Changing Northern Hemisphere Snow Seasons

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ABSTRACT

Spatial and temporal patterns in the onset, offset, and length of the snow season across Northern Hemisphere continents are examined for the period from 1967 to 2008. Full snow seasons (FSS) and core snow seasons (CSS) are defined based on the consistency of snow cover within a location over the course of the cold season. Climatologically, the seasonal onsets of FSS and CSS progress more rapidly across the continents than the slower spring northward offset. Average Northern Hemisphere FSS duration has decreased at a rate of 0.8 week decade^{-1} (5.3 days decade^{-1}) between the winters of 1972/73 and 2007/08, while there is no significant hemispheric change in CSS duration. Changes in the FSS duration are attributed primarily to a progressively earlier offset, which has advanced poleward at a rate of 5.5 days decade^{-1}. A major change in the trends of FSS offset and duration occurred in the late 1980s. Earlier FSS offsets, ranging from 5 to 25 days, and resultant abbreviated durations are observed in western Europe, central and East Asia, and the mountainous western United States. Where regional changes in CSS were observed, most commonly there were shifts in both onset and offset dates toward earlier dates. Results indicate that it is important to pay close attention to spring snowmelt as an indicator of hemispheric climate variability and change.

1. Introduction

Snowfall is a transient seasonal phenomenon over Eurasia and North America. Depending on when and where it falls, snow may remain on the ground for hours to many months. In a given location, it may accumulate and disappear several times over the course of the season. For example, this may be the case in Arctic locales during the fall, whereas it may be common throughout the winter in the middle latitudes. Northern Hemisphere continental snow extent approaches 47×10^6 km^2 in January, while in August it is reduced to 4×10^6 km^2, the vast majority lying on the Greenland ice sheet (Robinson and Frei 2000).

Snow cover affects spatial patterns of thermal energy and hydrological resources on longer time scales. The high albedo of snow cover contributes to the suppression of surface air temperature by as much as 4°–8°C compared with snow-free conditions (e.g., Dewey 1977; Leathers and Robinson 1993). In addition, snow cover serves as a reservoir, which as it melts supplies a considerable amount of water for ecosystems, irrigation, and human consumption, in some locations well into the spring. For instance, agricultural regions adjacent to high mountains such as northern India have a high dependence on melting snow (Bagla 2007). Thus, continued monitoring of changes in the timing of snow season onset and offset as well as the interannual variability of snow cover is prudent.

Previous studies have documented the timing of spring peak streamflow; noting that it has advanced during the recent 30–50 yr in Canada (Zhang et al. 2001) and in the U. S. Rockies (e.g., Cayan et al. 2001) and in the Northeast (e.g., Hodgkins et al. 2003). Moreover, an earlier disappearance of snow cover in spring in recent decades (Robinson and Dewey 1990; Dye 2002) and subsequently an increase of snow-free days on a continental scale

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(Bamzai 2003) have been documented. Furthermore, where snowmelt advanced, problems relevant to hydrological imbalance such as spring droughts and more frequent, intensive wild fires have been reported (Westerling et al. 2006). Nonetheless, to date, the hemispheric spatial and temporal dynamics of snow seasons have been not fully explored.

In this paper, spatial and temporal patterns in the onset, offset, and length of the snow season across Northern Hemisphere continents are examined for the period from 1967 to 2008.

2. Data and methods

Weekly snow cover extent data from 1967 to 2008 are used to define the initiation and termination of snow seasons. The weekly files consist of gridded binary counts of snow or no snow digitized from maps generated by trained NOAA and National Ice Center meteorologists, primarily using visible satellite imagery (Robinson 1993). If at least 50% of the cell is covered with snow, it is assigned as snow covered; otherwise, it is snow free. The snow data are digitized using the National Meteorological Center Limited-Area Fine Mesh 128 $\times$ 128 Cartesian grid laid over a polar stereographic projection. Grid sizes range from 16 000 to 42 000 km^2. These snow files have been reprocessed, standardized, and archived at the Rutgers University Global Snow Laboratory (available online at http://climate.rutgers.edu/snowcover).

Snow cover can melt and reappear over the course of the snow season. At higher latitudes or elevations, this may only occur at the beginning or end of the season, whereas at lower latitudes this may occur throughout the winter. This study is confined to those regions (grid cells) where snow covered the ground for at least one week in 75% of the years during the satellite era. Also, considering discontinuities in coverage during transitional seasons, for this study we have defined two snow seasons. The full snow season (FSS) is the interval between the first appearance (FSS onset) and the last disappearance (FSS offset) of snow cover. The continuous snow season (CSS) is defined as the longest interval of the season with an unbroken string of weeks for which a grid cell is snow covered. As such, there are CSS onset and offset dates and the CSS duration. Snow cover must last from two or more weeks in the late January to mid-February period for a cell to be considered to have a CSS season. Onset dates for either the FSS or CSS seasons must lie between 1 August and 31 January, and FSS or CSS offset dates lie between 1 February and 31 July. Thus, CSS allows us to monitor variability or changes in snow cover in the midwinter, whereas FSS permits us to detect variability or changes in either tail of the entire snow season. FSS and CSS are calculated as shown in the subsequent two equations:

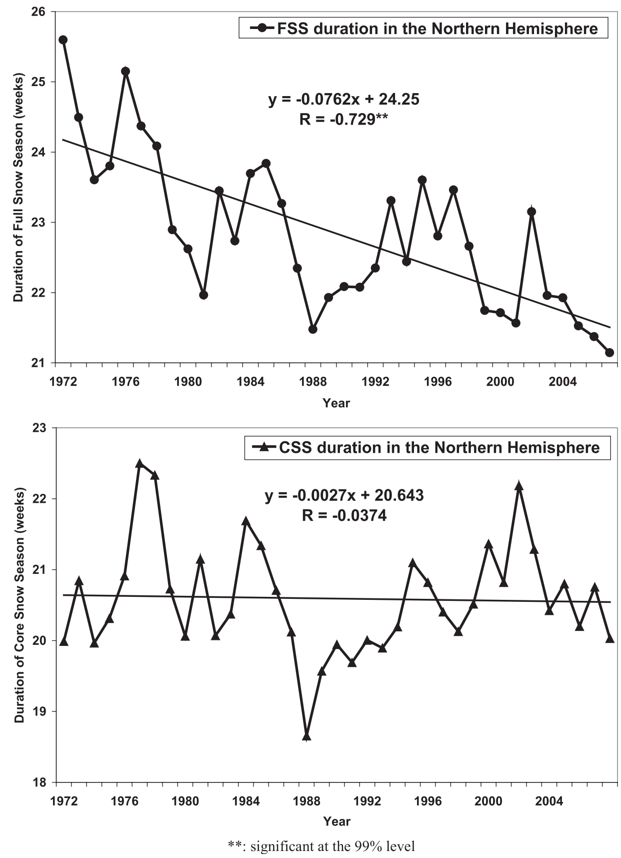


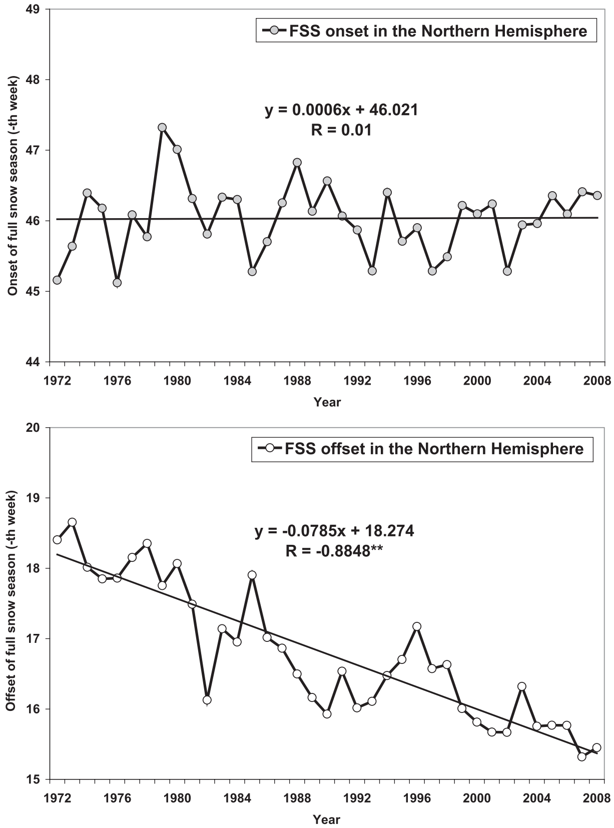
FIG. 1. (top) Full snow season (FSS) and (bottom) full core season (CSS) durations across Northern Hemisphere continents between the winter of 1972/73 and 2007/08.

$$\text{full snow season (FSS)} = (52\text{weeks} - \text{FSS onset week}) + \text{FSS offset week}$$

and

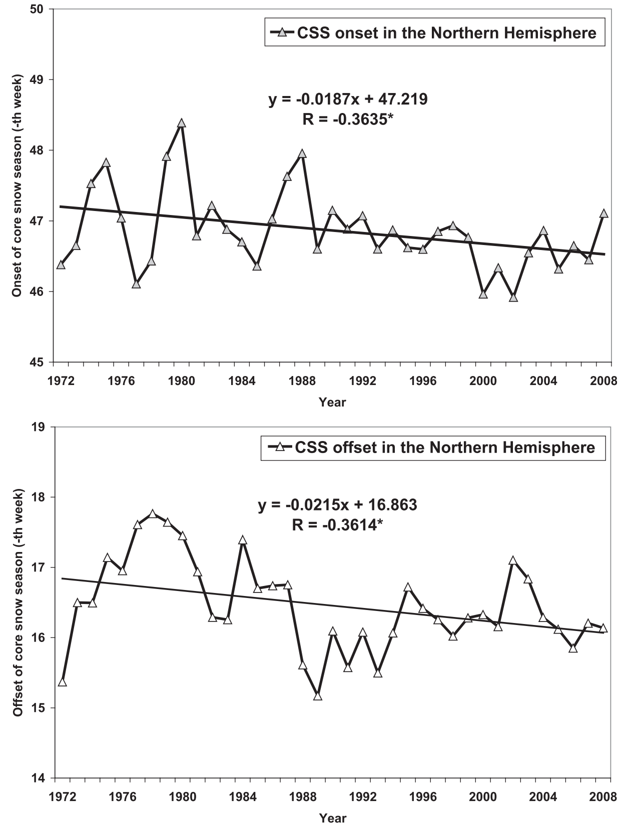
$$\text{core snow season (CSS)} = (52\text{weeks} - \text{CSS onset week}) + \text{CSS offset week}.$$

In this study, climatologies are generated from data from 1967 to 2008. Owing to some missing months in the 1967–71 interval (summer and fall months only), time series are only examined from 1972 to 2008. It is also worth noting that in 1999 the NOAA weekly product became a daily one at a higher resolution. However, for purposes of this study, these recent maps (now being produced by the National Ice Center; available online at http://www.natice.noaa.gov/ims/) have been reduced to the spatial and temporal dimensions of the earlier maps. To examine



**: significant at the 99% level

FIG. 2. Annual (top) onsets and (bottom) offsets of FSS from 1972 to 2008.



*: significant at the 95% level

FIG. 3. As in Fig. 2 but for CSS.

changes in Northern Hemisphere snow seasons, linear regression lines are fitted to each time series of interannual areally weighted spatial averages over all grid cells, and t tests are carried out to determine the significance of the linear trends. Areas for CSS are smaller than those for FSS when the spatial average is calculated.

3. Results and discussion

Both the FSS onset and offset in the Northern Hemisphere show zonal patterns. The earliest FSS onset occurs in Arctic regions in week 39 (late October), with the latest onset in lower-midlatitude regions in week 55 (mid-January in the following year). Spatial patterns of the latest FSS offset are reversed and the propagation period of the offset (weeks 5–27 in the second year of the snow season) is 6 weeks longer compared with the onset. Combined spatial patterns of the onset and offset lead to more than a 36-week-long (9-month-long) FSS along the high mountain ranges such as the Himalayas as well as pan-Arctic areas above 60°N, whereas FSS is less than one month in low-elevation regions at 25°–40°N. The Northern Hemisphere CSS onset occurs between weeks 43 and 55, whereas the CSS offset occurs between weeks 5 and 27. CSS duration ranges from 2 weeks (lower-midlatitude regions) to 36 weeks (Arctic). The CSS onset period is 2.5 weeks shorter than the offset interval. Both the earliest CSS onset and the latest CSS offset are observed on the Canadian Arctic islands, whereas both the southernmost latest CSS onset and the southernmost earliest CSS offset are found in the Himalayas. The CSS onset and offset in circumpolar regions progress more rapidly than across southern fringe CSS regions.

The FSS duration has decreased at the rate of 0.8 week decade^{-1} (5.3 days decade^{-1}) during the entire 1972/73–2007/08 period (Fig. 1). The reduction of FSS duration is due to earlier FSS offset dates throughout Eurasia and North America (Fig. 2). The FSS offset has advanced at the rate of -0.8 week decade^{-1} (-5.5 days decade^{-1}) since the early 1970s—a statistically significant ($r = -0.88$) change. This is more obvious between 1972/73 and 1987/88 compared with more recent years. The most significant changepoint in FSS duration is shown by a Mann–Whitney U test to center on 1988. There is no noticeable trend in Northern Hemisphere average FSS onset dates (Fig. 2).

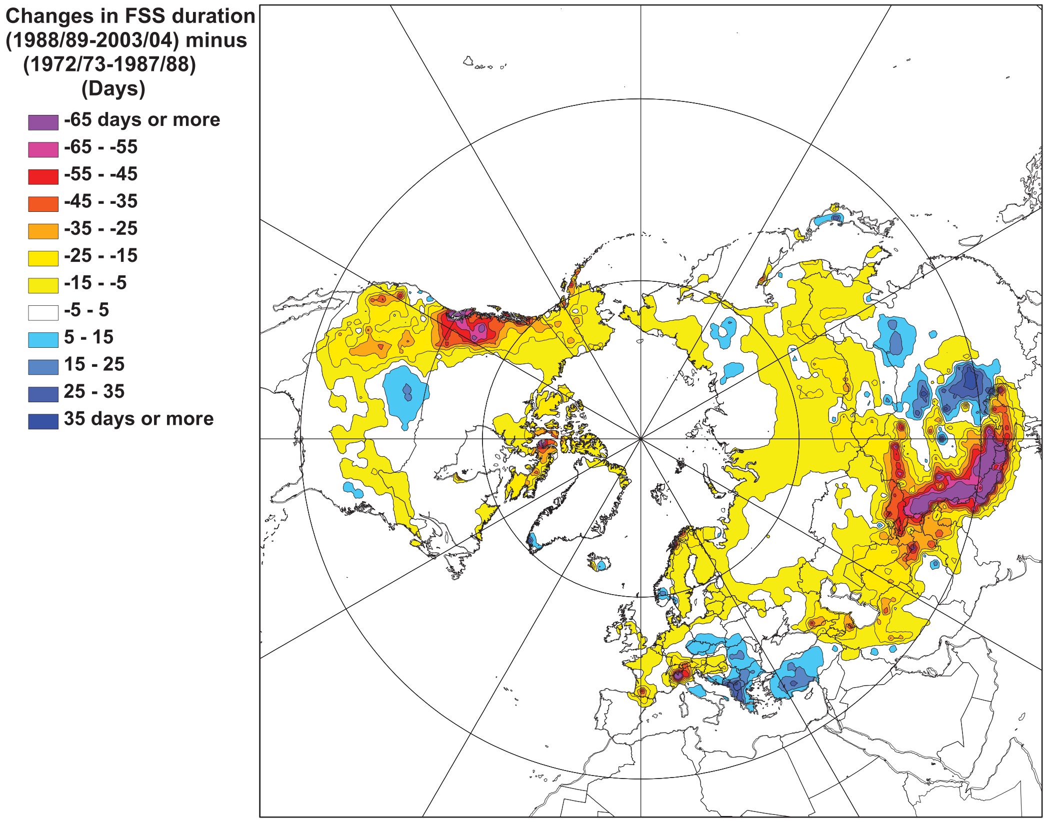


FIG. 4. Changes (the post-1987 period minus the pre-1988 period) in FSS duration. See text for cautionary information associated with the largest changes seen in mountainous regions.

CSS duration does not show any noticeable increasing or decreasing trends between 1972/73 and 2007/08 (Fig. 1). While there is some suggestion of both earlier CSS onsets and offsets at regional scales, there is no noticeable change in CSS onsets and offsets across the Northern Hemisphere (Fig. 3). It appears as if the variability of CSS onset has decreased since the 1990s. The overall interannual variation of the CSS duration is similar to that of the CSS offset.

Potential associations among FSS or CSS onsets, offsets, and durations show the most significant relationships ($\geq$99%, Pearson correlation analysis) between FSS duration and termination ($r = 0.770$) and between CSS duration and CSS termination ($r = 0.716$). Correlations between CSS duration and onset ($r = -0.591$) and between FSS duration and onset are also significant ($r = -0.552$). FSS and CSS offsets show a significant correlation ($r = 0.491$), as between FSS and CSS onsets ($r = 0.545$). These analyses demonstrate that the spring snow extent is exhibiting the greatest changes (loss) of the snow season in recent decades. While the earlier snowmelt is most apparent with relation to FSS offset, CSS offset is also somewhat earlier in the latter half of the satellite era.

An examination of the early 16 yr (1972/73–1987/88) of the temporally complete snow extent record and the following 16 yr (1988/89–2003/04) shows a reduction of FSS duration ranging from 5 to 25 days in regions poleward of 60°N (Fig. 4). In the middle latitudes of Eurasia, FSS duration has also decreased by 5–25 days. In midlatitude North America, FSS duration has decreased by 5–10 days along the New England–central Great Plains corridor in the United States and by 15–45 days along the Rockies. As a word of caution, variations in snow mapping techniques over the course of the satellite era, particularly the change to a higher resolution product in 1999, suggest that the larger duration changes may be somewhat inflated (Robinson and Estilow 2006). We are confident, however, that any inflated changes are limited to several mountainous regions such as the Himalayas.

Most of the regional decreases in FSS duration are attributable to earlier FSS offsets. In Manchuria, Mongolia, central Asia, and the Canadian Arctic islands, the FSS offset has advanced by 5–25 days. Within the Siberian Arctic and Europe above 60°N, the FSS offset has advanced by 5–15 days. Similarly, the FSS offset has advanced by 5–15 days from New England to the central

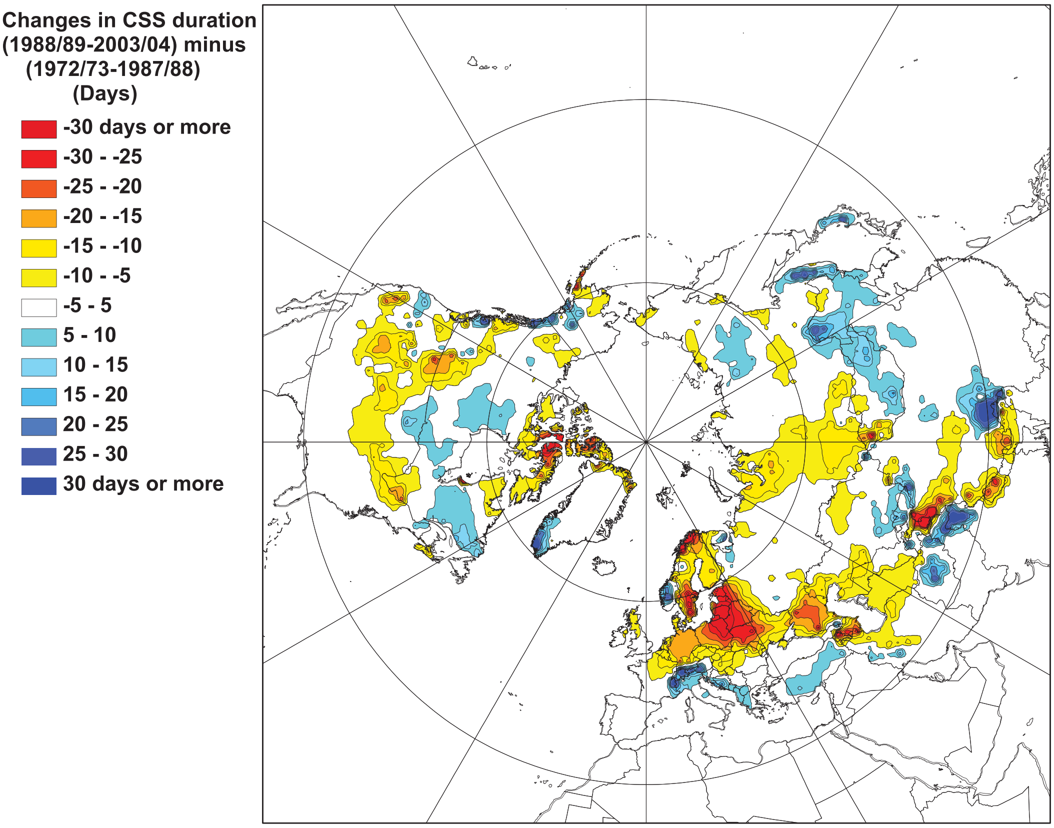


Fig. 5. As in Fig. 4 but for CSS.

Great Plains. Along the Rockies, the FSS offset has advanced by 5–35 days.

FSS duration has increased in southeastern Europe, northern China, and the northern U.S. Great Plains by 5–15 days (Fig. 4). This is mainly due to earlier FSS onsets. In the Himalayas and the Tibetan Plateau, the FSS onset has been delayed by up to 30 days, but again, this to some degree is likely a result of changing mapping practices.

Regional variations in CSS duration between the two 16-yr intervals mentioned previously are of a smaller temporal magnitude than FSS changes and are more balanced in terms of the sign of the change (Fig. 5). A 20-day reduction of CSS duration is found in northern and eastern Europe and the Canadian Arctic islands, whereas a 5–15-day decrease has occurred between 40° and 45°N in the western United States and in central Siberia. CSS duration has increased by approximately 10 days over extreme western Canada, the Mongolia–Manchuria corridor, the eastern Tibetan Plateau, northern Pakistan, and southern Europe.

4. Summary and conclusions

Temporal and spatial patterns of Northern Hemisphere snow extent have been examined during the 40-yr satellite era. Two means of characterizing a snow season, the full snow season (FSS) and the core snow season (CSS), have been introduced. The most significant study result is the identification of a decrease in FSS duration of 0.8 week decade^{-1} (5.3 days decade^{-1}) between the winters of 1972/73 and 2007/08. This change is primarily a function of earlier FSS offset, which has advanced at a rate of -0.8 week decade^{-1} (-5.5 days decade^{-1}). Earlier offsets of one to several weeks are most notable over western Europe, central and East Asia, and in the mountainous western United States. No appreciable changes in the FSS onset or in any CSS variable are found, although there are regional variations that are a week or longer. These differences in changes between the FSS and CSS may be associated with the critical relationship between temperature and snowmelt. Thus, during late winter and early spring, the temperature may be just warm enough to lead to melt, while in the winter, even when temperatures are above average, they may still be below freezing. Furthermore, with increasing spring solar radiation, enhanced snow–albedo feedback may reinforce snow melting processes (Déry and Brown 2007).

While the tendency for the transient spring snow extent season to end earlier during the 40-yr satellite era has yet to greatly impact the end of the core snow season, such a significant change will have to be carefully monitored in the years to come. So, too, must efforts continue to explain the early disappearance of spring snow cover. Is there winter ''conditioning'' of the snowpack associated with decreased depths or more frequent melting episodes? Have there been changes in circulation and/or overall warming of air masses? A few studies have examined regional lead–lag relationships between the timing of snow appearance/disappearance or duration and atmospheric circulation features such as temperature (Leathers and Luff 1997), the Arctic Oscillation (Bamzai 2003), summer monsoon (Ye et al. 2003), warm moisture advection (Shinoda et al. 2001; Ueda et al. 2003; Iijima et al. 2007), and meridional oscillations in geopotential height fields (Frei and Robinson 1999). More emphasis needs to be placed on the spring season.

Regional differences, including opposite signs in observed seasonal snow onsets and offsets, require more detailed dynamic and thermodynamic study. To monitor regional changes in the accumulated thermal energy associated with earlier snow melting trends, it may be useful to develop thermal indices such as snowmelt degree–days. Associations with the positioning of the polar front and storm tracks are suggested. These would be associated with hemispheric-scale investigations of circumpolar vortex and jet stream dynamics and kinematics.

Snow cover warrants continued, careful monitoring. A better understanding of linkages between seasonal snow and feedbacks within the boundary layer or changes in upper-atmospheric circulation will help us to understand the mechanisms of hemispheric-scale changes. Such efforts will also improve the predictability of future changes in cryospheric conditions within a warmer twenty-first-century climate.

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