Projections of North American Snow from NA-CORDEX and their Uncertainties, with a Focus on Model Resolution.

R. R. McCrary[1], L. O. Mearns[1], M. Hughes[2], S. Biner[3], M. S. Bukovsky[1]

[1] National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.

[2] NOAA Physical Sciences Laboratory, Boulder, CO, USA

[3] Ouranos, Montreal, Quebec

* Corresponding Author: rmccrary@ucar.edu, 1-303-497-2482

ORCID: https://orcid.org/0000-0003-0741-6773

Resubmitted to Climatic Change on 7 December 2021

Keywords: climate change, snow, regional climate modeling, North America, CORDEX

Abstract

Snow is important for many physical, social, and economic sectors in North America. In a warming climate, the characteristics of snow will likely change in fundamental ways, therefore compelling societal need for future projections of snow. However many stakeholders require climate change information at finer resolutions that global climate models (GCMs) can provide. The North American Coordinated Regional Downscaling Experiment (NA-CORDEX) provides an ensemble of regional climate model (RCMs) simulations at two resolutions (~0.5º and ~0.25º) designed to help serve the climate impacts and adaptation communities. This is the first study to examine the differences in end-of-21st-century projections of snow from the NA-CORDEX RCMs and their driving GCMs.

We find the broad patterns of change are similar across RCMs and GCMs: snow cover retreats, snow mass decreases everywhere except at high latitudes, and the duration of the snow covered season decreases. Regionally, the spatial details, magnitude, percent, and uncertainty of future changes varies between the GCM and RCM ensemble, but are similar between the two resolutions of the RCM ensembles. Increases in winter snow amounts at high latitudes is a robust response across all ensembles. Percent snow losses are found to be more substantial in the GCMs than the RCMs over most of North America, especially in regions with high-elevation topography. Specifically, percent snow losses decrease with increasing elevation as the model resolution becomes finer.

1. Introduction

Terrestrial snow plays a key role in the climate, ecology, hydrology, and economy of North America (NA). Snow's high albedo alters the surface energy budget consequently influencing both long-term climate and short-term weather (e.g. Vavrus, 2007). It also provides an important habitat for wildlife that are adapted to living in snow conditions (Campbell et al, 2005; Barsugli et al, 2020). Seasonal snow accumulation is a natural reservoir for water storage and the timing and amount of snowmelt is critical for water supply (Barnett et al, 2005), agriculture (Qin et al, 2020) and hydropower production (Markoff and Cullen, 2008). The timing and amount of snowmelt is linked to droughts (Harpold, 2016) and wildfires (Westerling et al, 2006). Snow is crucial for winter transportation (Palko and Lemmen, 2018) and tourism (e.g. skiing, snowmobiling, snowshoeing; Chin et al, 2018; Wobus et al, 2017) which drive regional economies (Burakowski and Magnusson, 2012). In addition to the many benefits of snow, it also contributes to a wide range of hazards including damages to roads and buildings (Palko and Lemmen, 2018; Jeong and Sushama, 2018), avalanches (Campbell et al, 2007) and spring flooding (Berghuijs et al, 2016).

Future changes in snow conditions that are expected to be associated climate change will have important implications for all of these sectors. This drives a strong societal need for regional projections of snow and their uncertainties. Researchers and stakeholders alike need such information to determine the regional and local impacts of future changes in snow as well as to inform decision makers regarding how to adapt to future changes.

Changes in snow result from the combined interactions between increasing temperatures and changing precipitation patterns. Future projections of snow for NA have been investigated using modeling techniques across multiple time and space scales including global climate models

(GCMs; Raisanen, 2008; Brown and Mote, 2009; Mudryk et al, 2020, Krasting et al, 2013), regional climate models (RCMs; McCrary and Mearns, 2019; Rhoades et al, 2018a; Rasmussen et al, 2011), variable resolution climate models (Rhoades et al, 2018b), and statistical downscaling applied to hydrologic models (Christensen and Lettenmaier, 2007; Notaro et al. 2014). These studies show that increasing temperatures will dominate the climate change signal over most of NA resulting in widespread decreases in snowfall, snow cover extent and duration, and snow water equivalent (SWE). However, mid-winter snowfall and SWE may increase over the cold high latitudes and high elevations (Raisanen, 2008; McCrary and Mearns, 2019; Rasmussen et al., 2011).

The North American Coordinated Regional Downscaling Experiment (NA-CORDEX; Mearns et al, 2017) consists of an ensemble of regional climate projections for NA where multiple RCMs were driven with boundary conditions from multiple GCMs to produce downscaled climate projections at two resolutions (~0.5º and ~0.25º). NA-CORDEX fills a need for scientists and stakeholders who desire spatially uniform and consistent climate change data at higher resolutions than GCMs can provide, and with enough models to explore uncertainty. RCM ensembles like NA-CORDEX are heavily used across multiple disciplines in order to study climate change and its impacts (Mearns et al, 2015; McGinnis and Mearns, 2021). While there exists an abundance of papers examining temperature and precipitation projections in RCM ensembles, far fewer studies have looked at snow, even over Europe where CORDEX simulations have been available for longer.

Our goal here is to evaluate snow and examine future changes and their uncertainties in the NA-CORDEX RCMs and their driving GCM simulations. Since NA-CORDEX provides downscaled simulations at two resolutions, we focus on the differences between the RCM and

GCM ensembles to identify what, if any, additional information is gained by increasing resolution from GCM scales (ranging from 1.25° to 2.8°) down to 0.5° and 0.25°. To do this we performing a side-by-side comparison of the GCMs and RCMs used in NA-CORDEX, parsing NA-CORDEX by resolution. We focus on how the spatial distribution, magnitude, and percent change of future projections and their uncertainties differ across the ensembles. Our analysis starts broadly over all of NA, but then narrows down to three unique regions (Figure 1a) to further explore regional differences in model fidelity and future change. In this work, we define uncertainty as the spread across either the observations or the individual climate model ensembles.

2. Models, Datasets, and Methods

2.1 Models

In NA-CORDEX, multiple RCMs were driven with boundary conditions from multiple GCMs that were part of phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). Many of the RCM simulations in NA-CORDEX were performed at two resolutions (0.44° or 50km and 0.22° or 25km, depending on the model configuration). All RCM simulations cover at least 1951-2098, and future projections (2006-2098) follow the Representative Concentration Pathway 8.5 (RCP 8.5). In this work the historical time period spans 1976-2005 and the end-of-21st-century future time period spans 2070-2098.

We analyze the subset of NA-CORDEX simulations that have SWE output (Table 1). Although SWE is available from the RegCM4 NA-CORDEX simulations (na-cordex.org), unbounded snow accumulation was found to occur in many mountainous regions so this RCM was excluded from the analysis (Supplemental Information (SI) Section S1). We split the NA-CORDEX models into two climate ensembles based on resolution. As discussed more in Section

2.3.2, we regrid the 0.44°/50km simulations to a common 0.5° grid, and the 0.22°/25km simulations to a common 0.25° grid. Throughout the paper we refer to these ensembles as either NA-CORDEX-0.5° (8 members) or NA-CORDEX-0.25° (11 members).

Of the 7 driving GCMs used in NA-CORDEX, daily SWE was available from 6 (Table 1). Throughout the paper we refer to this set of 6 GCMs as the CMIP5-Driver ensemble. We also look at broad changes in SWE from all of the models in CMIP5 with daily SWE output which we refer to as the CMIP5-ALL ensemble (SI Table S1, 18 members). In our analysis, the CMIP5-All ensemble is included on all timeseries plots, but not on the spatial maps.

2.2 Snow Datasets

A major challenge for evaluating SWE in climate models is a lack of long-term, high-resolution (spatial and temporal), well-vetted gridded observations (e.g. McCrary et al, 2017). The insufficiency of snow observations has led many to create gridded SWE datasets that are observationally-constrained and informed by models, which we call Modeled-Observations, or MObservations (MObs). These include atmospheric and land-surface reanalysis products and statistical and physical models that are constrained by in-situ snow observations.

Following McCrary et al, (2017) we use a multi-dataset approach to capture the uncertainty in observed snow by creating an ensemble of MObs datasets (Table 2). All of the MObs datasets included are gridded products with 0.25° or finer resolution, at least 5 years of data between 1981-2010, and cover CONUS or North America. These datasets have considerable uncertainties related to sparse observational networks and surface meteorological forcing, satellite retrieval algorithms, and the use of models that must parameterize snow processes. While this ensemble will not capture the full uncertainty in snow observations, it serves as a reference dataset in which to assess the climate models used in this study.

Optical satellite products can be used to identify the presence of snow. To evaluate snow cover metrics we include the Interactive Multisensor Snow and Ice Mapping System (IMS) 24km daily snow cover dataset (U.S. National Ice Center, 2008) in combination with snow cover estimated from the SWE MObs.

2.3 Methods

2.3.1 Calculation of Snow Cover

Similar to McCrary and Mearns (2019), we calculate snow cover from SWE by applying a 5mm threshold to daily SWE fields from the MObs and the simulations to produce a binary yes-no snow cover field. Snow cover extent (SCE) is calculated by first averaging this binary field over each month to produce monthly snow cover fraction (SCF) at each gridbox and then summing over NA. The daily binary snow cover field is also used to calculate snow cover duration (SCD), defined as the number of days with snow on the ground. SCE, SCF and SCD are also calculated from the satellite IMS dataset which provides estimates of yes-no snow cover. Snow-on-ice (sea ice or land ice) is a complex process that is not well simulated by many climate models. We remove any points which may be ice covered or strongly influenced by land/sea ice. See SI Section S3 for a description of how these points were removed.

2.3.2 Ensemble Analysis

As regridding snow onto different grids can greatly impact mass budgets, regionally averaged time series plots are calculated on the native grids of the climate models. However, since each model uses a different grid, for ensemble mean spatial calculations we regridded the MObs and models to common grids using conservative remapping. The CMIP5 models have been regridded to a 1.5º grid, and the NA-CORDEX ensembles have been regridded to 0.5º and 0.25º.

3. Results

3.1 Evaluation of Climate Models

In the following section we compare the historical simulations from the CMIP5 and NA-CORDEX ensembles with the MObs ensemble.

3.1.1 Snow Cover Extent

The annual cycle of SCE from the MObs and climate models is shown in Fig 2. Only, IMS and ERA5-land have daily data covering all of NA. The timing of the annual cycle of SCE in the MObs follow each other closely. SCE is near zero in July-August, starts to increase in September, reaches a maximum in January and declines throughout the spring and early summer. Between December-April IMS has higher values than ERA5-land, otherwise the two datasets are closely matched the rest of the year. Spatially, the largest differences in January snow cover fraction (SCF) occur in the Central Plains and Great Basin (SI Fig. S4.)

Ensemble mean SCE for the CMIP5-Driver and CMIP5-All ensembles are similar to each other and are lower than both MObs (Fig. 2; individual models results SI Fig. S8). The spread in historic SCE in the both CMIP5 ensembles is much larger than the MObs spread. In both NA-CORDEX ensembles, the ensemble mean annual cycle of SCE is on the higher end of the MObs, following the IMS dataset almost exactly, with half the individual RCMs slightly overestimating SCE compared to IMS (SI Fig. S8). The spread in the NA-CORDEX-0.5º ensemble is larger than the NA-CORDEX-0.25º ensemble, primarily due to the HIRHAM5 EC-EARTH simulation being a low outlier which is only present in the 0.5º ensemble (SI Fig S8). The spatial distribution of January snow cover fraction (SCF) highlights where differences in simulated SCE arise (SI Fig. S5-S7).

3.1.2 Climatological SWE

Maps of ensemble mean annual maximum monthly SWE (AM-SWE) from the MObs and climate simulations are shown in Fig. 3. For the MObs, ensemble mean AM-SWE is calculated across all available datasets at each gridbox (Fig 3a-c). Although the spatial patterns of AM-SWE are similar across the three resolutions, distinct topographic features such as the Sierra Nevada's in California, the Cascade Range in the Pacific Northwest, and the Rocky Mountains deteriorate with decreasing spatial resolution. Results from the individual MObs and MObs ensemble statistics highlight the uncertainty across the MObs ensemble (SI Figs. S9-S12). In this study we use them as a reference to qualitatively evaluate the models.

The spatial patterns of AM-SWE in the CMIP5-Driver and NA-CORDEX ensembles are broadly similar to the MObs ensemble (Fig 3 d-f; individual model results SI Figs. S13-15). Compared to the MObs ensemble mean, the CMIP5-Driver GCMs underestimate SWE in the mountains and overestimate SWE in the lower elevation regions of western NA (Fig. 3. d,g,j; SI Fig. S16). As the mountains in these coarse GCMs are relatively smooth and low (Fig. 1b) there is limited orographic enhancement of precipitation in the mountains resulting in too much moisture penetrating inland, likely contributing to positive biases east of the mountain ranges in the west (e.g., Rasmussen et al, 2011). The smoothed topography in the GCMs also results in artificially high terrain in the interior valleys of western NA, which likely contributes to cold biases, and excess SWE accumulation and suppressed ablation. In the CMIP5-Driver ensemble negative biases also occur over most of Canada. AM-SWE in the CMIP5-Driver ensemble falls within the range of the MObs over much of CONUS, however biases fall outside the MOBs range near the western mountains and Northeast Canada (SI Fig. S19) .

AM-SWE in the two NA-CORDEX ensembles differs from the MObs ensemble in similar ways (Fig 3, h,i,k,l; individual model results SI Figs. S14-S15, S17-S18). The only real difference is that the spatial details of SWE patterns are finer with increasing resolution. In both ensembles, positive biases dominate over the domain, with negative biases near some mountains and across central Canada. Over the western half of the domain, AM-SWE is greatly overestimated on the western side of the mountains and underestimated just east of the highest peaks of the mountains (SI Fig. S20). Relative to the MObs ensemble mean, the magnitude of positive SWE biases are larger in the mountains than the lower elevation regions, however, percent SWE biases are much larger at lower altitudes. The percent bias figures (Fig. 3 j-l) highlight regions where the climate models simulate snow but the MObs do not. When compared to the range of the MObs ensemble, AM-SWE values in both RCM ensembles are greater than the MObs on the western side of Mountain ranges, in the Central US, and Northern Canada/Alaska (SI Fig. 19).

The similarities in the AM-SWE bias patterns in the RCMs suggests that biases in large-scale forcing and RCM configuration/parameterizations play a similar role in the simulation of SWE at both resolutions. As the mountains in the NA-CORDEX simulations are higher than the GCMs, orographic precipitation is larger in the RCMs due to enhanced lifting (See Mahoney et al, 2021) resulting in higher SWE values. However, winter precipitation in NA-CORDEX far exceeds observations in the RCMs (Mahoney et al, 2021). This is possibly because even at 0.25º convection is insufficiently resolved and convective parameterizations play a large role in precipitation biases (Hughes et al. 2021). The bias in precipitation likely translates to a positive bias in SWE, however SWE biases will also be linked to temperatures the evolution of snowpack in the RCMs (McCrary et al., 2017).

3.1.3 Snow Cover Duration

The length of the snow covered season or SCD may also change in the future. In the MObs, SCD increases with latitude and elevation (Fig. 4a-f; individual MObs in SI Figs. S21-S23). The broad spatial patterns of SCD are similar across the different resolutions, but the details are lost as resolution coarsens. Much like winter SWE values, SCD is reduced in the mountains when aggregated to coarse scales (Fig. 4a).

The CMIP5-Driver GCMs underestimate SCD in the mountains and most of the eastern half of the domain, although SCD is positively biased at low-elevation regions in the western half of the domain (Fig. 4g; individual models results SI Fig S24). Both RCMs ensembles overestimate SCD over most of the domain, with larger positive biases at lower-elevation in the Great Basin and east of the middle and southern Rockies and negative biases over north-central Canada (Fig. 4h,i; individual model results SI Figs. S25-S26).

3.2 Future Change over North America

3.2.1 Snow Cover Extent

SCE is projected to decrease in all months of the year in all of the models examined (Fig. 2, c-d; individual model results SI Fig. S8). The largest percent losses are projected to occur in October, May and June when snow cover is marginal in the historic climate period. Average SCE losses are larger in both CMIP5 ensembles than both NA-CORDEX ensembles. Although ensemble mean changes in SCE are similar for the CMIP5-Driver and CMIP5-All model ensembles, the uncertainty (measured here as the multi-model spread) is considerably larger in the CMIP5-All ensemble. This may indicate that our subset of CMIP5 models does not capture the full potential of the combination of temperature and precipitation changes that drive changes in snow. The NA-CORDEX 0.5° and 0.25° ensembles have nearly identical projections for SCE loss, both of which are smaller than the CMIP5-Driver ensemble mean. The uncertainty in future SCE changes is slightly larger in the NA-CORDEX ensembles than the CMIP5-Driver ensemble during October-February but slightly smaller in March-July.

3.2.2 Annual Maximum SWE

All three model ensembles project large-scale losses in AM-SWE over most of the domain, with the exception of the high-latitude regions of NA (Fig. 5; individual model results SI Figs. S27-S32). These results are consistent with previous studies (McCrary and Mearns, 2019; Raisanen, 2008). Absolute losses are larger in the mountains over the western and eastern portions of the domain, while percent losses are higher at low latitudes and lower elevations. Total snow losses are projected in all of the ensembles along the southern edge of the snow boundary (Fig 5. d-f). The individual models in all of the ensembles also show total losses along the southern snow boundary (SI Figs. S28, S30, S32).

While the three ensembles tell broadly the same story, details emerge in the RCMs, that are not found in the GCMs. Focusing on percent change, as it reduces the influence of simulated difference in baseline historical AM-SWE amounts, it is apparent that percent losses are generally larger in the CMIP5-Driver ensemble than in both of the NA-CORDEX RCM ensembles, especially in regions of complex topography. By the end of the 21st century, the CMIP5-Driver ensemble projects that 50.5% of NA will experience AM-SWE losses of greater than 50% and that 15.9% of NA will experience losses of greater than 90% . While the NA-CORDEX-0.5° ensemble projects greater than 50% losses over 38.9% of NA and 90% losses over 9.16% of the domain, the NA-CORDEX-0.25º ensemble projects greater than 50% losses 36.4% of NA and 90% losses over 8.8%. The reduced losses in the RCMs is partially due to the fact that they have more higher-elevation mountain points (Fig. 1 and Section 3.1.1) where temperatures can remain below freezing during winter. But also, percent change is affected by the historical snow amount where for the same magnitude loss, smaller percentage loss will be found if there is more SWE in the historical baseline climate.

3.2.3 Snow Cover Duration

Along with losses in SCE and SWE, the duration of the snow covered season is also projected to decrease (Fig. 4, j-l; individual model results SI Figs S33-S35). The largest decreases in SCD are found over the mountains in the western half of the domain, over Southwestern Alaska, and the eastern half of Newfoundland/Labrador and New England. While the broad spatial patterns of changes in SCD are similar across the ensembles, again the spatial details are lost in the GCMs. For example, in the western mountains the RCMs demonstrate that SCD will decrease more at higher elevations than lower elevations. While AM-SWE is projected to increase at high-latitudes (Fig 5) and at high-elevations in a few of the models (SI Figs. S28, S30, S32), SCD is found to decrease everywhere, indicating while AM-SWE may increase in some locations, the snow covered season will still contract.

3.3 Regional Changes

In the previous section we explored the continental-scale patterns of changes in snow conditions over NA. While important from a large-scale climate perspective, most researchers and stakeholders often want to know what will happen over smaller-scale regions. Here we zoom in on three unique climate regions, to explore more deeply how resolution influences future projections of SWE. These regions (Fig. 1a) are, the U.S. Intermountain West (IMW), North-Central Canada (NC-Canada), and Northeast U.S. and Southeast Canada (referred here as the Northeast). The considerable changes in snow projected along the west-coast of the domain in the NA-CORDEX models have been explored in Rhoades et al. (2018a) and Mahoney et al. (2021).

3.3.1 U.S. Intermountain West (IMW)

The IMW region is large and contains portions of the middle and southern Rocky Mountains and the Great Basin (Fig. 1a). We chose this region because of its complex topography including high elevation mountains where seasonal snowpacks and spring snowmelt are critical for water supply, ecosystem health, forest fire risk, and recreation.

First we examine the annual cycle of monthly averaged total snow mass (SM) for the region (Fig. 6 a,d; individual models results SI Fig. S36). The observational uncertainty is very high as the MObs disagree on the magnitude of SM during most months of the year (excluding August and September) and the timing of peak SM (showing either a February or March maximum). There is a clear separation between the 4 highest MObs and the 3 lowest MObs over the region. Lundquist et al. (2020) demonstrated that most snow reanalysis datasets underestimate SWE in the mountains, so our judgement here is that datasets with higher SM values are more realistic.

The spread in historical SM in both CMIP5 ensembles is larger than the spread of the MObs with a few GCMs greatly underestimating peak SM. Ensemble mean SM in the GCMs falls within the middle of the MObs range. The NA-CORDEX ensembles have considerably more snow than their driving GCMs and about half the spread during peak months. Between December-April, ensemble mean SM in the RCMs falls within the 4 highest MObs, but spring snowmelt occurs more rapidly in the RCMs than those same datasets.

To examine future changes in regional SM, we again primarily focus on percent changes (Figure 6 h,k), however, the annual cycle of future snow and the magnitude of snow changes are shown in SI Fig. S37. Average IMW SM is projected to decrease for all months of the year in all of the models, except for one CMIP5-ALL ensemble member (Fig. 6, h,k). Regional percent SM losses are smaller in the NA-CORDEX ensembles than the CMIP5 ensembles. For example, in March (around the timing of peak snow amounts) SM is projected to decrease by 84.1% in CMIP5-ALL, 76.8 in CMIP5-Driver, 58.2% in NA-CORDEX-0.5º, and 52.4% in NA-CORDEX-0.25º. The uncertainty in future losses is also much larger in the GCM ensembles than the RCM ensembles. For example, in March the spread in future change is 2.05 times larger in the CMIP5-ALL ensemble than the NA-CORDEX-0.25º ensemble. In most of the models the largest absolute SM losses occur when historical maximum SM occurs, and the timing of peak SM occurs one month earlier in the future (SI Fig. S36-S37).

Fig. 7 examines the spatial distribution of historical and future changes in AM-SWE over the IMW. Terrain plays a large role in determining precipitation, snowfall and SWE patterns in the IMW. In the coarse CMIP5-Driver GCMs, topography is fairly smooth and the Rocky Mountains are captured as one mountain feature (Fig 7a) although this varies slightly with GCM, see SI Fig. S38). With increasing resolution, individual mountain ranges begin to appear and become more distinct (Fig 7b-c). Comparisons of the distribution of elevation over the IMW (Fig. 8a) highlights that all of the ensembles, but in particular the CMIP5-Driver ensemble, have too many grid points at mid-elevations between 1500-2500m and too few points at lower elevation valleys and higher elevation mountains.

In both the historical and future simulations, AM-SWE generally increases with elevation and latitude (Fig 7d-i; individual models SI Figs. S39-S41). As with topography, distinct spatial patterns of SWE become more refined with increasing resolution. Comparison to the MObs AM-SWE (SI Fig. 20) reveals unrealistic patterns in the CMIP5-Driver ensemble related to the GCMs' unrealistic underlying terrain, as the Middle and Southern Rockies should have distinct peaks in SWE.

By the end of the century, ensemble mean AM-SWE is projected to decrease at all gridpoints over the IMW region in all of the ensembles, (Fig. 7 g-i) although some individual models do have regions with small increases (SI Figs. S42-S47). In terms of magnitude, the largest losses generally correspond with the largest historical SWE values (in the high elevations and northern part of the domain) (Fig. 7j-l; individual model results SI Figs S42-S44). However, the largest percent losses can be found at lower elevation, lower latitude regions, with smaller percent losses projected at high elevations (Fig. 7m-o; individual model results SI Figs S45-S47). The RCM ensembles both have lower percent losses than the GCMs in many areas, which appear for the most part to correspond with higher topography. Although temperatures are projected to increase everywhere over the IMW, we might expect higher-elevation SWE to be partially preserved as temperatures can still remain below freezing during the heart of winter.

To further explore the relationship between elevation and snow over the IMW we bin annual maximum snow mass (AM-SM) over the IMW by elevation (Fig. 8). To calculate AM-SM we take the climatological AM-SWE (e.g. Fig 7) from each model and the four highest MObs in Fig. 6a and calculate the mass of snow stored in each elevation bin for each dataset.

None of the datasets have grid points below 500m, the CMIP5-Driver models have no grid-points above 3000m, and only the MObs and the NA-CORDEX-0.25º ensemble have grid-points above 3500m (Fig. 8a). Most of the observed AM-SM occurs between 2000-3000m (Fig. 8b), with lower values at higher and lower elevations. In the climate models, most of the AM-

SM occurs at lower elevations, between 1500-2500m. On average the RCMs overestimate AM-SM at mid elevations (1500-2500m) and underestimate AM-SM above 2500m, with larger biases in the NA-CORDEX-0.5° ensemble. The GCMs skew toward negative AM-SM biases, except between 1500-2000m, where ensemble mean values are slightly higher than observed. There is also large uncertainty in historical AM-SM in the CMIP5-Driver ensemble between 1500-2500m, likely linked with the large spread horizontal resolution and topography (SI Fig S38 and Fig 8a).

In terms of magnitude, the largest losses in AM-SM for all the models occurs between 1500-2500m, corresponding with the elevations bins with the largest historical AM-SM. Percent losses in the CMIP5-Driver GCMs are also highest between 1500-2500m, but in the RCMs, percent losses are highest at lower elevations (1000-2000m). In all the models, percent losses steadily decrease above 2000m, where temperatures will remain below freezing more frequently than the lower elevation bins. Since vast majority of gridpoints in the GCMs occur between 1500-2500m where the largest AM-SM losses (magnitude and percent) occur and the GCMs have no gridpoints at the higher elevation bins, this supports the idea that reduced relative snow losses occur in the RCMs because they have higher mountain elevations, which help to buffer snow losses. However, percent AM-SM losses are higher in the GCMs at all elevation bins, which suggests differences are not solely due to elevation, but also related to baseline SM amounts (Fig. 8b) and the magnitude of total SM loss that occurs in each elevation bin (Fig. 8c)

3.3.3 North-Central Canada (NC-Canada)

We next examine changes over North-Central Canada (NC-Canada, Fig. 9) as this is the one area of NA where the climate model ensembles project potential increases in winter snowpacks. In this region, increases in SWE could have important implications for winter transportation, wildlife, and indigenous populations. Here we examine how robust these projected changes are.

Only three members of MObs ensemble have SWE data for NC-Canada, and there are large difference between them (Fig 6b,e; individual model results SI Fig. S48). Also, given the very few in-situ observations (snow or surface meteorology) over the region (e.g. Mekis et al, 2018), observed snow amounts are highly uncertain. Over NC-Canada, much of the year is snow covered, with only a short snow-free period in summer. Snow accumulates between October and March/April and declines quickly between March/April and July, with the timing of peak SM varying across the datasets. Over the region, ERA5-land has the highest SM values compared to CMC and GlobSnow. Values are likely underestimated in GlobSnow, as the mountains in the south-west part of the domain are masked (see SI Fig. S11). SM in all four of the model ensembles lie on the upper-end of the MObs estimates (following ERA5-land). The spread is higher in the GCM simulations than the RCM simulations and the RCMs tend to have more snow than the GCMs.

In the future, losses are projected in all of the models examined between May-November. However, from December-April most of the RCMs and many of the GCMs project up to 20% increases in SM for the region. Snow increases in this region are likely associated with increases in the amount of moisture in the atmosphere associated with warming temperatures which result in increases in precipitation and snowfall, as winter temperatures remain well below freezing (Raisanen, 2008). In the future the timing of peak SM occurs one month earlier in most of the models, and the largest magnitude decreases in SM occur in May for all ensembles (SI Figs. S48-S49).

Spatially, most of the increases in AM-SWE occur over the northern and eastern portions of the domain (Fig. 9) although this is model dependent (SI Figs. S50-S58). At individual points, ensemble mean AM-SWE increases by 1-50mm or 1-20%. The areal extent over which AM-SWE is projected to increase is largest in the NA-CORDEX-0.5º ensemble, and smallest in the CMIP5-DRIVER ensemble. All of the models in all of the ensembles project increase in SWE along the northern edge of continental Nanavut (Fig. 9, p-r); however, model agreement regarding where increases in SWE may occur is lower for the west and south of the domain.

3.3.3 Northeast U.S. and Southeast Canada (Northeast)

While the vast majority of previous studies have examined future projections for snow over western NA, snow is also important over the Northeast (Fig. 1a). In this region, heavy snowfall and snow loads are hazards for transportation and building infrastructures and snowmelt plays a key role in spring flooding. The Northeast region is also home to over 180 ski resorts (https://www.skicentral.com/). Lake effect snow may play a role in driving SWE amounts in this region, and the ability of the models to capture lake effect snow will depend on if the models use a lake model for the Great Lakes or interpolate lake temperatures from sea surface temperatures (see RCM Characteristics at https://na-cordex.org/).

As in the previously examined regions, the spread across the MObs ensemble is substantial over the Northeast (Fig. 6c). There is also disagreement on whether SM peaks in February or March over the region. Compared to the MObs the spread in both the CMIP5 ensembles is larger than the estimated observed spread, with the ensemble mean values falling in the middle of the MObs (Fig. 6c, SI Figs. S59-S60). The spread across the NA-CORDEX RCMs is smaller than the MObs, with the RCMs following the upper end of the Mobs (Fig. 6f). It is possible that all of the MObs underestimate SWE in the region, as observations are limited.

Substantial losses are projected for the region in all of the models (Fig. 6 j-m; individual model results SI Figs. S59-S60). Percent losses are largest October-November and April-May, and smaller in the middle of winter. However, even in winter, most models project that the region will lose more than 40% of its total SM. The uncertainty range for SM losses is twice as large in the CMIP5-All ensemble than the CMIP5-Driver ensemble, again suggesting CMIP5-Driver models may not capture the full range of climate possibilities. Regional scale losses are nearly identical in the two NA-CORDEX ensembles. The uncertainty of the change in the RCMs is smaller than the CMIP5-All ensemble, but larger than the CMIP5-Driver ensemble.

At first glance, the spatial representation of winter SWE in the CMIP5-Driver and NA-CORDEX RCM ensembles appears to be very similar, with higher values in the Northeast portion of the region, and lower values to the Southwest (Fig. 10, d-f; SI Figs. 61-69). However, an examination of the spatial details and comparison with topography highlights that even though topographic variations are less extreme in this region than in the IMW, mountains still play a role in driving SWE patterns (e.g. Adirondack Mountains in New York).

The broad spatial patterns of SWE changes for the end of the century are similar across the ensembles, with larger total losses to the northeast and smaller total losses to the south and larger percent losses over the southern portion of the domain and smaller relative losses over the north. However at closer inspection we see that percent snow losses are smaller with increasing elevation and higher resolution, indicating topography also dampens snow losses here. While beyond the scope of this study past RCM studies suggest warming of the Great Lakes may result in increased lake-effect snowfall possibly mitigating some snow losses in the future (e.g. Notaro et al, 2015).

4. Summary and Discussion

RCM ensembles like NA-CORDEX are widely used by scientists and stakeholders across multiple fields. While a plethora of studies have examined temperature and precipitation changes, far fewer have examined critical variables such as snow. In this study we performed a side-by-side comparison of historical and future snow over NA between the NA-CORDEX dynamically downscaled 0.5º and 0.25º RCM simulations and their driving GCMs (1.25º-2.8º). The primary goals of this study were to evaluate model performance and examine how end-of-century projections for snow differ between the different resolution ensembles.

To evaluate model performance, we used an ensemble of observationally constrained SWE datasets. We demonstrate that the uncertainty in gridded snow datasets is large, even across datasets with high resolutions. This uncertainty is associated with difficulties in measuring snow and is a major challenge for the snow science community.

In their historical climate simulations, the CMIP5-Driver and CMIP5-ALL ensembles underestimate NA while both NA-CORDEX ensembles tend to follow the higher end of the MObs. Simulated biases in SCE can have an impact on the radiation budget thereby influencing surface temperatures and weather patterns (Vavrus et al, 2007). On average the CMIP5-Driver ensemble underestimates AM-SWE and SCD over eastern Canada and at high elevations, but overestimate them everywhere else. In both RCM ensembles, AM-SWE and SCD biases are positive everywhere except the highest elevations and across tracts of central Canada. While the 0.25º simulations have greater spatial details and higher mountains than the 0.5º models, the spatial pattern of SWE and the magnitude of the biases are similar between the ensembles. Over the three regions examined, the spread in historical SM is greater across the GCM ensembles than the RCM ensembles, especially in the IMW and Northeast regions.

End-of-century projections for snow over NA are broadly similar across the ensembles considered. In all ensembles, SCE, AM-SWE, and SCD are projected to decrease over most of NA, with the exception of increases in AM-SWE at high-latitudes. In terms of magnitude, the largest losses in AM-SWE and SCD occur over the mountains in the western half of the domain and over coastal-eastern Canada. However, percent losses in AM-SWE are largest at low-elevations and low-latitude regions. Comparison of these ensembles shows that in terms of percent change, which can be more useful in the application of climate model data to climate change impacts, the CMIP5 GCMs tend to project a more severe picture of total snow loss for NA. For example, the CMIP5-Driver ensemble project that just over half of NA will experience greater than 50% losses in AM-SWE, while the RCMs that only 36-38% of NA will experience greater than 50% losses in AM-SWE. These differences are likely largely related to the poor representation of topography in the GCMs, but are also related to differences in baseline snow amounts (see more below).

While the large-scale picture of future changes in snow are similar between the ensembles, zooming in on individual regions helps highlight where differences between the ensembles occur. Over the IMW and Northeast regions, percent SM losses are larger in the GCMs than the RCMs, while over NC-Canada percent increases in winter SM are smaller in the GCMs. The uncertainty in these future changes is larger in the CMIP5-Driver GCMs than the RCM ensembles over the IMW and NC-Canada, but smaller in the Northeast region. While SM is projected to decrease during all months of the year in all of the models over the IMW and Northeast region, 70% of the models examined show winter SM increasing over NC-Canada. The largest differences across the ensembles are found over the IMW region where topography plays a large role driving snowfall and SWE amounts through orographic enhancement of precipitation and lower temperatures. As the GCMs oversample low-to-middle elevations and under-sample the higher elevations, historical SM is under-represented at most elevations, percent snow losses are larger in the GCMs than the RCMs at most elevations, and the GCMs have no information about snow at the higher elevations. Our results suggest that a that a more accurate representation of snow (especially at high elevations) allows for the buffering of snow losses, which we don't see in coarse models. In contrast to the IMW, over NC-Canada the GCM and RCM ensembles also show the greatest agreement in historical SM and percent SM changes in this region, which we suspect could be due to the lack of significant topographic features in the region.

Overall, while we find interesting differences in the specific regional details between the between the CMIP5-Driver GCMs and the NA-CORDEX RCMs, we do not see significant differences between two NA-CORDEX ensembles. The largest differences between the GCMs and RCMs are found in regions of complex topography, but even over the IMW the two RCM ensembles have very similar climate change responses. So while the spatial details of snow are more refined in the 0.25º ensemble, the overall impact to regional snow is small. However, as shown in Walton et al (2021), fine-scale details associated with snow in the mountainous may be important for end-users who statistically downscale temperature from climate models, as incorrectly capturing snow to no-snow transitions in the future can result in the incorrect amplification of surface temperatures associated with the snow albedo feedback.

While these results are similar to other studies which have examined snow over NA (e.g. McCrary and Mearns, 2019; Rasmussen et al. 2011). Our study highlights that the severity of future changes in snow, their uncertainties, and regional details are a function of the size and configuration of the model simulations/ensembles examined and the resolution of the simulations. The result that the GCMs tend to project a more severe picture of relative snow losses, in part because they have fewer high-elevation points, is important to remember when considering studies such as Diffenbaugh et al (2012), which used the CMIP5 models to assess hydrologic extremes and water availability over regions of the Northern Hemisphere, including the western US.

There are also a few notable limitations to this study. First, while our focus has been on how increases in resolution impacts the representation of historical and future snow over NA and their uncertainties, the NA-CORDEX-0.5º and NA-CORDEX-0.25º ensembles consist of different combinations of RCM/GCM pairs. These differences in ensemble configuration may also contribute to the differences we found in this study. As discussed in McGinnis and Mearns (2021), funding was extremely limited for NA-CORDEX and the choice of simulations included in the experiment was opportunistic and required leveraging other modeling activities (McGinnis and Mearns, 2021). While the archive consists of simulations with available SWE from 5 RCMs driven with boundary conditions from 7 GCMs with simulations performed at 2 resolutions (Table 2), the simulation matrix itself is both sparse and unbalanced, limiting our ability to dive deeply into the different roles the choice of RCM, GCM, or resolution have on climate change uncertainty. In this work we chose to include all available ensemble members to highlight the differences in the available datasets that end users may consider. In SI Section S17, we compare results from using the full ensemble with the 7 simulations that have matching RCM/GCM pairs and both resolutions. We find the uncertainty in the historical simulations to be lower in the smaller subset of models, but that the projections of future change and their uncertainties for all snow variables are similar between the full and subset ensembles.

Second, while the NA-CORDEX simulations are higher resolution than their GCM counterparts, they are still relatively coarse for capturing precipitation, snowfall, and SWE especially in topographically complex areas. Many of the sectors discussed in the introduction require very high resolution data to study the impacts of future changes in snow. Statistical downscaling techniques are often employed to get at very high-resolution climate information, but this can break the coupling between the atmosphere and the land-surface leading to inconsistent results especially in snow dominated regions (Walton et al, 2021).

Past RCM studies have found that resolutions of 4-6km to be necessary to match in-situ point observations of precipitation, snowfall, and SWE (Garvert et al, 2007; Rasmussen et al, 2011). The argument for this is that terrain-induced convection and local air circulation patterns associated with smaller ridges and valleys that are important for snowfall patterns are better resolved, and surface temperatures are better represented. Wind redistribution of snow is also important, which is also not captured in many models (Musselman et al, 2015). Many high-resolution modeling studies have examined changes in snow over regions of NA (e.g. Sun et al, 2019; Rasmussen et al, 2011; Musselman et al, 2017). While these studies have been able to look at detailed process level changes that are important, they have been limited in either domain size or by the use of only one RCM or one GCM, limiting the examination of uncertainty. As computing power, storage, and analysis of big data continues to advance, we expect to see the creation of larger ensemble convection permitting simulations (CPSs) over larger domains. The coordination of regional CPSs is ongoing over Europe in one CORDEX Flagship Pilot Study (Coppola et al, 2020), but such studies are not being coordinated over NA yet. Until that time, NA-CORDEX fills a need in the community as it provides spatially uniform, higher resolution simulations with enough model diversity to explore uncertainty while covering a large enough domain to be useful for many regional interests and are adequate for efforts such as the US National Climate Assessment and the IPCC.

Acknowledgements

The authors acknowledge Ross Brown and the two anonymous reviewers for their constructive feedback. This work was supported by the DoE Regional and Global Climate Modeling program via grants DE-SC0016438 and DE-SC0016605 and the NCAR Regional Climate Uncertainty Program managed by Dr. Mearns, funded by NSF under the NCAR cooperative agreement. We acknowledge the WCRP's Working Group on Coupled Modelling and the CMIP5 modeling groups for producing and making available their model output. We also acknowledge high-performance computing support provided by NCAR's CISL (Computational and Information Systems Laboratory 2017), and NCL (The NCAR Command Language 2019). NCAR is sponsored by the NSF. Livneh data was provided by NOAA/OAR/ESRL PSL. The CRCM5-O data has been generated and supplied by Ouranos.

Declarations

Funding: This work was supported by DoE Regional and Global Climate Modeling grant DE-SC0016438 and the NCAR Regional Climate Uncertainty Program managed by Dr. Mearns, funded by NSF under the NCAR cooperative agreement.

Conflicts of Interest/Competing Interests: None.

Availability of data and material: Snow data from NA-CORDEX will soon be available on NCAR's Climate Data Gateway (https://na-cordex.org/data-access.html) (approximately by January 2022). Until that point, please reach out to rmccrary@ucar.edu for data access. CMIP5 Data is available from the WCRP's Earth System Grid Federation Website (https://esgf-node.llnl.gov/projects/cmip5/).

Code availability: The code used for this work is available on Rachel McCrary's GitHub account: (https://github.com/mccraryclimo/nacordex_ClimaticChange_Code)

Authors' contributions: McCrary: Writing- Original Draft, Conceptualization, Methodology, Formal Analysis, Visualization. Mearns: Conceptualization, Supervision, Funding acquisition, Writing - Review & Editing. Hughes: Writing - Review & Editing. Biner: Investigation (model simulations), Writing - Review & Editing. Bukovsky: Investigation (model simulations), Writing - Review & Editing

References

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature,* 438:303–309.

Barsugli, J. J., et al. (2020). Projections of mountain snowpack loss for wolverine denning elevations in the Rocky Mountains. *Earth's Future,* 8.

Berghuijs, W. R., et al. (2016) Dominant flood generating mechanisms across the United States. *GRL*, 43:4382– 4390.

Brown, R. D., and P. W. Mote (2009) The Response of Northern Hemisphere Snow Cover to a Changing Climate. *J. Climate,* 22:2124–2145.

Brown, R. D. and B. Brasnett (2010) updated annually. Canadian Meteorological Centre (CMC) Daily Snow Depth Analysis Data, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/W9FOYWH0EQZ3. Accessed: *15-03-2021*.

Broxton, P., X. Zeng, and N. Dawson (2019) Daily 4 km Gridded SWE and Snow Depth from Assimilated In-Situ and Modeled Data over the Conterminous US, Version 1. NASA NSIDC. Accessed: *19-06-2020*.

Burakowski, E. and M. Magnusson (2012) Climate Impacts on the Winter Tourism Economy in the United States. *National Resources Defense Council*, 36 pp.

Campbell, C., et al. (2007) Current and Future Snow Avalanche Threats and Mitigation Measures in Canada. *Canadian Avalanche Center report prepared for Public Safety* Canada.

Campbell, J. L., et al. (2005) Winter in northeastern North America: A critical period for ecological processes. *Front. Ecol. Environ*., 3, 314–322.

Chin, N., et al. (2018) Assessing potential winter weather response to climate change and implications for tourism in the US Great Lakes and Midwest. *J. Hydrology: Regional Studies*, 19:42-56.

Christensen, N. S., and Lettenmaier, D. P. (2007). A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydro Earth Syst. Sci.,* 11(4):1417–1434.

Diffenbaugh, N. S., M. Scherer, and M. Ashfaq (2012) Response of snow-dependent hydrologic extremes to continued global warming. *Nature Climate Change* 3:379–384.

ETOPO5 (1988) Data Announcement 88-MGG-02, Digital relief of the Surface of the Earth. NOAA, National Geophysical Data Center, Boulder, Colorado.

Garvert, M. F., , B. Smull, , and C. Mass, 2007: Multiscale mountain waves influencing a major orographic precipitation event. *J. Atmos. Sci.*, **64**, 711–737.

Harpold, A. A. (2016) Diverging sensitivity of soil water stress to changing snowmelt timing in the Western U.S. *Adv.Water Res.,* 92:16–129.

Hughes, M. et al, (2021) Cool season precipitation projections for California and the Western United States in NA-CORDEX models. *Clim Dynamics*, 56, 3081-3102.

Jeong, D. I., and L. Sushama (2018) Projected changes to extreme wind and snow environmental loads for buildings and infrastructure across Canada. *Sustainable Cities and Society,* 36:225–236.

Krasting, J. P., et al., (2013) Future changes in Northern Hemisphere snowfall. *J. Climate*, 26:7813–7828.

Livneh B., et al. , 2013: A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions, Journal of Climate, 26, 9384–9392.

Luojus, Kari, et al., 2020: GlobSnow v3.0 snow water equivalent (SWE). PANGAEA. https://doi.org/10.1594/PANGAEA.911944

Lundquist, J., et al. (2020) Our Skill in Modeling Mountain Rain and Snow is Bypassing the Skill of Our Observational Networks. *BAMS* 100: 2473–2490.

Mahoney, K. et al. (2021) Precipitation Projections for California and the Western United States in NA-CORDEX models. *Climate Dynm*., 56, 3081-3102.

Markhoff, M.S. and A.C. Cullen (2008) Impact of climate change on Pacific Northwest hydropower. *Climatic Change,* 87:451-469.

McCrary, R.R., S. McGinnis, and L.O. Mearns (2017) Evaluation of Snow Water Equivalent in NARCCAP Simulations, Including Measures of Observational Uncertainty. J. *Hydromet*., 18:

McCrary, R. R., and L. O. Mearns (2019) Quantifying and Diagnosing Sources of Uncertainty in Midcentury Changes in North American Snowpack from NARCCAP. *J. Hydromet*. 20: 2229–2252.

McGinnis, S. and. L. Mearns (2021) Building a climate service for North America based on the NA-CORDEX data archive. *Climate Services*, 22, 100233.

Mearns, L.O., et al. (2015) Uses of Results of Regional Climate Model Experiments for Impacts and Adaptation Studies: the Example of NARCCAP. *Curr Clim Change Rep*, 1, 1-9.

Mearns, L.O., et al. (2017) The NA-CORDEX dataset, version 1.0. NCAR Climate Data Gateway, Boulder CO, Accessed: 01-06-2020.

Mekis, E., et al. (2018) An Overview of Surface-Based Precipitation Observations at Environment and Climate Change Canada, *Atmosphere-Ocean*, 56:2, 71-95,.

Minder, J.R., Letcher, T. W., and Skiles, S. M. (2016) An evaluation of high-resolution regional climate model simulations of snow cover and albedo over the Rocky Mountains, with implications for the simulated snow-albedo feedback, *J. Geophys. Res. Atmo*s. 121: 9069– 9088.

Mudryk, L., et al. (2020) Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. The Cryosphere 14:2495-2514.

Muñoz-Sabater, J., (2019): ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Accessed:10-06-2020), 10.24381/cds.e2161bac

Musselman et al. (2015) Impact of windflow calculations on simulations of alpine snow accumulation, redistribution and ablation, *Hydro. Processes*, 29(18) 3983-3999.

Musselman et al, (2017) Slower snowmelt in a warmer world. *Nature Climate Change*. 7, 214-219.

NOHRSC, 2004: *Snow Data Assimilation System (SNODAS) Data Products at NSIDC, Version 1*. NSIDC. Accessed: 12-06-2019.

Notaro, M., et al. (2014) Twenty-first-century projections of snowfall and winter severity across central-eastern North America. *J. Climate* 27:6526–6550.

Notaro, M., et al. (2015) Dynamically Downscaled Projections of Lake-Effect Snow in the Great Lakes Basin. J. Climate 28: 1661-1684.

Palko, K. and Lemmen, D.S. (Eds.). (2017). Climate risks and adaptation practices for the Canadian transportation sector 2016. Ottawa, ON: Government of Canada.

Qin, Y et al. (2020) Agricultural risks from changing snowmelt. Nat. Clim. Chang. 10:459–465.

Räisänen, J. (2008) Warmer climate: less or more snow? *Climate Dynamics,* 30: 307–319.

Rasmussen, R., et al. (2011) High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. *J.Climate* 24:3015–3048.

Rhoades, A. M., A. D. Jones, and P. A. Ullrich, 2018a: The Changing Character of the California Sierra Nevada as a Natural Reservoir. *GRL*, 45, 13,008-13,019.

Rhoades, A. M., P. A. Ullrich, and C. M. Zarzycki, 2018b: Projecting 21st century snowpack trends in western USA mountains using variable-resolution CESM. *Clim Dyn*, 50, 261–288.

Sun et al. (2018) Understanding End-of-Century Snowpack Changes over California's Sierra Nevada. *GRL*. 46(2). 933-943.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012) An Overview of CMIP5 and the Experiment Design. *BAMS* 93:485–498.

U.S. National Ice Center. 2008, updated daily. IMS Daily Northern Hemisphere Snow and Ice Analysis at 1 km, 4 km, and 24 km Resolutions, Version 1. *[1997-2010].* Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N52R3PMC.

Vavrus, S. (2007) The role of terrestrial snow cover in the climate system. *Climate Dynamics,* 29: 73–88.

Walton, D et al. (2021) Understanding Differences in California Climate Change Projections Produced by Dynamical and Statistical Downscaling. *JGR Atmo*., 125(10).

Westerling, A. L. et al. (2006) Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science,* 313:940–943.

Wobus, C. et al., (2017) Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change,* 45:1-14, doi:10.1016/j.gloenvcha.2017.04.006.q

Xia, Y., et al., NCEP/EMC (2012), NLDAS Noah Land Surface Model L4 Hourly 0.125 x 0.125 degree V002, Edited by David Mocko, NASA/GSFC/HSL, GES DISC, Accessed: [*10-06-2019*], 10.5067/47Z13FNQODKV

Tables

Table 1. The NA-CORDEX RCMs and their driving CMIP5 GCMs examined in this study. Each column displays the resolution (0.44º or 50km; 0.22º or 25km) of the RCM simulations or the resolution of the driving GCM. Snow is not available from the EC-EARTH GCM simulation, but is available from the HIRHAM5 RCM driven with EC-EARTH boundary conditions.

GCM/RCM	CanRCM4	CRCM5-U	CRCM5-O	WRF	HIRHAM5	GCM Resolution
HadGEM2-ES	-	-	-	50km/25km	-	1.25 x 1.875º
CanESM2	0.44º/0.22º	0.44º/0.22º	-/0.22º	-	-	~2.8º x ~2.8º
CNRM-CM5	-	-	-/0.22º	-	-	~1.4ºx ~1.4º
MPI-ESM-LR	-	0.44º/0.22º	-/0.22º	50km/25km	-	~1.87º x ~1.87
MPI-ESM-MR	-	0.44º0/.22º	-	-	-	~1.87º x ~1.87
EC-EARTH	-	-		-	0.44º/-	-
GFDL-ESM2M	-	-	-/0.22º	50km/25km	-	~2.0º x 2.5º

Table 2. Table of model-informed observational datasets (MObs) used in this study.

Product	Resolution	Domain	Frequency	Time Period	Reference
SNODAS	1km	CONUS	Daily	2003-2020	NOHRSC (2004)
UA-SWE	4km	CONUS	Daily	1981-2020	Broxton et al. (2019)
Livneh	0.0625º (~6km)	CONUS	Daily	1950-2013	Livneh et al. (2015)
ERA5-land	0.1º (~9km)	Global	Hourly	1981-2020	Munoz-Sabater (2019)
NLDAS-noah	0.125º (~13km)	CONUS	3-hourly	1979-2020	Xia et al. (2012)
NLDAS-vic	0.125º (~13km)	CONUS	3-hourly	1979-2020	Xia et al. (2012)
GlobSnow v.3	25km	N. Hemisphere	Daily	1979-2020	Luojus et al. (2020)
CMC	24km	N. America	Monthly	1998-2020	Brown and Brasnett (2010)

Figures

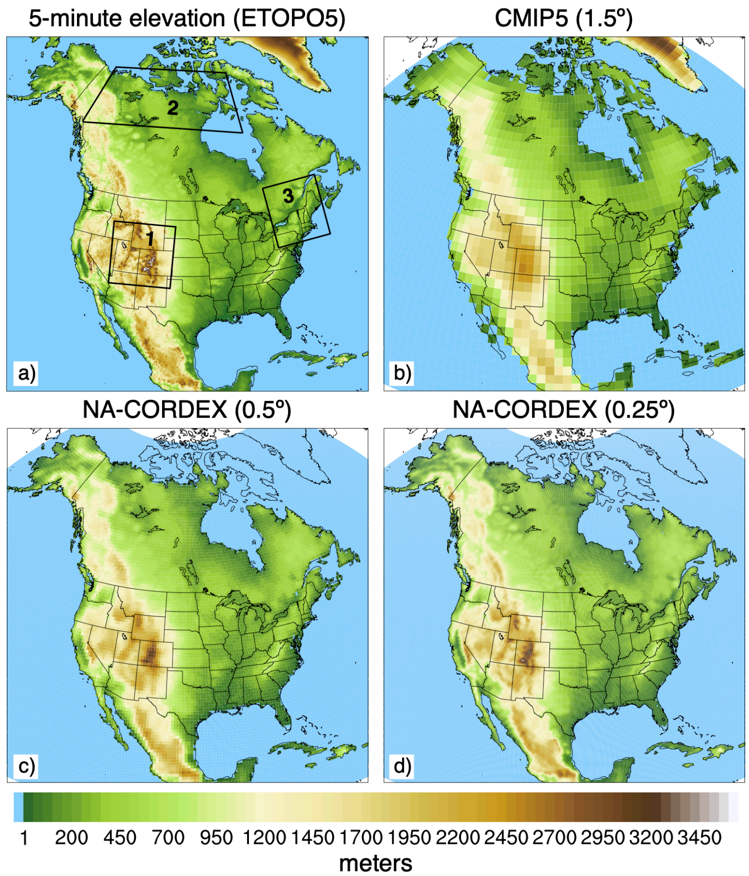

Fig. 1 Representation of topography from the 5-minute ETOPO5 (1988) dataset (a), the ensemble-average topography from the CMIP5-Driver ensemble (b), the NA-CORDEX-0.5º ensemble (c) and the NA-CORDEX (0.25º) ensemble. The three sub-regions examined are outlined in (a) where (1) is the U.S. Intermountain West, (2) is North-Central Canada, and (3) is the Northeast U.S. and Southeast Canada.

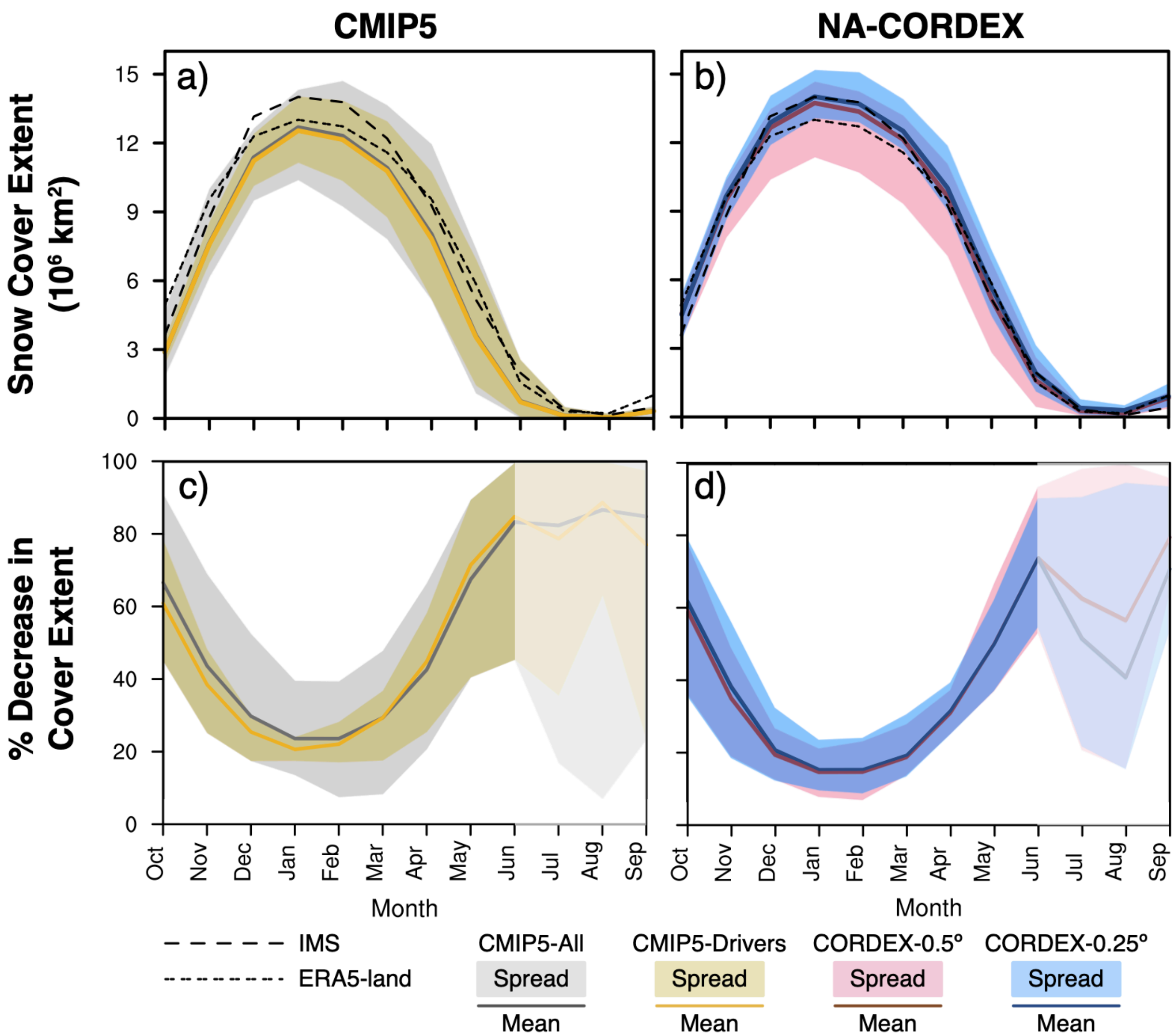

Fig. 2 The annual cycle of monthly mean NA SCE from the MObs (dashed lines on a and b) and the historical climate simulations from the two CMIP5 ensembles (a) and two NA-CORDEX ensembles (b) examined in this study. Also shown is the annual cycle of the percent decrease in NA SCE projected for the end-of-century from the CMIP5 ensembles (c) and the NA-CORDEX ensembles (d). The spread of each ensemble is displayed with colored shading. The average of each ensemble is plotted with a corresponding solid line. Percent decreases in SCE for July-September have been masked as they are skewed by small number division. NA SCE has been calculated using the native grid of all models and datasets.

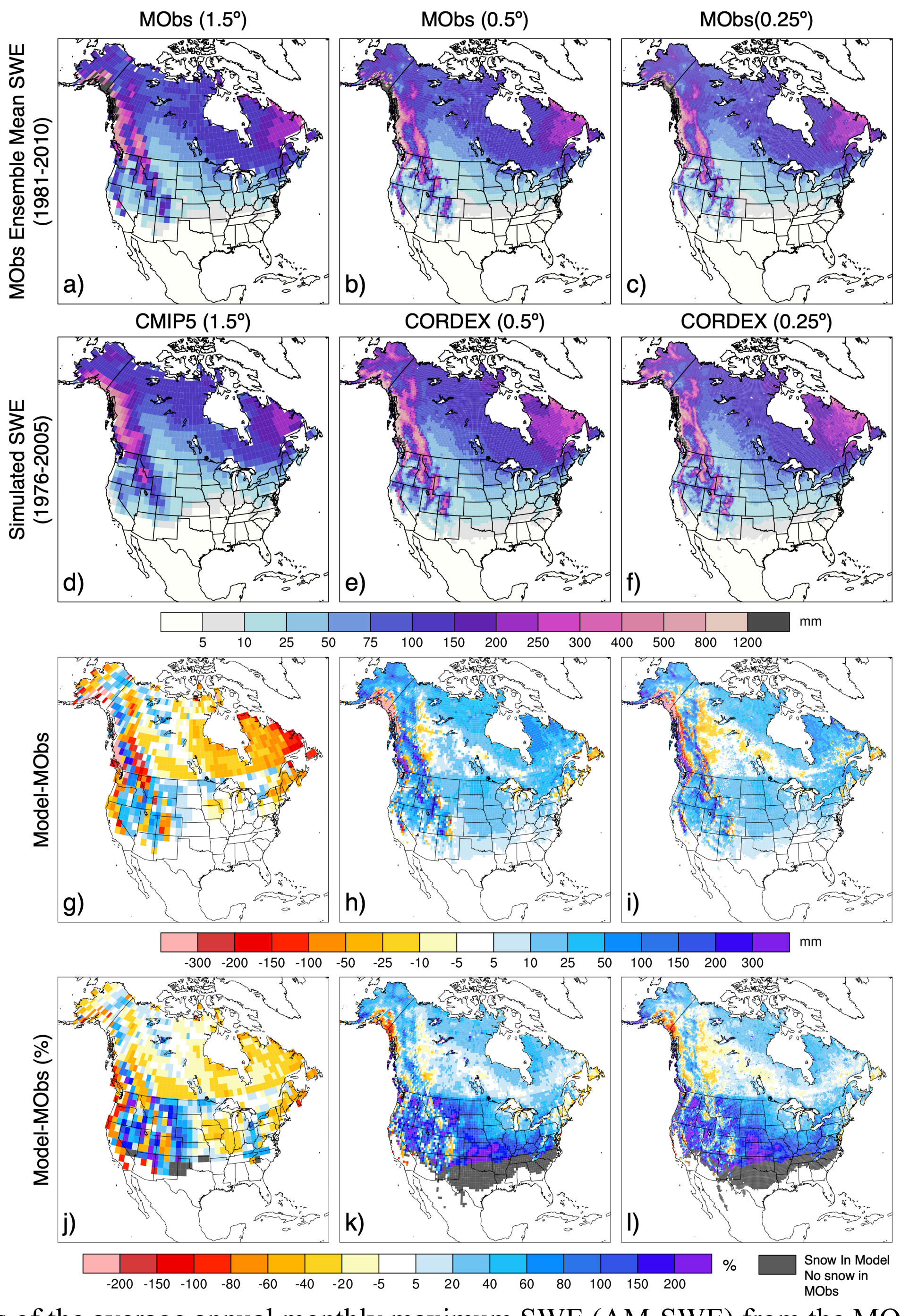

Fig. 3 Maps of the average annual monthly maximum SWE (AM-SWE) from the MObs ensemble mean which has been regridded to the common 1.5º, 0.5º and 0.25º resolution (a-c). Ensemble mean AM-SWE from the historical time period for the three model ensembles (d-f). Also shown are the magnitude (g-i) and percent (j-l) of the simulated bias (model – MObs) of AM-SWE. The MObs ensemble mean is calculated independently at each gridbox using datasets with available data (See SI Figs. S9-S11).

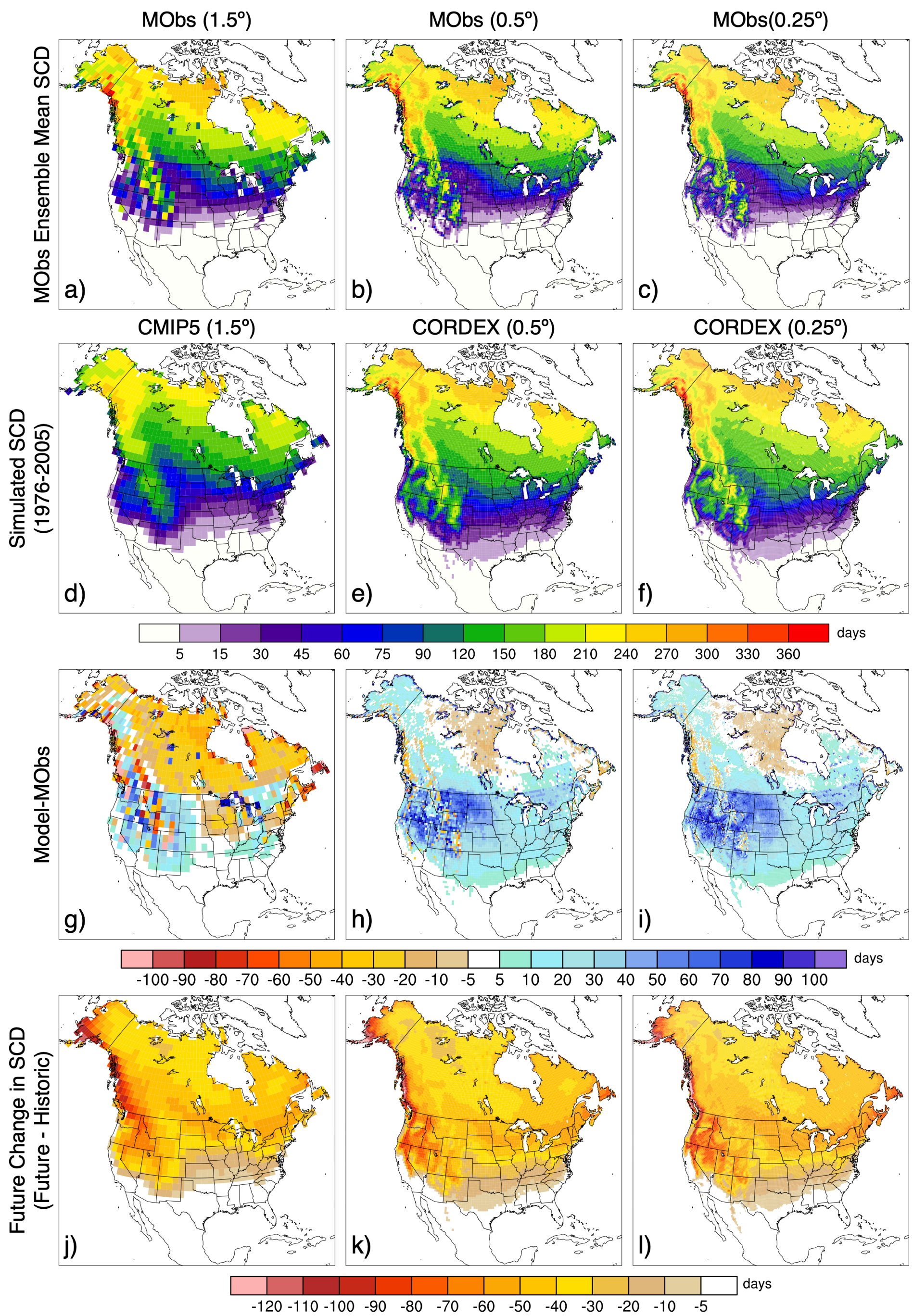

Fig. 4 Maps of snow cover duration (SCD) from the MObs ensemble mean regridded to the common 1.5º, 0.5º and 0.25º grids (a-c), and the ensemble mean SCD from the historical time period from each model ensemble (d-f). Also shown are the simulated bias in SCD (model-MObs, g-i) and the future change in SCD (future-historical, j-l). The MObs ensemble mean is calculated independently at each gridbox using datasets with available data (See SI Figs. S21-S23).

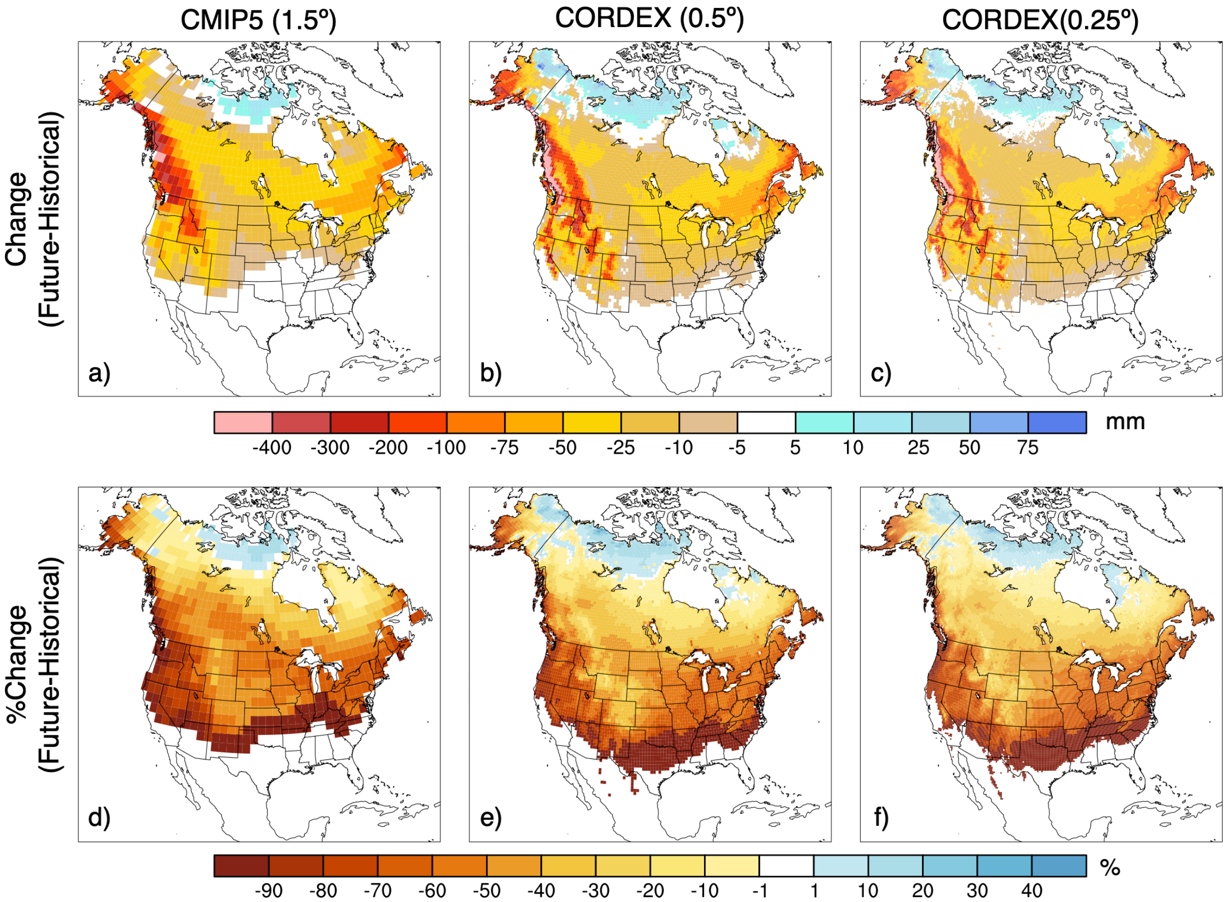

Fig. 5 Maps of the magnitude (a-c) and percent (d-f) change in ensemble mean AM-SWE projected by the end-of-the century by the three model ensembles (Future-Historic).

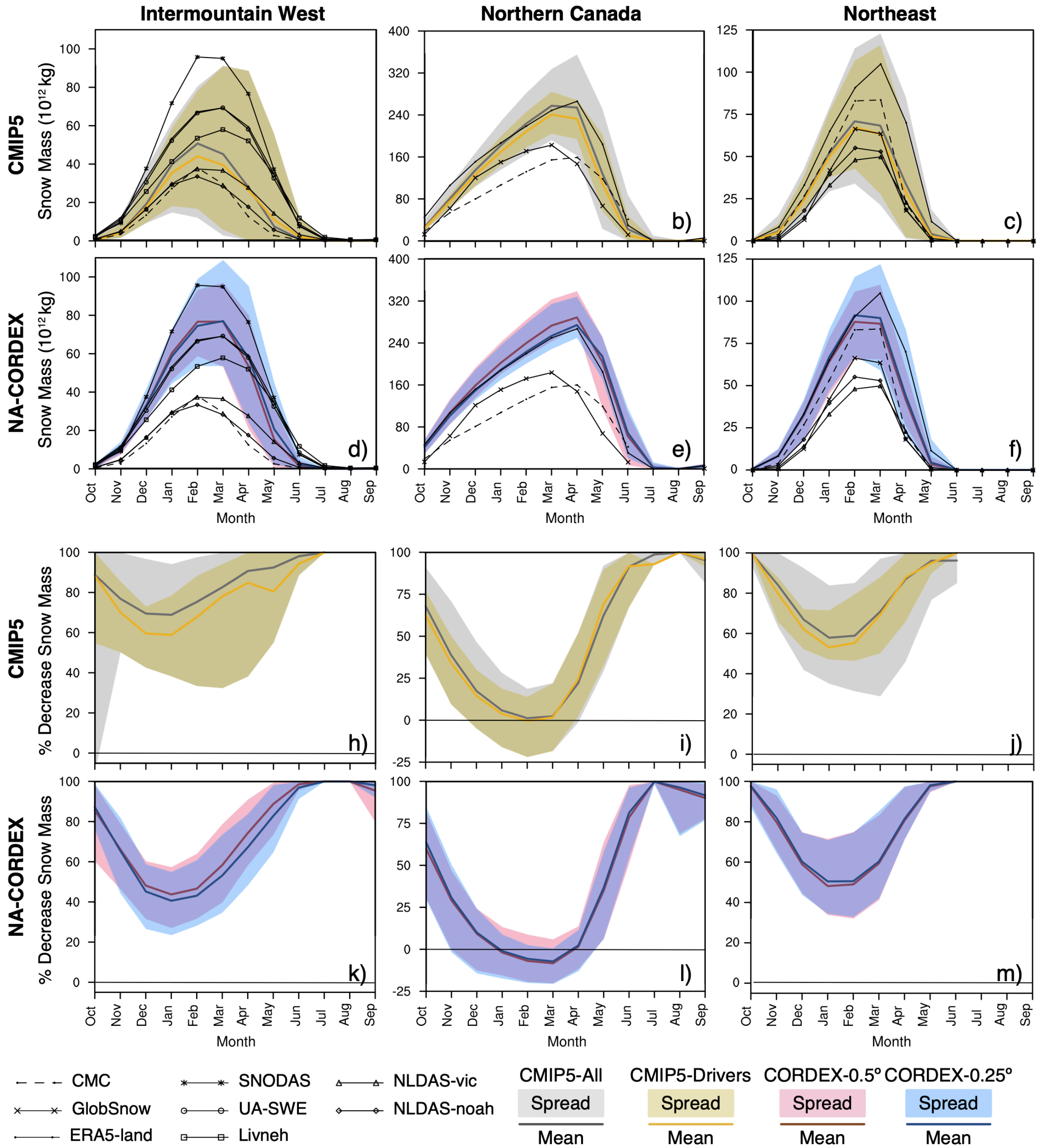

Fig. 6 The first two rows show the annual cycle of SM from the CMIP5-All and CMIP5-Driver ensembles (a-c), the NA-CORDEX ensembles (d-f) and available MObs, for the IMW (a,d), NC-Canada (b,e), and Northeast (c,f) regions. The last two rows show the percent decrease SM projected for the end of the century for the CMIP5 (h-j) and NA-CORDEX ensembles (k-m). All regional averages are calculated on each model's native grid.

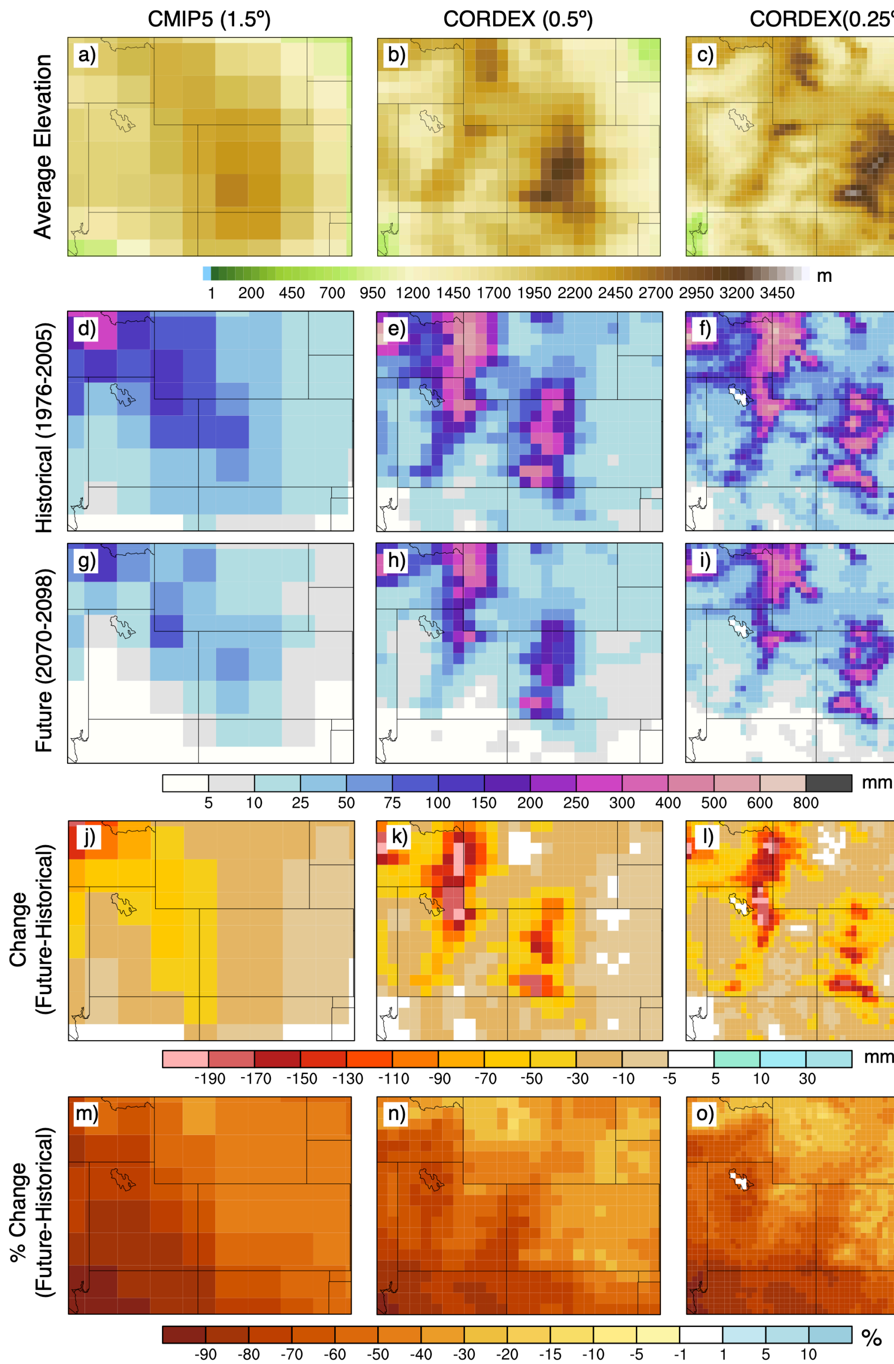

Fig. 7 Maps over the IMW region of the ensemble mean topography (a-c), ensemble mean historic AM-SWE (d-f), ensemble mean future AM-SWE (g-i), and the magnitude (j-l) and percent change (Future-Historic) in AM-SWE from the three model ensembles.

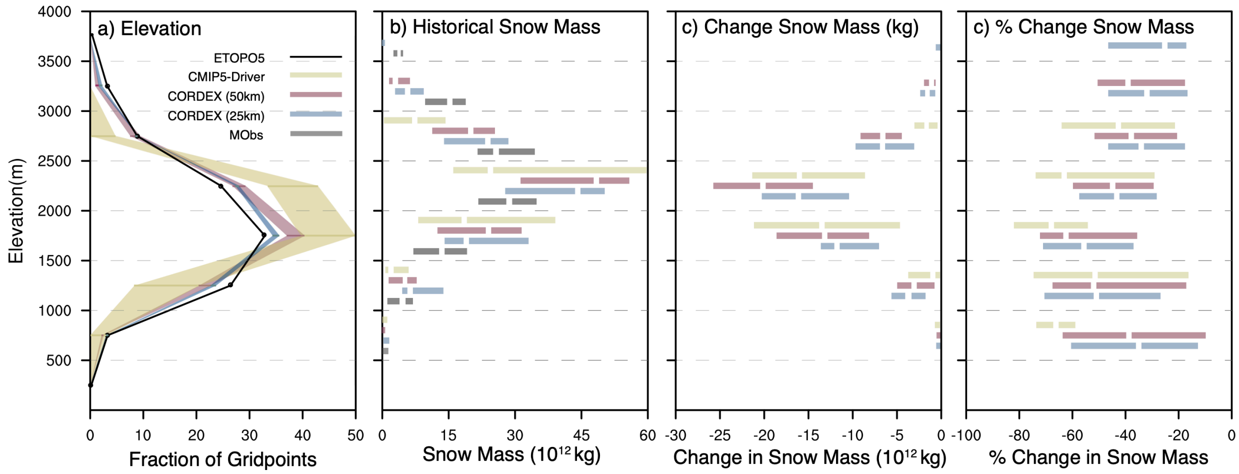

Fig. 8 The distribution of elevation for the IMW region from ETOPO5, and the three different model ensembles (a). The elevational distribution of historical AM-SM from the four MObs with the highest peak SM and the three model ensembles (b), the magnitude in future change in AM-SM (c), and the percent change in AM-SM (c). Elevation bins range from 0-4000m, incremented by 500m. Values are plotted between the elevation bins identified by the dashed lines. In (a) elevation is binned independently for each model using its native grid topography. The spread for each ensemble shows the minimum and maximum values calculated for each bin. In b-d the spread of each ensemble is shown, and the white space between the bars represents the ensemble mean change.

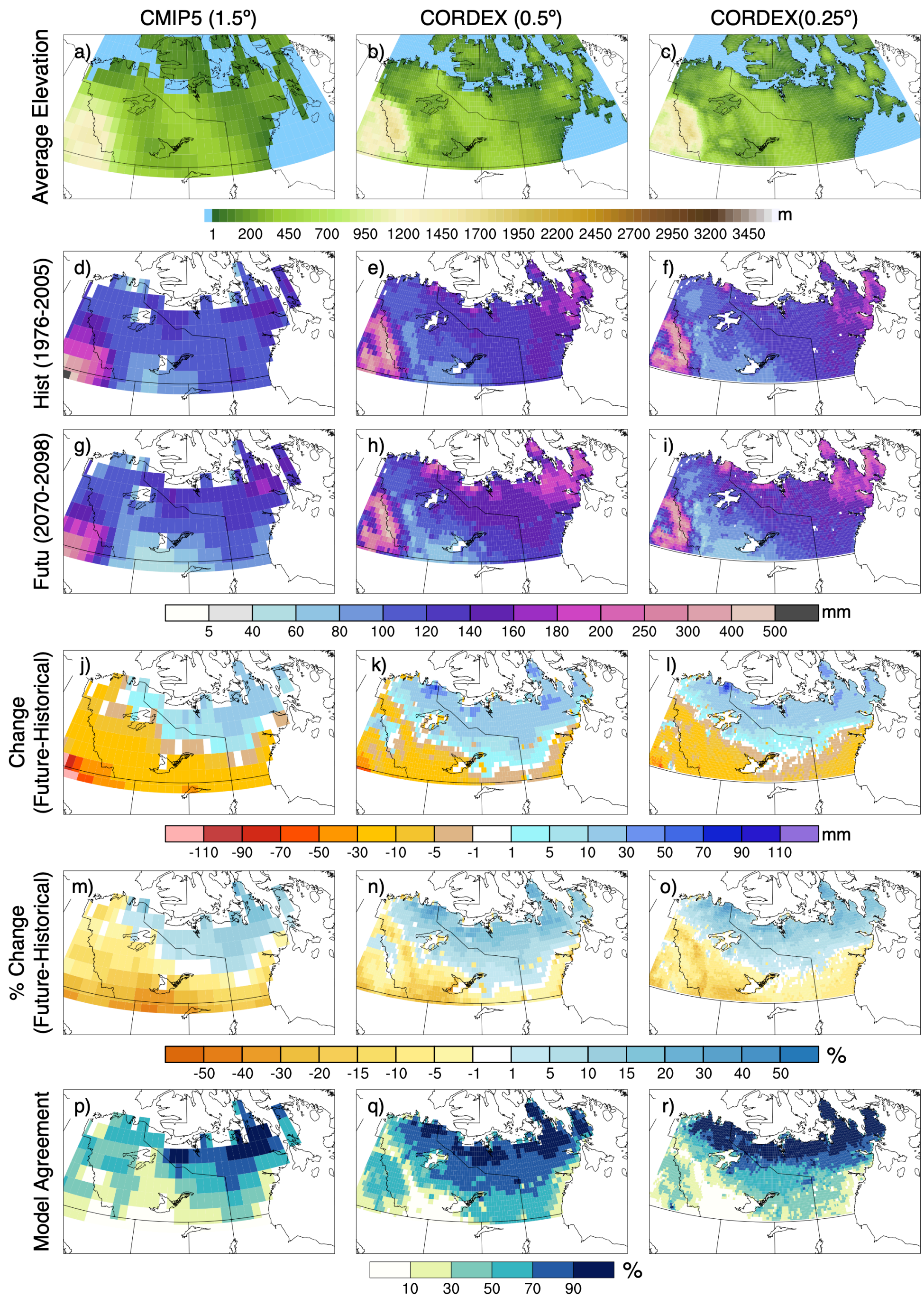

Fig. 9 Maps over the NC-Canada region of the ensemble mean topography (a-c), ensemble mean historic AM-SWE (d-f), ensemble mean future AM-SWE (g-i), the magnitude (j-l) and percent (m-o) change (Future-Historic) in AM-SWE, and the percent of models in each ensemble that agree AM-SWE will increase in the future (p-r).

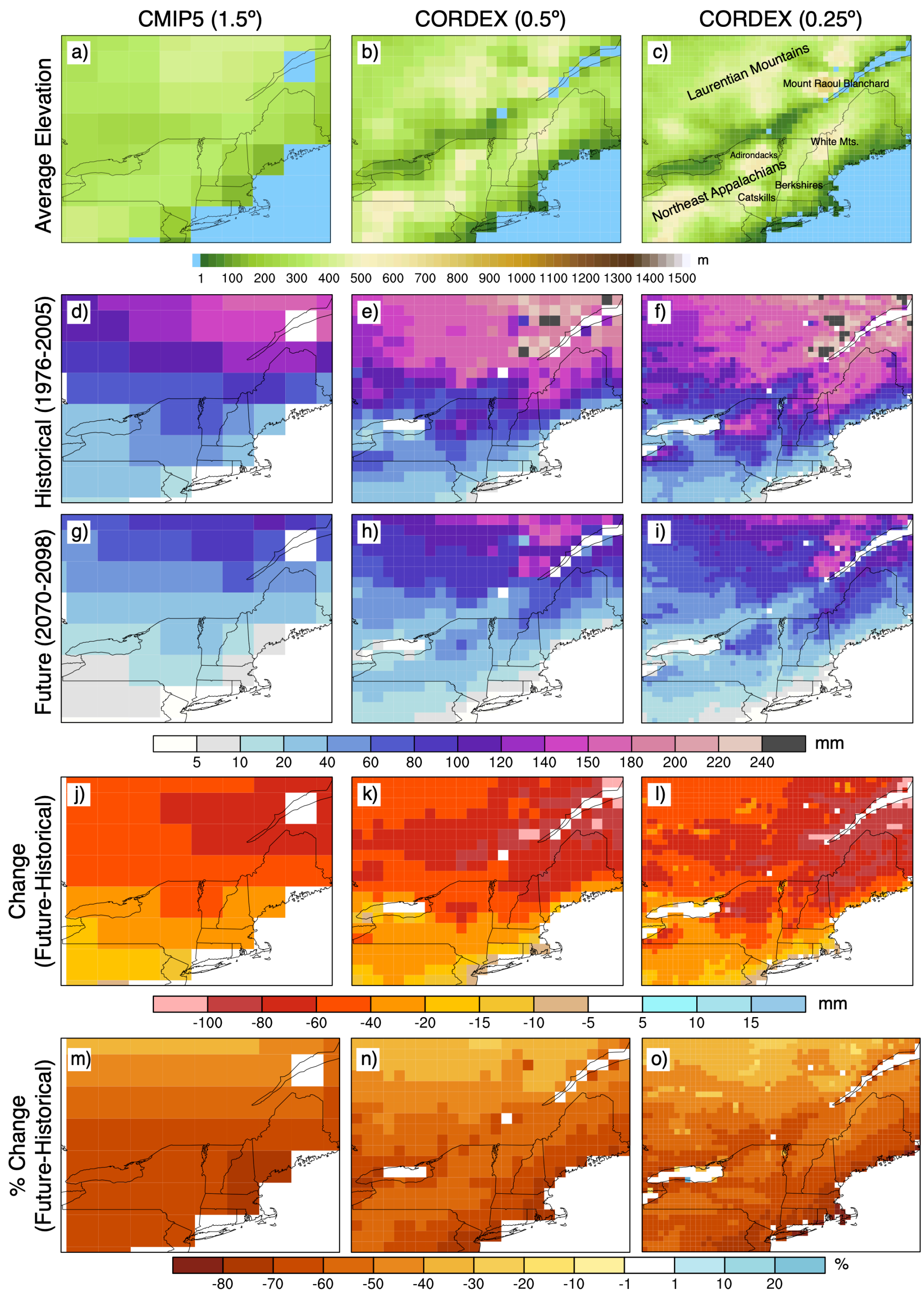

Fig. 10 Maps over the Northeast region of ensemble mean topography (a-c), ensemble mean historic AM-SWE (d-f), ensemble mean future AM-SWE (g-i), the magnitude (j-l) and percent (m-o) change (Future-Historic) in AM-SWE from the three model ensembles.