As part of their study, Frei and Robinson examined relations between atmospheric circulation and snow extent in North America. They indicate that snow extent over North America is associated with the longitudinal position of the North American ridge, and snow extent over eastern North America is associated with a meridional oscillation of atmospheric pressure. In another study of North American SCA, Frei et al. (1999) report a decrease in March SCA since about 1950. They suggest that this decrease may be due to a possible shift in the snow season. Karl et al. (1993) also examined variations in SCA for North America and reported a strong association between decreases in SCA and increases in North American and Northern Hemisphere temperature.

Brown (2000) examined Northern Hemisphere SCA using measured snow-depth data for the period 1915–1997. Although this dataset was limited in spatial and temporal completeness, especially during the early and late parts of the snow season, the data were adequate for an analysis of SCA during the middle part of the winter season. One of the significant findings of this study is that since 1950, the largest changes in SCA have occurred during March. Brown (2000) attributed the decreases in March SCA to increases in temperature.

The aforementioned research (Karl et al. 1993; Groisman et al. 1994; Frei and Robinson 1999; Frei et al. 1999; Brown 2000) demonstrated through empirical analyses that (1) late winter/spring SCA has decreased in the Northern Hemisphere and (2) the SCA decrease is associated with warmer temperatures and changes in atmospheric circulation. The objective of the current study is to explore these findings in more detail by constructing a more spatially and temporally complete dataset for the Northern Hemisphere. This is accomplished by applying a simple snowmelt and accumulation model to simulate March SCA for the Northern Hemisphere. The model uses monthly time-step temperature and precipitation data for the Northern Hemisphere on a 0.5° by 0.5° grid for the period 1901–2002. The specific questions addressed in the study are as follows. (1) Has the previously reported association between March SCA and temperature been consistent throughout the twentieth century? (2) Are the changes in SCA during recent decades unprecedented compared to earlier parts of the twentieth century? (3) What changes in broad-scale atmospheric circulation are related to the changes in SCA? (4) Are these changes in atmospheric circulation consistent with apparent trends in global temperature?

2 Data and methods

Monthly gridded snow cover data were obtained from the Rutgers University Global Snow Laboratory (http://climate.rutgers.edu/snowcover). These data, which span the period November 1966 through August 2007, are on a 1° by 1° grid (Robinson et al. 1993; Robinson and Frei 2000). The gridded snow cover data were used to generate a time series of March SCA for the Northern Hemisphere which could be used to assess the accuracy of the snowmelt and accumulation model (see next section). In addition to the data from Rutgers, a time series of Northern Hemisphere March SCA for the years 1922–1997 produced by Brown (2000, 2002) also was used to verify the snow model. The Brown (2002) time series was obtained from the National Snow and Ice Data Center (http://nsidc.org/data/g02132.html).

Monthly temperature and precipitation data for the globe were obtained from the Climate Research Unit at East Anglia, UK [the CRUTS2.1 dataset (Mitchell 2005; http://www.cru.uea.ac.uk/cru/data/)]. This dataset includes monthly temperature and precipitation data on a 0.5° by 0.5° grid for the land areas of the globe and spans the period 1901 through 2002. The data were used as input to the monthly snow accumulation and melt model (snow model) to generate time series of snow storage (in water equivalent units) for each grid cell.

Global monthly sea-level pressure data were used to explore relations of the temporal and spatial SCA patterns with broad-scale atmospheric patterns. The sea-level pressure data used in the analysis are from the Hadley Centre HadSLP2 dataset (http://dss.ucar.edu/datasets/ds277.4/) and are on a 5° by 5° grid for the years 1850–2004.

2.1 The snow accumulation and melt model

Hydrologic models have been used in a number of studies to simulate snow cover, depth, and water equivalent (Hamlet and Lettenmaier 1999; McCabe and Wolock 1999; Mote et al. 2005). The snow model used in this study is based on concepts previously used in monthly water balance models (van Hylckama 1956; McCabe and Ayers 1989; Tarboton et al. 1991; Tasker et al. 1991; McCabe and Wolock 1999; Wolock and McCabe 1999). Inputs to the model are monthly temperature (T) and precipitation (P). The occurrence of snow is computed as:

$$S = \begin{cases} P \ for \ T_a \leq T_{snow} \\ P\left(\dfrac{T_{rain} - T_a}{T_{rain} - T_{snow}}\right) for \ T_{snow} < T_a < T_{rain} \\ 0 \ for \ T_a \geq T_{rain} \end{cases}$$

where S is monthly snow fall in millimeters (mm), P is monthly precipitation in mm, T_a is monthly air temperature in degrees Celsius, T_{rain} is a threshold above which all monthly precipitation is rain, and T_{snow} is a threshold below which all monthly precipitation is snow. When the monthly air temperature is between T_{rain} and T_{snow}, the proportion of precipitation that is snow or rain changes linearly.

In the snow accumulation and melt model, snow that occurs during the month is added to the snow pack and is subject to melt if conditions are such that melting can occur. Thus, for some cases, snow, rain, and snowmelt can occur in the same month. For this study, T_{rain} was set to 7°C and T_{snow} was set to −4°C; these values were determined from model calibration (explained later). Snowmelt is computed by a degree-day method:

$$M = \alpha \left(T_{air} - T_{snow}\right) d$$

where M is the amount of snow storage that can be melted in a month, α is a melt rate coefficient, and d is the number of days in a month. A melt rate coefficient of 0.47 was used in this study; this value was determined through the calibration procedure and is in the mid-range of values used in previous studies (Rango and Martinec 1995).

This study focuses on Northern Hemisphere SCA in March because of its sensitivity to temperature changes and the reported variability in March SCA during the twentieth century (Brown 2000). Northern hemisphere March SCA was computed each year by summing the areas of model grid cells with snow storage during March. A grid cell was considered to be completely snow covered if March snow storage was at least 40 mm. For grids with less than 40 mm of snow storage, the fraction of the grid cell covered with snow was computed as a ratio of the estimated snowpack divided by 40 mm. The 40-mm snow storage threshold value was selected through the calibration process. Application of the storage threshold approach was necessary because the snow model estimates a storage depth, not the fraction of snow-covered area, for a grid cell. In previous studies, Brown (2000) used a threshold of 20 mm in an analysis of North American snow cover, and Walsh et al. (1982) used thresholds of 15 and 25 mm.

Parameters for the snow accumulation and melt model (i.e. T_{rain}, T_{snow}, melt rate coefficient, and the snow storage threshold used to determine the fraction of snow cover for each grid cell) were determined using an exhaustive search calibration procedure (Hay et al. 2002). In this calibration procedure, combinations of parameter values selected from a range of values for each parameter were used to compute time series of Northern Hemisphere SCA for March. The time series of Northern Hemisphere March SCA was standardized and then compared with standardized March SCA from the Rutgers dataset for the period 1967 through 2002. The parameter values associated with the model-estimated time series that produced the best fit (determined using the Nash–Sutcliffe statistic (Nash and Sutcliffe 1970) with the Rutgers time series were used for remaining analyses. A comparison of the final model-estimated time series of March SCA with March SCA from the Brown dataset (1923 through 1986) provided a verification of the model-estimated values.

A comparison of Northern Hemisphere March SCA from the Rutgers global snow-cover dataset with snow-model estimated SCA for 1967 to 2002 (the period of overlap) indicates a correlation of 0.68 (significant at a 99% confidence level ($p < 0.01$)) with a bias of 0.0% (Fig. 1a, b). A comparison of snow-modeled SCA with March SCA from Brown (2002) for the years 1923 through 1996 produces a correlation of 0.82 ($p < 0.01$) with a bias of 0.0% (Fig. 1a, c). Although there clearly is scatter in Fig. 1b, c, the time series in Fig. 1a and the statistics of SCA comparisons suggest that the snow-model estimated SCA reproduces the overall temporal pattern

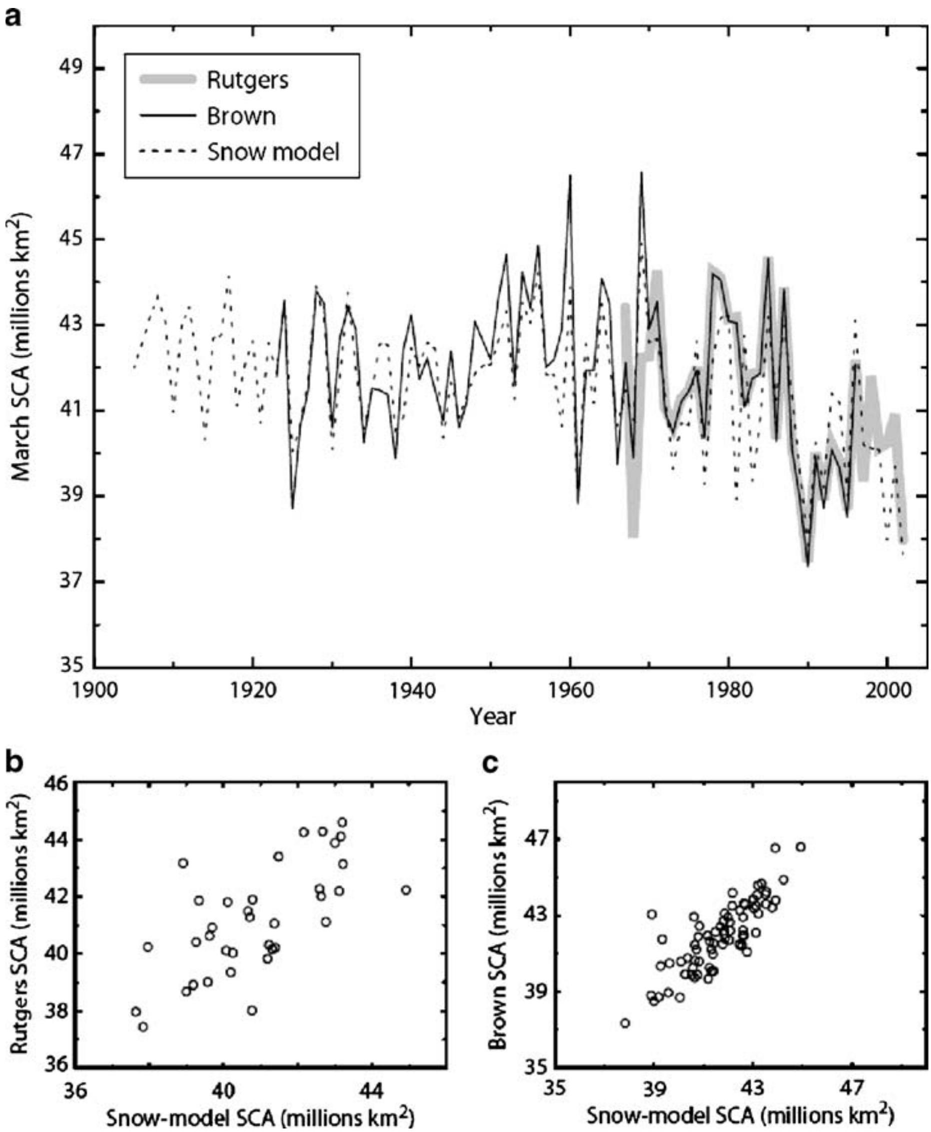

Fig. 1 **a** Time series of March snow-covered area (*SCA*) for the Northern Hemisphere (in square kilometers from the Rutgers University Global Snow Laboratory (Rutgers), Brown (2000, 2002) and the snow model, **b** scatter plot of snow-model March SCA and Rutgers SCA (1967–2002), and **c** snow-model SCA and Brown SCA, (1923–1996)

of the measured SCA. Errors in snow model estimates of SCA are introduced by several factors which include errors in (1) the gridded climate data used as inputs to the model, (2) the simplified snow model, and (3) differences in the methodologies used to estimate SCA. Considering the potential errors introduced by these various factors, the agreement between SCA estimated by the snow model and the Rutgers and the Brown (2002) SCA time series indicates that the snow model is adequate for the objectives of this study.

Most of the analyses that form the basis of this study used the time series of Northern Hemisphere March SCA, estimated from the snow accumulation and melt model, for the period 1905 through 2002. The model-estimated March SCA time series provides an analysis period that is longer than those used in previous studies. Although climate data required for the model are available beginning in 1901, the first few years of model simulations were not analyzed in order to avoid the effects of initial model conditions (e.g., the need to build snow pack from zero).

3 Results and discussion

The model-estimated time series of Northern Hemisphere March SCA shows a negative trend, especially since about 1970 (Fig. 2a). In addition, since about 1980, standardized departures of Northern Hemisphere March SCA (computed using 1905–2002 long-term statistics) have been mostly negative. Since about 1990, negative departures have been more frequent and have reached the lowest levels of the twentieth century. An examination of SCA time series computed for 5° latitudinal bands indicates decreases in March SCA for most of the Northern Hemisphere and statistically significant (at a 95% confidence level ($p < 0.05$)) decreases in March SCA for Northern Hemisphere mid-latitude regions (Fig. 3f).

A comparison of time series of mean Northern Hemisphere winter (November through March) temperature (Fig. 2b) and estimated March Northern Hemisphere SCA for 1905–2002 (Fig. 2a) indicates a substantial correspondence between temperature and March Northern Hemisphere SCA (Fig. 2c). The correlation between Northern Hemisphere March SCA departures and winter temperature departures is negative ($r = -0.64$) and significant at $p < 0.01$. In addition, the correlation of March

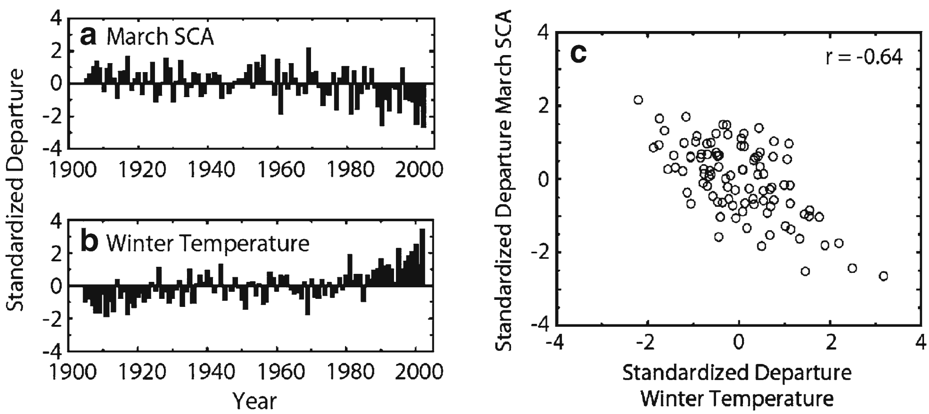

Fig. 2 **a** Time series of standardized departures of March snow-covered area (SCA) for the Northern Hemisphere, **b** time series of standardized departures of mean winter (November through March) Northern Hemisphere temperature, and **c** scatter-plot of standardized departures of winter temperature versus standardized departures of March SCA. The standardized departures are computed from long-term statistics for 1905–2002

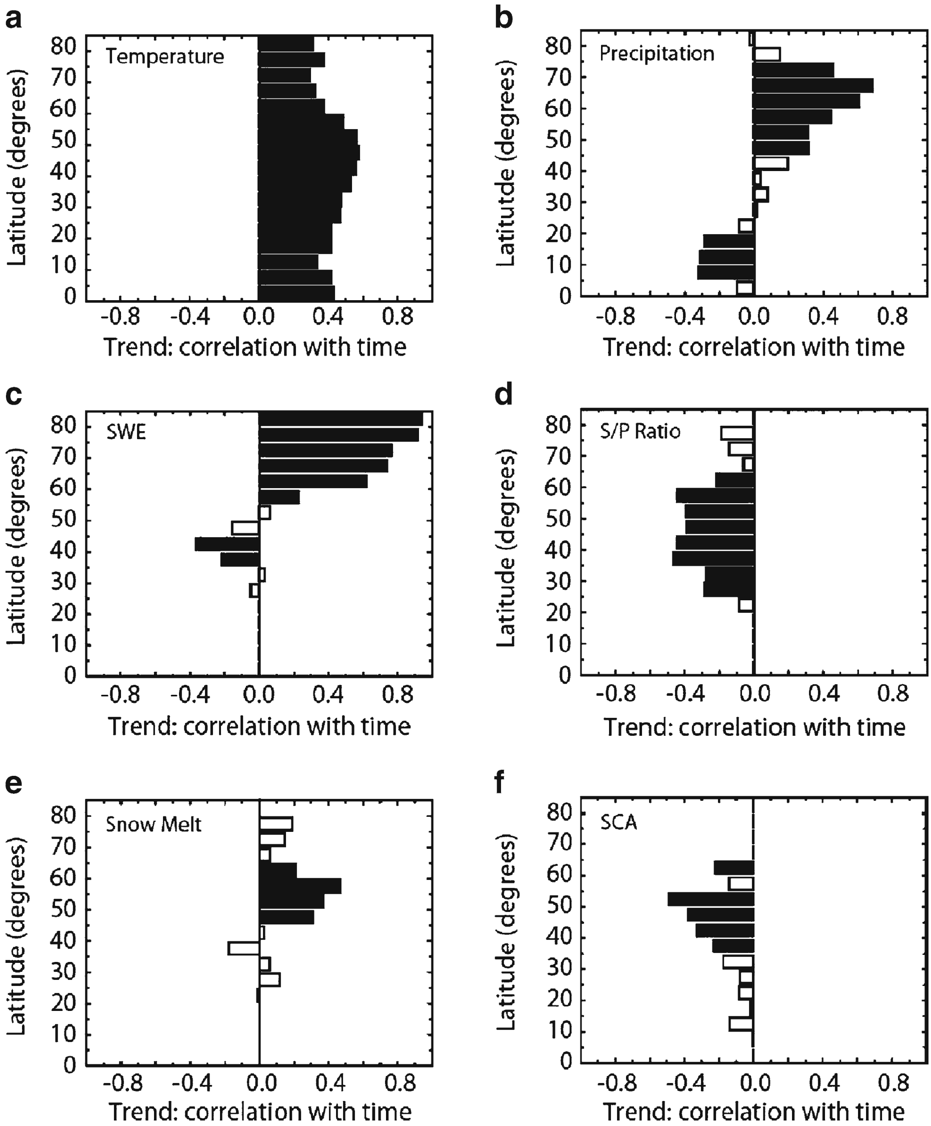

Fig. 3 Linear trends (correlations with time) for 5° latitudinal bands of **a** mean winter (November through March) temperature, **b** mean winter precipitation, **c** March snow-water equivalent (*SWE*), **d** the ratio of winter snow to winter precipitation (*S*/*P Ratio*), **e** March snowmelt (thus, positive (negative) trends indicate greater (lesser) snowmelt with time, and **f** March snow-covered area (*SCA*), 1905–2002. *Solid bars* indicate trends that are significant at a 95% confidence level

SCA with winter temperature for moving 20-year periods indicates that the inverse relation between temperature and SCA has strengthened during recent decades when the warming has been most significant (Fig. 4).

Temperature appears to affect SCA in several ways. First, increases in temperature have caused decreases in the fraction of winter precipitation that occurs as

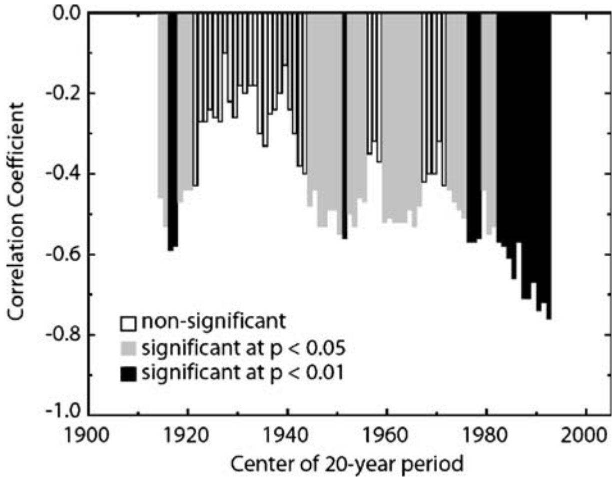

Fig. 4 Twenty-year moving correlations between Northern Hemisphere March snow-covered area and mean winter (November through March) Northern Hemisphere temperature, 1905–2002. *Open bars* indicate correlations that are non-significant, *gray bars* indicate correlations that are significant at a 95% confidence level ($p < 0.05$), and *black bars* indicate correlations that are significant at a 99% confidence level ($p < 0.01$)

snow (Fig. 3d). During the 1905–2002 period, the ratio of snow to total winter precipitation has decreased for all latitudinal bands in the Northern Hemisphere where snow occurs. This negative trend is associated with the positive trend in winter temperature.

Effects of temperature also likely influence snowmelt (Fig. 3e). Trends in snowmelt for 5° latitudinal bands indicate increases in snowmelt for high latitudes and decreases for low latitudes. The increases in snowmelt for high latitudes are likely due to two factors: (1) increases in precipitation (Fig. 3b) and SWE (Fig. 3c) in high latitudes provide more snow available to melt, and (2) increases in temperatures (Fig. 3a) cause snow to melt more often. The decreases in snowmelt for low latitudes are a result of decreased precipitation (and SWE). The trends in snowmelt are consistent with the trends in precipitation, SWE, and temperature.

The increases in precipitation and snow for high latitudes are consistent with trends reported in other studies. Increases in precipitation and SWE have been shown for the Northern Hemisphere (Bradley et al. 1987; Vinnikov et al. 1990), North America (Brown 2000), Russia (Ye et al. 1998), Canada (Groisman and Easterling 1994), and the Greenland Ice Sheet (Johannessen et al. 2005).

Temperature also affects SCA through variations in atmospheric circulation caused by changes in temperature (Frauenfeld and Davis 2003). Correlations between winter temperature and winter sea-level pressures (SLPs) for 1905–2002 are negative near the Northern Hemisphere polar region and positive for most of the low- to mid-latitudes (Fig. 5b). Given that temperature generally has increased over the 1905–2002 period, the correlations mapped in Fig. 5b indicate that twentieth century warming has been accompanied by decreasing SLPs in the polar region and increasing SLPs in the low- to mid-latitudes. Increases in SLPs in the mid-latitudes and decreases in SLPs in the polar region are indicative of a poleward movement of the polar front and storm tracks. This result is supported by prior work which showed that storm tracks shifted poleward in the Northern Hemisphere during the 1959–1997 period (McCabe et al. 2001).

Correlations between March SCA and winter SLPs (Fig. 5a) are opposite of those between winter temperature and winter SLPs (Fig. 5b); the correlation between the

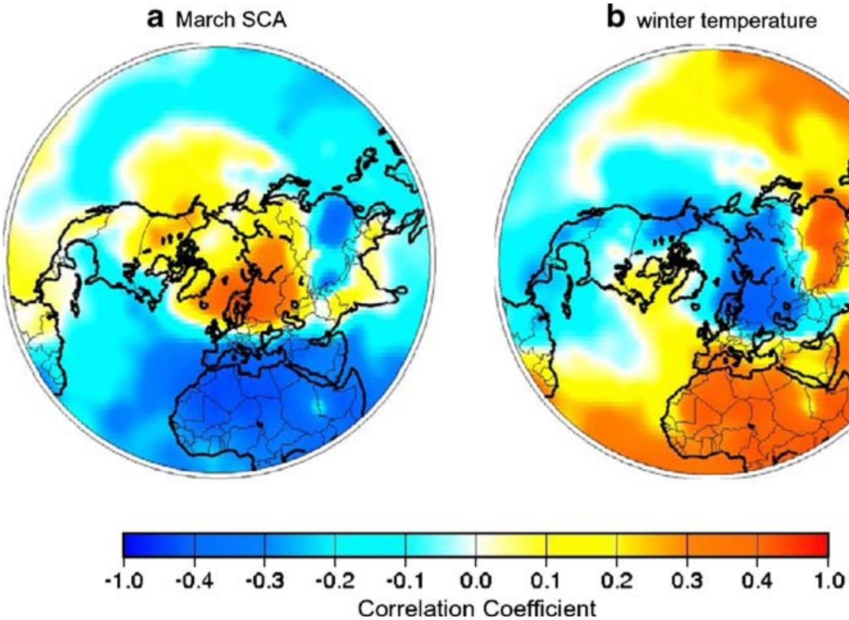

Fig. 5 Correlations between winter (November through March) sea-level pressures and time series of **a** Northern Hemisphere March snow-covered area (*SCA*), and **b** winter (November through March) Northern Hemisphere temperature, 1905–2002

patterns of correlations shown in Fig. 5a, b is −0.89 ($p < 0.01$). The correlations between March SCA and winter SLPs indicate negative correlations for the mid-latitudes and positive correlations for the high-latitudes. This pattern of correlations is consistent with a poleward movement of storm tracks, resulting in less precipitation (and snow) in mid-latitude regions and increased precipitation (and snow) in high-latitudes (Fig. 3b, c). This pattern of trends in precipitation is similar to the spatial pattern of precipitation trends projected by general circulation models (Dai et al. 1997; Nijssen et al. 2000; McCabe and Wolock 2008) for climatic conditions associated with global warming. This spatial pattern of precipitation trends may become stronger if global temperatures continue to rise.

The circumpolar vortex is often used as an index of hemispheric atmospheric circulation variability (Angell 1998, 2006; Davis and Benkovic 1992, 1994; Burnett 1993; Frauenfeld and Davis 2000, 2003). Frauenfeld and Davis (2003) defined and examined variability in the location and size of the circumpolar vortex. One of the time series (1949–2000) from their analysis is the mean latitude of the southern contour of the circumpolar vortex for the 300 hPa atmospheric pressure level (hereafter referred to as the circumpolar vortex size index (CVSI)). A time series of the CVSI for the winter months (November through March) indicates a negative trend (expanding circumpolar vortex) from 1949 to about 1970 and then a positive trend (contracting circumpolar vortex) after 1970 (Fig. 6c). The contraction of the circumpolar vortex after 1970 suggests poleward movement of storm tracks.

The temporal pattern of the winter CVSI (Fig. 6c) also shows a shift to positive values just before 1990. Angell (1998) describes this change around 1990 as a

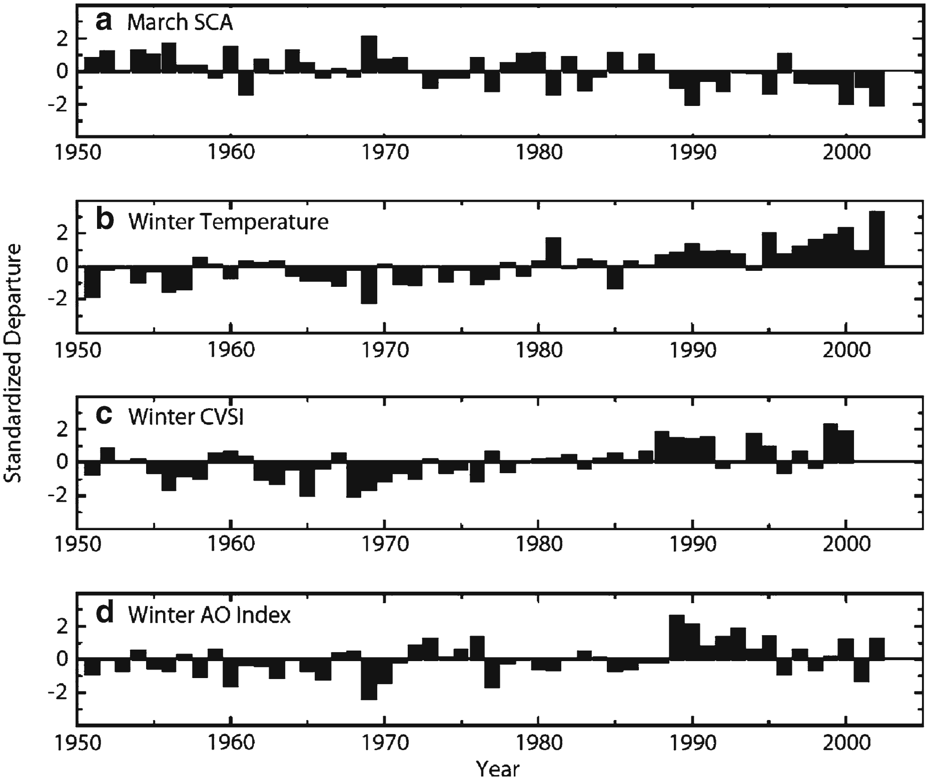

Fig. 6 Time series of standardized departures of **a** Northern Hemisphere March snow-covered area (*SCA*), **b** mean winter (November through March) Northern Hemisphere temperature, **c** mean latitude of the southern contour of the winter circumpolar vortex at the 300 hPa atmospheric pressure level (referred to in the text as the circumpolar vortex size index (*CVSI*); positive values indicate a contraction of the circumpolar vortex), and **d** mean winter Arctic Oscillation (*AO*) index, 1951–2002. The standardized departures were computed using long-term statistics for 1951–2000

contraction of the circumpolar vortex. This shift to positive values in the winter CVSI around 1990 also corresponds with an increase in winter temperature (Fig. 6b) and a decrease in March SCA (Fig. 6a) at the same time. In expanded research of the circumpolar vortex, Angell (2006) reported a statistically significant and physically meaningful decreasing trend (contraction) in the size of the circumpolar vortex during 1963 through 2001. This reported contraction of the circumpolar vortex is consistent with the trends in winter temperature and March SCA illustrated in Fig. 6b, c.

The Arctic Oscillation (AO) index quantifies the leading mode of Northern Hemisphere winter SLP variability. The AO is defined as the first empirical orthogonal function of Northern Hemisphere (20° latitude to 90° latitude) winter SLPs and is an index of the magnitude and variability of the circumpolar vortex (Thompson and Wallace 1998). Variations of the AO have been associated with variability of winter surface air temperature in the Northern Hemisphere (Thompson and Wallace 1998). Positive (negative) trends of the AO have been associated with increases (decreases) in Northern Hemisphere temperature (Thompson and Wallace 1998; Frauenfeld and Davis 2003).

Angell (2006) reported a strong inverse association between the winter AO and the size of the circumpolar vortex. An examination of a time series of the winter AO indicates a shift to positive values just before 1990 (Fig. 6d). This shift in the AO corresponds with the shift to positive values in the CVSI (a contraction of the circumpolar vortex; Fig. 6c), an increase in winter temperature (Fig. 6b), and a decrease in March SCA (Fig. 6a). Bamzai (2003) examined relations between the AO and snow cover variability in the Northern Hemisphere and found a statistically significant correlation between winter season AO and winter/spring snow cover variability. Similarly, Johannessen et al. (2005) reported a relation between the winter North Atlantic Oscillation (which is a component of the AO) and winter precipitation and snow over Greenland.

In a study of Eurasian snow cover Clark et al. (1999) found signals of the North Atlantic Oscillation (NAO) in snow cover. Clark et al. found the NAO signals primarily to be restricted to central Europe. Although the NAO produces large temperature anomalies over a large part of the Eurasian continent, much of this region experiences mean temperatures that are so cold that temperature variability has little effect on snow cover. However, over central Europe positive NAO conditions are associated with increased temperatures and decreased snow cover. Clark et al. also suggest that subtle shifts in atmospheric circulation may have large effects on snow cover.

The decrease in Northern Hemisphere SCA and the general poleward movement of snow cover in the Northern Hemisphere are illustrated by comparing SCA for 1908–1917 (the decade with the largest mean SCA) and SCA for 1993–2002 (the decade with the smallest snow covered area) during the 1905–2002 period. The difference between these two periods indicates a loss of snow cover across much of North America and eastern Europe (Fig. 7). If Northern Hemisphere winter temperatures continue to warm, snow cover is likely to continue to decrease, as depicted for a hypothetical 2°C temperature increase from the 1993–2002 climate (Fig. 7).

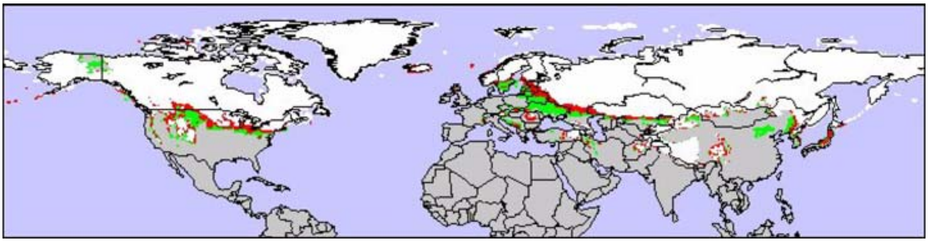

Fig. 7 March snow-covered area (SCA) derived using the snow model (grid cells are considered snow-covered if the fractional snow cover is at least 50% for at least 50% of the years analyzed): sum of *white*, *green*, and *red*—the snow covered area during 1908–1917 (the decade with the most extensive SCA); *green*—the area without snow in 1993–2002 (the decade with the smallest SCA) that was previously covered during 1908–1917; and *red*—the area without snow for the 1993–2002 climate with a 2°C temperature increase compared to the area which was snow covered in 1908–1917 with no temperature increase

4 Conclusions

Results indicate that Northern Hemisphere March SCA has been decreasing since about 1970 and that this decrease is associated with increased winter temperatures. In addition, the negative correlation between March SCA and winter temperature has been strengthening during recent decades.

The increases in winter temperatures have resulted in a decrease in the fraction of winter precipitation that occurs as snow and an increase in winter snowmelt for most of the Northern Hemisphere. These changes are particularly significant in the mid-latitudes. In addition, in the mid-latitudes, increases in winter temperatures have resulted in decreases in SWE. These changes in snow statistics appear to be associated with a poleward shift in winter precipitation through changes in atmospheric circulation, which is consistent with climate model projections of global warming. These results indicate a clear link between higher winter temperatures and decreased SCA in the Northern Hemisphere during the latter half of the twentieth century. If winter temperatures continue to warm, SCA for March will continue to decrease with a poleward contraction of SCA.

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