UNCERTAINTY IN THE FUTURE OF SEASONAL SNOWPACK OVER NORTH AMERICA

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ABSTRACT

Snow cover extent and snow water equivalent (SWE) are rapidly changing over North America. This study investigates the uncertainty in the projected changes in North American snow cover for the middle of the 21st century using the North American Regional Climate Change Assessment Program (NARCCAP) ensemble of dynamically downscaled regional climate models (RCMs). Across the NARCCAP models, temperature is projected to increase everywhere while precipitation is shown to increase everywhere except the western U.S. In this region, the NARCCAP models disagree on the sign of the change in precipitation during the Fall and Winter. Corresponding with these changes in temperature and precipitation, the NARCCAP models robustly show that SWE is projected to decrease over most of North America. The only exception to this is in the high-latitudes, where SWE is projected to increase during the coldest months corresponding with increases in precipitation. There is considerable uncertainty in the magnitude of changes in SWE over north America, especially in the west. Variations in magnitude correspond with baseline SWE amounts from the current climate simulations as well as variations in the drivers of the change, namely temperature and precipitation. Changes in temperature and precipitation also lead to changes in the timing of the snow cover season. The first snow covered date is projected to occur later in the fall while the last snow-covered date is shown to occur earlier in the spring. These shifts result in a reduction in the total number of snow-covered days. There are notable differences across the ensemble in the change in the number of snow-covered days in the western US. Also, changes in the first and last dates with snow cover are uncertain in the central plains of North America, primarily due to interannual variability in this region. (KEYWORDS: North American snow cover, snow water equivalent, climate change, climate models, NARCCAP)

INTRODUCTION

Snow is a critically important part of Earth's climate system, both for its physical properties, including its high albedo and low thermal conductivity, and its role in the hydrological cycle and hence the provision of water resources. Snow cover extent (SCE) and snow water equivalent (SWE) are rapidly changing over North America, especially in spring. Changes in snow related variables result from the complex interaction between increasing temperatures and changing precipitation patterns. Observational studies have found that numerous snow-related variables have decreased over the past 60 years over North America. This includes the spatial extent of snow cover (Karl et al., 1993; Groisman et al., 1994; Brown and Robinson, 2011), the duration of the snow cover season (Brown and Mote, 2009; Callaghan et al., 2011; Knowles et al., 2015), snowfall (Kunkel et al., 2009; Knowles et al., 2006), and SWE (Mote et al., 2005; Kapnick and Hall, 2010; Kapnick and Hall, 2012; Fassnacht et al., 2016; Gan et al., 2013; Huntington et al., 2004). In the western U.S., the impact of changes in the timing and amount of snow in the mountains is already being seen. Reductions in snowfall and earlier snowmelt are linked to increases in summer temperature extremes and droughts (Mahanama et al., 2012) as well as an increased risk for wildfires (Westerling et al., 2003).

Model projections of future climate that are forced with increasing greenhouse gas concentrations project further increases in surface temperature over all of North America, with amplified warming in the high-latitudes (Solomon, et al., 2007; IPCC, 2013; Mearns et al., 2013; Maloney et al., 2014; USGCRP, 2017). Models also generally agree that winter precipitation amounts will increase everywhere except the Southwest U.S. (Solomon et al., 2007; IPCC, 2013; Mearns et al., 2013; Maloney et al. 2014; USGCRP, 2017). Future projections of snow conditions over North America are aligned with observations and indicate that the effects of temperature will dominate changes such that snow cover and SWE will continue to decrease in the future. However, there is uncertainty about the sign of the changes in winter SWE over high-latitudes (Räisänen, 2008; Brown and Mote, 2009; Maloney et al., 2014) and high-elevations (Brown and Mote, 2009; Rasmussen et al., 2014), where precipitation increases may dominate if temperatures remain below freezing in winter.

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Previous studies that have looked at future changes in snow over North America have been limited in one of two ways. First, many studies use coarse global climate model (GCM) ensembles to study changes in snow (e.g. Räisänen, 2008), which allows for the exploration of uncertainty in projected changes, but relies on coarse models which cannot adequately represent changes in regions of complex topography (Leung et al, 2004; Brown and Mote, 2009). Second, other studies use high-resolution climate simulations to characterize changes in snow, which greatly improve the ability to capture heterogenous snow processes, but high-resolution experiments are so computationally expensive only one simulation of the future is typically possible, preventing an analysis of the uncertainty of future changes (e.g. Rasmussen et al., 2014).

Given the limitations of previous studies, there is a need to examine the uncertainty in the response of snow cover and SWE over North America to a warming climate at higher resolution than GCMs can provide. This study uses the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2009, 2012) suite of RCMs to explore the uncertainty in future changes in snow metrics over North America across multiple models at high resolution. The NARCCAP suite provides a unique opportunity to investigate the uncertainty of future climate change due to structural differences in climate models run at relatively high resolution with high-frequency (three-hourly) output. With this model ensemble, we look at the details of the complexity in SWE changes with greater spatial and temporal detail and with increased confidence in regions of complex topography. The high temporal frequency of the model output provides a unique opportunity to study changes in duration of the snow cover as well as the timing of the start and end of the snow-covered period.

CLIMATE MODEL SIMULATIONS

This study uses regional climate model simulations from NARCCAP (Mearns et al., 2007) to study future changes in snow cover and SWE over North America. NARCCAP is an ensemble of regional climate models (RCM) driven by different GCM simulations designed to study climate change processes and provide climate change projections to the impacts and adaptation communities. As a part of NARCCAP, four different coarse resolution GCMs from the Climate Model Intercomparison Project versions 3, (CMIP3, Meehl et al., 2007) provided boundary conditions for six RCMs resulting in a total of 12 dynamically downscaled simulations at 50km resolution. Details about the RCMs and driving GCMs used in this study can be found in Tables 1 and 2. Higher spatial resolution has shown to improve the representation of climate in regions of complex topography such as mountains and coastlines (Mearns et al., 2015). In NARCCAP, simulations for the current/historical period span 1971-99 while the future simulations are representative of the middle of the 21st century and span 2041-69. Greenhouse gas emission projections for the future climate simulations are based on the Special Report on Emissions Scenarios (SRES; Nakićenović´ et al., 2000) A2 scenario. Additionally, while all RCM simulations were performed at the same spatial resolution (50km), each model uses a distinct map projection; therefore, for ensemble calculations the simulations were first interpolated to a common 0.5º x 0.5º grid. SWE was only available from 11 of the 12 NARCCAP simulations (Table 2), so the ensemble analysis shown consists of 11 models.

METHODS

The goal of this paper is to examine the uncertainty in changes in North American snow cover and SWE from the NARCCAP ensemble. Climate changes are calculated as the difference between the average values from the future time period (2041-2070) and the average values from the current time period (1971-2000). We use the model spread to represent uncertainty in future climate. In this study, the uncertainty from the NARCCAP ensemble is shown in two ways. First we show the seasonal cycle of climate variables averaged over all of North America (see Figure 1 for an example). By averaging over the NARCCAP domain, we can show how the model spread changes throughout the season and we can highlight which models have the smallest or largest climate change response. While area averaged plots can show a lot of important information, the spatial patterns of climate change are often more interesting. The second way we demonstrate the uncertainty in future change in the NARCCAP ensemble is to show maps of the 25th, 50th (median), and 75th percentiles of the change (See Figure 2 for an example). To make these maps, at each grid point we rank the climate change of each variable from each model from highest to lowest. We then plot the 25th, 50th (median) and 75th percentiles of the simulated changes at each grid box. As 11 NARCCAP ensemble members are used in this study, the 25th percentile represents the third lowest value at each grid point while the 75th percentile represents the 9th highest value of each grid point. Maps of the 50th percentile show values where 5 of the models have smaller climate changes and 5 of the models have larger climate changes.

Table 1. GCMs and RCMs used in NARCCAP, their identifying acronyms, and relevant references. All RCMs were run at a 50km resolution. For the GCMs, horizontal resolution is listed.

	Acronym	Model	References
GCMs	CCSM	NCAR Community Climate System Model, version 3 (CCSM3), T85	Collins et al. (2006)
	CGCM3	Third Generation Canadian Coupled GCM, version 3 (CGCM3), T47	Flato et al. (2000)
	GFDL	GFDL Climate Model, version 2.1 (GFDL CM2.1), 2.0º x 2.5º	Anderson et al. (2004)
	HadCM3	Hadley Centre Coupled Model, version 3 (HadCM3), 2.5º x 3.75º	Gordon et al. (2000); Pope et al. (2000)
RCMs	CRCM	Canadian RCM	Caya and Laprise (1999)
	ECP2	Experimental Climate Prediction Center's Regional Spectral Model	Juang et al. (1997)
	HRM3	Third-generation Hadley Centre RCM	Jones et al. (2003)
	MM5I	Fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model	Jones et al. (2003); Grell et al. (1993)
	RCM3	International Centre for Theoretical Physics RCM, version 3	Giorgi et al. (1993a,b); Pal et al. (2007)
	WRFG	Weather Research and Forecasting Model	Skamarock et al. (2005)

Table 2. NARCCAP RCM and GCM simulation combinations with SWE available. While the HRM3-GFDL simulation was performed, SWE was not archived.

	CCSM	CGCM3	GFDL	HadCM3
CRCM	X	X		
ECP2			X	X
HRM3			-	X
MM5I	X			X
RCM3		X	X	
WRFG	X	X		

RESULTS

Future changes in SWE are due to the combined changes in temperature and precipitation. Holding precipitation constant at current levels, increasing temperatures would decrease SWE by decreasing the amount of snowfall and increasing snow ablation through melt and evaporation. Holding temperatures at current values, increases (decreases) in precipitation would increase (decrease) SWE as the fraction of total precipitation that falls as snow would remain constant. But the combined effects of changes in both are potentially complex.

Figure 1 shows area averaged plots of the seasonal cycle of SWE (Figure 1a), temperature (Figure 1b), and precipitation (Figure 1c) for each model from the current climate simulation, as well as the change in the seasonal cycle of these variables (Figure 1d-f). Focusing on the spread in the current climate simulations, averaged over

North America, the NARCCAP models exhibit significant spread in the total amount of SWE during the peak months. SWE amount appears to be controlled more by RCM, rather than the GCM driver. For instance, both RCM3 simulations have more SWE than any other RCM while the WRFG simulations have the lowest SWE amounts. SWE over North America peaks in March in most of the models, although the two WRFG simulations and the HRM3 simulation with available SWE data peak in February. Differences in simulated SWE are a function of differences in simulated temperature and precipitation. In general, the models with more winter precipitation (e.g. RCM3) have larger area averaged SWE values, while the models with lower winter precipitation (e.g. WRFG) have lower SWE values. Area averaged temperature does not appear to play as large of a role in the differences in SWE. This may be because, as long as temperatures are below zero, precipitation will fall as snow and melt will be minimal. For more information on the causes of bias in the NARCCAP models, including a discussion of land-surface model configuration and parameterizations, see McCrary et al. (2017).

By mid-century, when averaged over North America, SWE decreases during all months of the year, with the largest losses in late winter or spring (February-May) depending on the model. There is considerable spread across the models in terms the magnitude of SWE changes. While these differences scale somewhat with current SWE amounts, the MM5I simulations show large losses in SWE relative to their current baseline amounts, while the

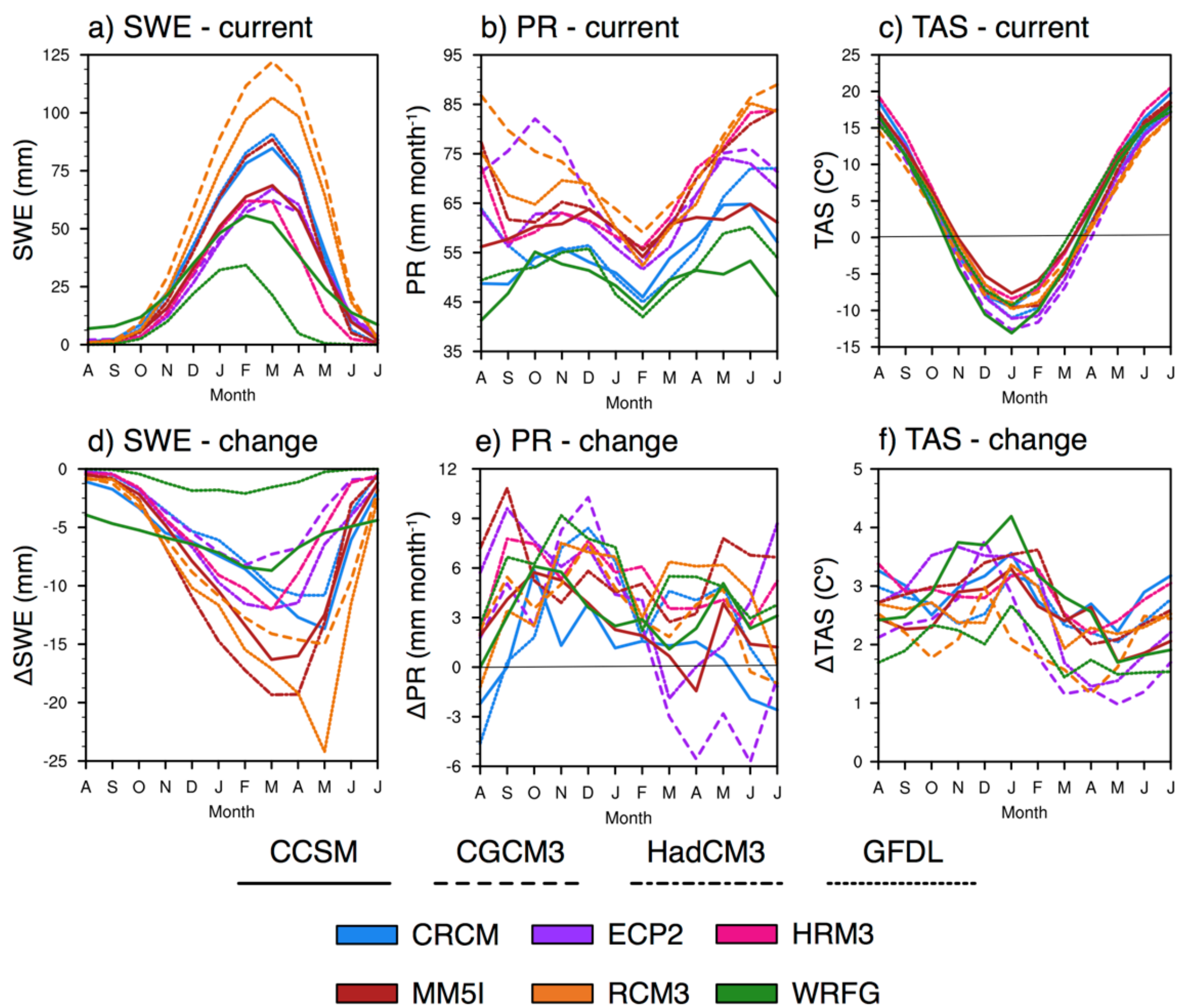

Figure 1. Seasonal cycle from each NARCCAP RCM for the current climate simulations (top) of SWE (a), precipitation (b), and temperature (c) and the mid-century change in SWE (d), precipitation (e) and temperature (f) averaged over all of the North American NARCCAP domain.

CRCM simulations show relatively smaller losses relative to their baseline amounts. In all of the RCMs, area averaged temperatures are projected to increase, with the largest warming occurring in the winter months and ranging from 2-4.1ºC in January. As demonstrated in other studies (listed in the introduction), winter precipitation increases in the models.

While area averaged plots can be informative on a broad scale, regional variations in changes in SWE are considerably more interesting and complex. Figure 2 shows the spread (as defined in the methods section) in the change in average December-February SWE, average October-February temperature, and average October-February precipitation. As SWE is an accumulated field, changes in winter SWE are not only a function of the snow that accumulates or? melts during December-February, but also the snow accumulation and melt that occurred throughout the fall. For this reason, we include October-February in our analysis of temperature and precipitation (which drive snowfall and melt).

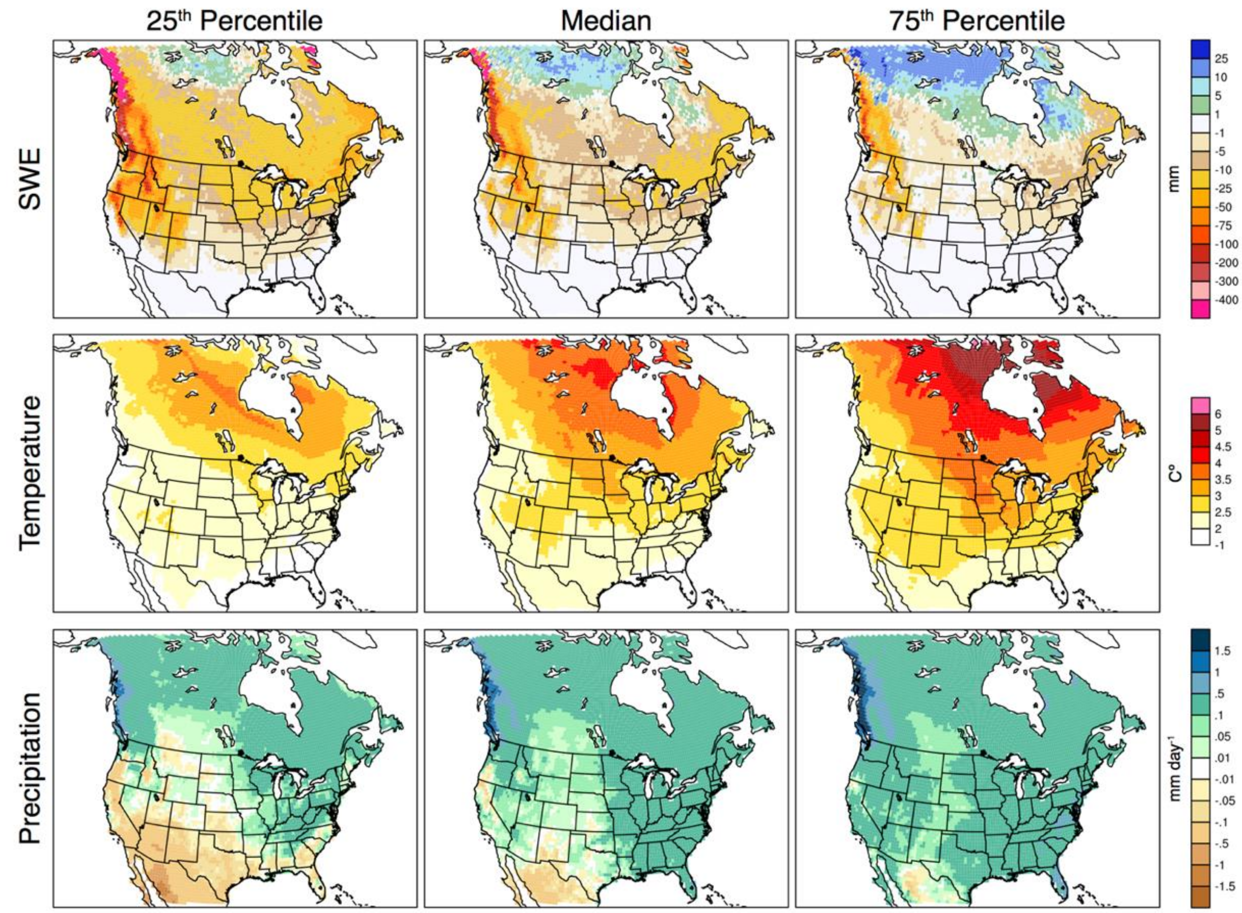

Figure 2. Maps of the change in average December-February SWE (top), average October-February surface temperature (middle), and average October- February precipitation (bottom) by mid-century as simulated by the NARCCAP ensemble. For each gridbox, the 25th (left), 50th (median, middle), and 75th (left) percentiles of the distribution of the change for each variable from the NARCCAP ensemble are shown. The change is calculated as the difference between the future and current time periods.

Consistent with GCM studies, temperatures are projected to increase over the entire domain, with the largest increases occurring in the arctic. There is considerable spread in arctic temperature changes, ranging from less than 3º in the lowest model quartile, to greater than 5º in the upper model quartile. Total precipitation is also projected to increase over much of the domain, however there are large differences across the models in the western U.S. In this region the lower quartile and upper quartile of the ensemble disagree on the sign of the change in precipitation. This uncertainty likely results in the large variations (losses of 100 to 400 mm) found in the changes in SWE in the western U.S. Over much of the domain SWE is projected to decrease by mid-century. The only exception to this is in the high-latitudes, where the inter-quartile range of the models shows increases in winter SWE. As discussed in previous studies, temperatures in this region remain well below freezing during the winter months. Therefore, the projected increases in precipitation in this region result in increased snowfall and increases in snow accumulation. While not shown in this paper, SWE shows reductions in the future in the high latitudes during the fall and spring.

As temperatures increase and precipitation patterns shift, the timing and duration of the snow-covered season will also change. In the following analysis, a gridbox is snow covered if SWE is greater than 2.54 mm (1 in.). Also, all annual counts and statistics are based on a snow year which is defined as August 1- July 31. Figure 3

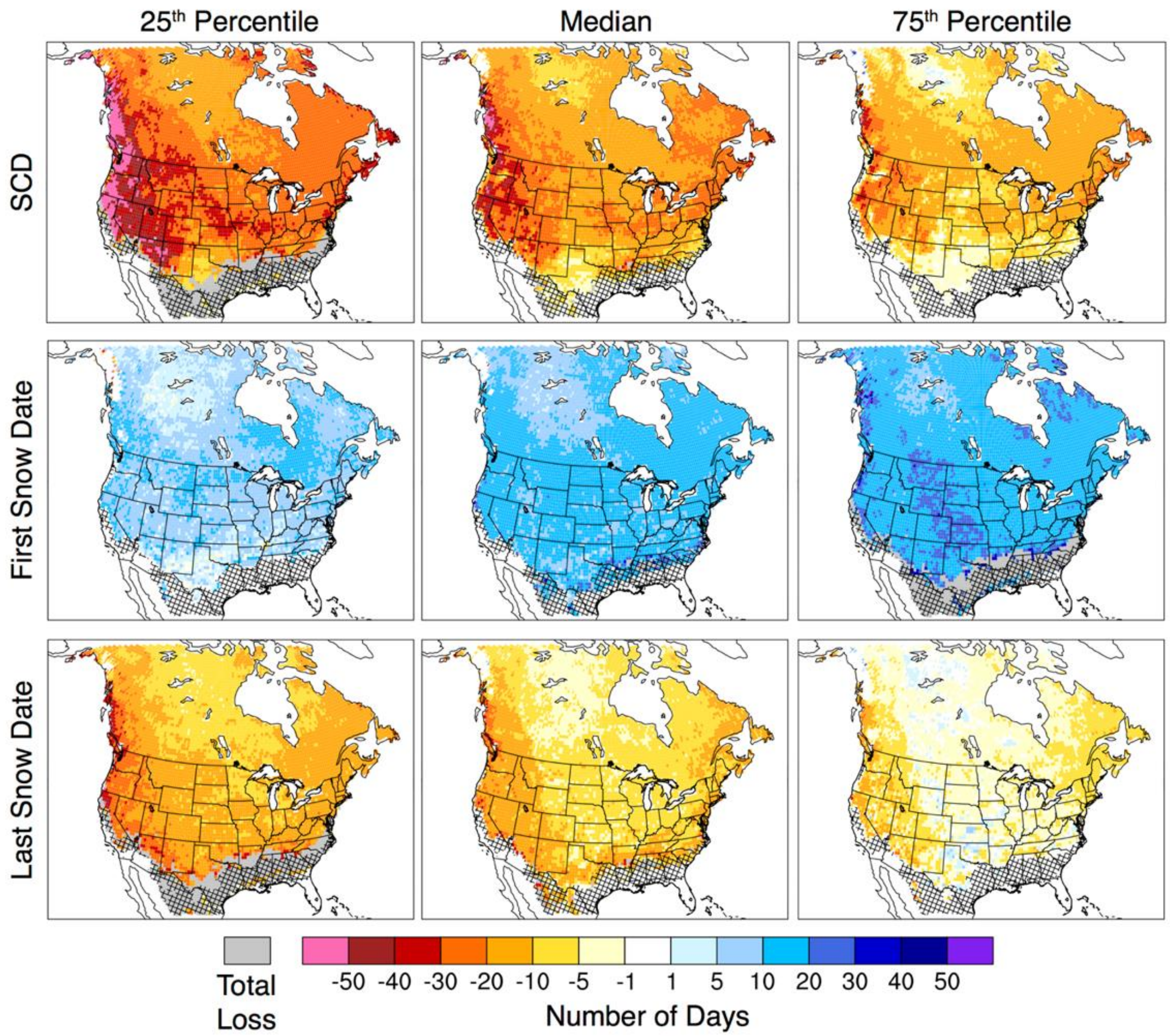

Figure 3. Maps of the change in snow cover duration (SCD) (top), first snow date (middle) and last snow date (bottom) by mid-century as simulated by the NARCCAP ensemble. For each gridbox, the 25th (left), 50th (median, middle), and 75th (left) percentiles of the distribution of the change for each variable from NARCCAP ensemble are shown. The change is calculated as the difference between the future and current time periods. Hatching denotes where fewer than 11 models agree on the location of snow cover in the current time period. Gray indicates regions where the models within that percentile have a total loss of snow in the future.

shows maps of the ensemble spread in changes in the snow cover duration (SCD), defined as the first snow covered date of the year versus the last snow-covered date of the year. SCD is defined here as the total number of snow-covered days each year. The NARCCAP models show that domain wide, the number of snow-covered days per year will decrease in the future. There is considerable spread in the change in SCD in the western US, ranging from ~30 days in the models with the smallest losses, and greater than 50 days in the models with the largest losses. Losses are smallest in the high latitudes, but the models generally agree that the number of snow-covered days will decrease in the future in spite of increases in average winter SWE amounts found at high latitudes (Figure 2). A decrease in the total number of snow-covered days corresponds with a contraction of the snow-covered season. The models all agree that the first snow covered date will occur later in the season in the future. This is likely because increasing temperatures will push the first date with below freezing temperatures farther into fall and winter. The largest disagreement about the magnitude of the change in the first snow date occurs in the central US, east of the Rocky Mountains. The models also show the last snow-covered date occurring earlier in spring in the future, although a few models show increases in this date in the central US. Over the central US, the timing of the onset and end of the snow cover season is highly variable from year-to-year (not shown) and the ~29-year time slices for the current and future climate simulations may not be sufficient to capture robust changes in the timing of the snow season in this region. Results over the central US may be more uncertain than the model spread suggests.

DISCUSSION AND CONCLUSIONS

We used the NARCCAP ensemble to explore the uncertainty in projections of future change in snow cover and SWE by mid-century over North America. There is significant spread in the simulation of the baseline current climate SWE in the NARCCAP models. These differences correspond to differences in simulated precipitation, temperature, and the representations of snow in the land-surface model of each RCM (McCrary et al., 2017). Differences in snow cover and SWE in the current climate likely influences projections of change, but that analysis is beyond the scope of this study. Averaged over North America, all of the models show SWE decreasing during all months of the year. SWE decreases correspond with increases in temperature and increases in precipitation, indicating that the fraction of precipitation falling as snow must decrease in the future. Spatially, temperature is projected to increase everywhere, with the largest changes occurring in the Arctic. While the magnitude of the temperature change varies across the models the signal is consistent. For precipitation, the NARCCAP models are in agreement that precipitation amounts will increase everywhere except the western U.S. where the models disagree on the sign of the change. Models that have decreases in precipitation in the west likely have more extreme losses in SWE. Changes in temperature and precipitation also influence the timing of the snow cover season. The models agree that the first snow cover date will occur later in fall or winter, while the last snow-covered date will occur earlier in spring. The total number of days with snow cover also decreases, especially in the western U.S. While some of this change can be linked to the contraction of the snow cover season, changes in the frequency of snow-covered days may also indicate snow is becoming more ephemeral in the future, this is the focus of future research.

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