Projected Twenty-First-Century Changes in Temperature, Precipitation, and Snow Cover over North America in CCSM4

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ABSTRACT

Results from a suite of ensembles of twenty-first-century climate projections made using the Community Climate System Model, version 4 (CCSM4) are analyzed to document model bias and to explore possible future changes in air temperature, precipitation, and snow cover over North America. Large biases still exist in all analyzed fields in this version of the model, and the necessary assumption in future climate projections is therefore that the bias persists into the future, such that the differences in a field between two time periods are meaningful indications of potential changes. Projected temperature increases show strong regional patterns with spatial similarities for all the emissions scenarios considered, although there are considerable differences in the magnitude of the projected change. Projections indicate an increase in total precipitation over much of North America for all emissions scenarios, with the exception of the Southwest United States. All of North America except parts of northern Canada shows a projected decrease in snow cover over the twenty-first century.

1. Introduction

An ensemble of climate simulations has been carried out using the Community Climate System Model, version 4 (CCSM4), which included a 1300-yr-duration 1850 preindustrial “control” run, six ensemble members of the twentieth-century climate (1850–2005), six ensemble members for the “low emissions” representative concentration pathway (RCP; RCP2.6) scenario, six ensemble members for the “medium-low emissions” (RCP4.5) scenario, six ensemble members for the “medium-high emissions” (RCP6.0) scenario, and six ensemble members for the “high emissions” (RCP8.5) scenario.

Each of the Coupled Model Intercomparison Project phase 5 (CMIP5) emission scenarios is based on a “storyline” that differs in important ways from the emission scenarios used in the last (CMIP3) model intercomparison project, and therefore these new results are not directly comparable to those forced with the Special Report on Emissions Scenarios (SRES). The new RCP scenarios were designed to be compatible with the full range of stabilization, mitigation, and baseline emissions scenarios in the existing scientific literature, and each scenario assumes policies that impact future greenhouse gas emissions as well as aerosol concentrations, ozone levels, and changes in land use (Taylor et al. 2012; Moss et al. 2010, van Vuuren et al. 2011). Not only do the RCP emissions scenarios differ from those used in earlier studies but the base model has also changed considerably. Earlier model projections of the twenty-first century used a previous version of the model, CCSM3 (used in the CMIP3 analyses). One measure of model difference is the climate sensitivity. The equilibrium climate sensitivity of CCSM4 is 3.2°C (one-half-degree Celsius higher than for CCSM3), while the transient climate sensitivity is 1.72°C (just two-tenths of a degree higher than for CCSM3). These results are discussed in detail by Bitz et al. 2012. Major changes to the model between versions CCSM3 and CCSM4 are documented by Gent et al. 2011. A discussion of future global projected changes out to the year 2300 for the four RCP emissions scenarios can be found in Meehl et al. 2012. This paper focuses on the simulated temperature, precipitation, and snow cover changes over North America. Model bias in late twentieth-century temperature, precipitation, and snow cover is presented, in addition to bias-corrected
projections and projected changes in these fields over the twenty-first century.

2. Model description

The general circulation model used in this study is the most recent version of CCSM4, which consists of active atmosphere, ocean, land, and sea ice components. A pre-industrial control simulation with fixed CO₂ (284.7 ppm), fixed incoming solar radiation at the top of the atmosphere (1360.9 W m⁻²), and prescribed aerosols (black and organic carbon, sulfate, dust, and sea salt) was run for 1300 years to achieve an equilibrium climate and initial conditions for the twentieth-century simulations. An ensemble of six twentieth-century simulations were then run between January 1850 and December 2005, each with a slightly different initial condition [each initial condition was taken from a year near the end of the preindustrial control run and selected based on extremes in the Atlantic meridional overturning; details on this can be found in section 3 of Gent et al. (2011)]. For each ensemble member in a given RCP, the prescribed CO₂ (and other greenhouse gases) and aerosol trajectories are identical. For the simulations analyzed in this study, all model components have a nominal horizontal resolution of 1°.

For the twenty-first century, simulations were carried out using four different RCPs (Moss et al. 2010): RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The numerical value assigned to each RCP indicates the approximate radiative forcing in the year 2100 in the absence of climate feedbacks (e.g., RCP8.5 has specified greenhouse gases and aerosol trajectories consistent with a radiative forcing of 8.5 W m⁻² in the year 2100; the actual top-of-atmosphere imbalance in the model in 2100 is significantly smaller than this value). The atmospheric CO₂ concentrations, and the fossil fuel and industry CO₂ prescribed for each of the RCPs, can be seen in Fig. 1. Also shown in Fig. 1 are the observed fossil fuel and industry CO₂ emissions from 2005 to 2010 (black dots; see inset for clarity), which, despite the global-recession-induced dip in 2009, appear to fall very close to the high emissions RCP8.5 scenario.

In the low emissions (RCP2.6) scenario, atmospheric CO₂ concentration peaks at just over 440 ppm in 2050 and then declines to 420 ppm by the year 2100. Methane concentration (not shown) peaks at just over 1770 ppb in 2010 and then declines rapidly, reaching around 1250 ppb by 2100. The RCP2.6 scenario has total CO₂ emissions (total = fossil fuel + industry + land use change) similar to present-day levels (~10 Pg C yr⁻¹) until 2020 and then a sharp decline to zero carbon emissions by
2075. The medium-low (RCP4.5) scenario has atmospheric CO$_2$ concentrations climbing throughout the twenty-first century to a maximum value close to 540 ppm in 2100. Methane rises to a maximum of 1840 ppb in 2040 and then declines to 1575 ppb by 2100. Total CO$_2$ emissions in the RCP4.5 scenario increase slightly until 2040, after which there is a sharp decline to 4 PgC yr$^{-1}$ between 2080 and 2100. RCP4.5 is sometimes referred to as a “medium mitigation scenario.” The medium-high (RCP6.0) emissions scenario has CO$_2$ concentrations progressively rising to a maximum of 670 ppm in 2100 and CH$_4$ concentrations peaking at just above 1960 ppb in 2070. Total CO$_2$ emissions reach a maximum value of nearly 18 PgC yr$^{-1}$ in 2080 and then drop to 14 PgC yr$^{-1}$ by 2100. The high emissions (RCP8.5) scenario is characterized by a progressive increase in atmospheric CO$_2$ concentration over the twenty-first century, peaking at 935 ppm in 2100. Methane also shows a very significant rise in the atmosphere under this scenario, peaking at 3750 ppb in 2100. Total CO$_2$ emissions increase from present-day values to a maximum of 28 PgC yr$^{-1}$ in 2100 (at which point the emissions curve flattens). The CO$_2$-equivalent concentration for greenhouse gases in the year 2100 (i.e., the concentration of CO$_2$ that would be present in the atmosphere is CO$_2$ were the only greenhouse gas accounting for all the greenhouse forcing) is 475 ppm for the RCP2.6 scenario, 630 ppm for the RCP4.5 scenario, 800 ppm for RCP6.0, and over 1300 ppm for the RCP8.5 scenario.

For each of the RCPs, five ensemble members were run. For a single ensemble member from each emissions scenario, the daily output was saved for a large number of selected fields, publicly available for download from the Earth System Grid (http://www.earthsystemgrid.org).

3. Results

a. Temperature

1) Twentieth Century: Model and Observations

The Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) data (Hansen et al. 2010) are used to compare the model temperature trend over the twentieth century in North America with observations. The GISTEMP data were first interpolated onto the CCSM4 model grid, and then a spatially averaged value (over Canada, Alaska, and the contiguous United States) was computed for each month between 1880 and 2100, and from the monthly data annual means were constructed. Because of poor data coverage in the observational data before 1900 (especially in Canada and Alaska), only the period from 1900 onward is used to compare with the model output. The GISTEMP anomalies are relative to the 1951–80 mean values. The model was used to compute spatially averaged temperature anomalies for each month over Canada, Alaska, and the lower 48 states for each ensemble member and the ensemble mean, and these were used to construct annual mean values. Figure 2 shows the computed GISTEMP anomalies relative to the 1951–80 mean for each region as solid bars. The CCSM4 ensemble mean is shown by the solid lines in Fig. 2 (the period from 2006 to 2100 is based on the RCP8.5 scenario). It should be noted that no single model ensemble member, nor the model ensemble mean, should be expected to capture the timing of warm and cold anomalies, because these are controlled in large part by shifts in large-scale atmospheric internal modes of variability, such as El Niño and the Arctic Oscillation. However, it would be desirable for individual model ensemble members to capture the approximate magnitude of the temperature anomalies, while the ensemble mean might be expected to capture longer-term trends in spatially averaged temperature anomalies. While the agreement between GISTEMP and the model ensemble mean temperature is fairly good for the three regions considered up until about the year 2000, there appears to be a disagreement between the model and observations that is especially apparent in the lower 48 states in the last few years of the record (2008–10; Fig. 2, middle panel).
Over this period, the spatially averaged temperature anomalies over the contiguous United States show near-zero values, while the model ensemble mean temperature anomalies increase steadily. This apparent disagreement can be partly resolved by considering each of the six individual ensemble members in isolation. Figure 3 shows the GISTEMP data for the lower 48 states (again as bars), with the model ensemble mean superimposed as the light gray line, and in each of the six panels, one of the ensemble members shown by the darker gray line. In four of the six ensemble members (members 1–4), there is indeed a sharp dip in the temperature anomaly over the lower 48 states with a magnitude close to that observed within a few years of 2008. One of the ensemble members (member 5) shows further large dips in the temperature anomaly over the lower 48 states in the period 2010–20. Because the model is not able to reproduce the timing of observed weather events when in free-running mode (i.e., in the absence of data assimilation), it should not be expected that anomalously cold or warm years in the model and data line are synchronous. However, it is desirable that the magnitude of the
observed variability be captured by the model. When the individual ensemble members are considered, members can indeed be found that give a far better match with observational data than does the model ensemble mean. The dips seen in Fig. 3 for the individual ensemble members suggest that it is possible that there may be times over the next decade or so when the contiguous United States experiences average temperatures comparable to the 1951–80 mean, even on a high emissions trajectory.

Despite the fairly good agreement between trajectories of mean temperatures over North America with observations, there remain significant biases in the model simulation of mean temperature. The observed mean temperature over North America for the period 1950–2005 based on the Wilmott–Matsuura gridded observation-based data product (Willmott and Matsuura 1995) is shown in the left column of Fig. 4 (after re-mapping to the model grid), and the standard deviation of the observational data (computed for each month at each model grid point over the 56-yr period) is shown in the middle panel of Fig. 4. The model ensemble average temperature for January, April, July, and October (computed over the same 56-yr period as the observations) minus the observations (i.e., the model bias) is shown in the right column of Fig. 4. All the CCSM4 1°-resolution twentieth-century simulations show seasonally varying biases in 2-m (surface) air temperature, with very similar large-scale biases appearing in all ensemble members. The largest model biases are seen in winter.
over much of western Canada and Alaska (a positive model bias of up to 6°C), and in summer over the central parts of southern Canada and the northern United States, where model biases are positive and of a similar magnitude. There is also a positive model bias (1°–3°C) in spring in the Northeast United States and Canada, and a negative model temperature bias of 1°–4°C in spring extending southward along the Rocky Mountains of the western United States. Coastal California shows a persistent warm bias throughout the year, while the model bias in the Southeast United States is very small year-round.

2) PROJECTED MEAN TEMPERATURE CHANGES

The projected changes in surface air temperature for each of the RCPs in the late twenty-first century (2090–99 annual mean) relative to late twentieth-century temperature (1990–99 annual mean) are shown in Fig. 5. By far the largest projected temperature changes for all scenarios are in northern Canada and Alaska, and the smallest projected mean temperature changes are in Florida and coastal California. All scenarios are plotted on the same color bar in Fig. 5, so the polar amplification of the temperature response is clearest in the RCP8.5 scenario. Figure 6 shows the annual mean temperature changes averaged over 20-yr periods over the course of the twenty-first century for both the RCP6.0 and RCP8.5 scenarios, with each scenario having a separate color bar. This plot reveals the strong spatial similarities in the regional response for these two scenarios, with the amplitude of the change scaling with the forcing.

A more detailed view of the differences in regional temperature response over the twenty-first century in North America can be seen in Fig. 7, which shows the time series of spatially averaged model temperature anomalies between 1950 and 2100 for nine regions in North America for each of the emissions scenarios. Also shown (as bars) are the GISTEMP anomalies for the period 1950–2005 for each of the regions. For most of North America, over the late twentieth century, the
observed temperature anomalies generally fall within the spread of the model ensemble. The exceptions to this are for the period 2000–05 over southeastern Canada and the Midwest United States, where the envelope of the ensemble mean appears to fall a little above the observations. This slight overestimation of model temperatures relative to observations over the past decade may be due to the absence of an indirect aerosol effect in CCSM4 (Gent et al. 2011), which results in a top-of-atmosphere imbalance in radiative forcing slightly larger than observed over the past decade in CCSM4. It is clear from Fig. 7 that there is large spread within each of the ensembles, with significant overlap, particularly between the medium-low (RCP4.5) and medium-high (RCP6.0) emissions scenarios. Even for the low (RCP2.6) emissions scenario, annual mean temperatures over most of North America reach about 2°C over the 1951–80 mean values for that region. The Southwest and
Southeast United States show the smallest net warming in the annual mean for all scenarios, while northwestern North America and north-central Canada show the largest warming. In most regions, the projected warming across all scenarios is very similar up until about 2040, at which point the warming for different scenarios starts to diverge.

Figure 8 shows how the projected changes vary with season. The 2090–99 minus 1990–99 temperatures are shown for January, April, July, and October for each of the RCPs. In fall and winter, by far the largest projected changes are in northern Canada and Alaska, with changes as large as 14°C (25°F) in January for parts of northern Alaska and northernmost Canada under the RCP8.5 scenario. Even larger changes are projected for the fall in the northernmost part of the Nunavut Province. This strong amplification is largely due to polar amplification caused by ice-albedo feedbacks in the Arctic (Manabe and Stouffer 1980). The projected winter warming is also highly asymmetrical across the
continent, with far larger temperature increases in the Northeast United States than in the Northwest United States (note that this east–west asymmetry appears not to be apparent in the annual mean due to strong summertime warming in the west). Within the lower 48 states, the model projections show that the Northeast United States is likely to experience the most extreme wintertime increases in temperature. In this region, maximum projected changes by the end of the twenty-first century are around 7°C (~13°F) under the RCP8.5 scenario, 4.5°C (~8°F) under the RCP4.5 scenario, and up to 2.5°C (~4.5°F) under the RCP2.6 scenario.

The projected summertime temperature changes show a very different pattern, with relatively little warming in northern Canada (between 4° and 5°C, around 8°F, for the RCP8.5 scenario), and peak warming in southern Canada and the northern United States (where projected changes are order 6°–7°C, or around 12°F, under the high emissions scenario RCP8.5). This pronounced midcontinent summertime warming may be partly due to increased evaporation and decreased soil moisture over much of the United States during the summer months. The magnitude of the projected summer temperature changes in the northern United States and southern Canada is up to 8°C (~14°F) for the RCP8.5 scenario, up to 3.5°C (~6°F) for the RCP4.5 scenario, and up to 2.5°C (~4.5°F) for the RCP2.6 scenario. For all scenarios, the largest projected temperature changes within the contiguous United States come in the winter and summer months, with projected changes being much smaller in the spring and fall. The one exception to this is the projected change in springtime temperatures over the northern Rockies, where projected April temperature changes are somewhat larger than those elsewhere in the contiguous United States.

3) PROJECTED CHANGES IN EXTREME TEMPERATURES

Just as there are biases in the model’s mean temperature field, there are also biases in the model’s representation of extremes and, as is the case with biases in the mean fields, the biases in extremes vary both spatially and seasonally. Figure 9 shows a histogram comparing the annual maximum value of daily maximum/minimum temperatures for the period 1990–99 over every model grid point in North America as simulated by the model (red bars) with observations (blue bars; Alexander et al. 2006). In general, there is broad agreement between the shape of the observed and simulated maximum values of daily minimum/maximum
temperature distributions, but the model has longer/broader tails than the observations in both measures, to both sides of the distribution. Particularly noticeable is that the model appears to show many more maximum daily minimum/maximum temperatures than do the observations that are toward the lower end of the range. It is clear from the inset maps that this is largely due to model cold bias in two regions: along the Rockies and in northeastern Canada.

If there are large model biases in present-day climate, then the present-day model fields can be bias corrected and have this bias correction applied to future projections. The bias-corrected number of days per year on which the maximum temperature exceeds 25°C is shown for the late twentieth century (1990–99) and for the late twenty-first century (2090–99) under the RCP8.5 scenario in Fig. 10. The Hadley Centre Global Climate Extremes dataset (HadEX) used for assessing the same quantity based on observations (Alexander et al. 2006) was used to bias correct the model fields (the fields shown are model projection minus model bias, where the bias is simply defined as the difference between model and observations in the late twentieth century). In the observed record, only in the southern United States does the maximum daily temperature exceed 25°C (77°F) for more than 100 days yr⁻¹ in the late twentieth century. By contrast, nearly all of the contiguous United States and parts of southern Canada are projected to experience more than 100 days yr⁻¹ with a daily maximum temperature greater than 25°C by the end of the twenty-first century under the high emissions (RCP8.5) scenario. The only parts of North America that do not show a large increase in the projected number of hot summer days (defined here as having a daily maximum temperature greater than 25°C) are Alaska and northernmost Canada. As is clear from Fig. 8, the largest temperature changes in these regions occurs in the winter months (when the temperature does not
come near 25°C; the projected summer changes in northern Canada and Alaska are far smaller.

Also shown in Fig. 10 is the annual number of “frost days” (FDs), for which the daily minimum temperature falls below 0°C (32°F). Again, the model projections have been bias corrected using the HadEX dataset for the annual number of frost days. The bias-corrected fields show a dramatic northward spread in lower numbers of frost days at the end of the twenty-first century relative to the present day. The largest decrease in the annual number of frost days between the late twentieth and late twenty-first centuries under a high emissions scenario occurs in a band trending northwest along the Rocky Mountains and into Alaska.

Another way to look at expected changes in extreme temperature events is to consider how the distribution of anomalous hot and cold events might change through time. In Fig. 11, the model temperature data from each grid point over North America between 1951 and 1980 were used to define the mean and standard deviation “model climatology.” Temperature anomalies were defined at each grid point in each January and July of each year relative to the 1951–80 mean, and these temperature anomalies were divided by the 1951–80 January and

Fig. 10. (left) Average number of days per year for which maximum daily temperature exceeds 25°C (SU), and annual number of days per year on which minimum daily temperature falls below 0°C (FDs, right panel). (top) Bias-corrected model results (=observations based on the Alexander et al. (2006) HadEX data after remapping to the model grid) for the period 1990–99. (middle) Bias-corrected model projection under the RCP8.5 scenario for the period 2090–99. Rows (top) and (middle) share a common color bar in each column. Difference between the 2090 and 1999 and 1990 and 1999 values for each metric is shown in (bottom). Note that the color bars on the (left) are reversed between the (top) and (bottom) plots.
July standard deviation to obtain the departure from the mean in terms of sigma units. The percentage of the total land area of North America in each sigma bin was then computed for both January and July. Figure 11 shows, for the high emissions (RCP8.5) scenario, how the fractional area of land in North America covered by events that would be considered extreme in today’s climate increases dramatically toward the end of the twenty-first century. For example, 4σ–6σ events are never seen in the model before the year 2000; yet, by the end of the twenty-first century, these events typically cover more than 20% of the area of North America in the summer (note that the Russian heat wave of 2010 was considered a 3σ event; J. Hansen et al. 2012, unpublished manuscript). The increase in 4σ and higher events in winter is much smaller than the summertime increase. This may be in part because the standard deviation of temperature is very much higher in winter than in summer over North America (e.g., see Fig. 4, middle column), so it is “harder” to have very extreme events in the winter by this metric. The events in the 1σ–3σ window increase in summer until about 2050 and then decrease (at the expense of events of 3σ and higher), while in winter these 1σ–3σ events progressively increase through the twenty-first century. It is also worth noting that in the summer, the very cold events (−2σ to −4σ) are very rare in the twenty-first century, whereas in the winter there are still sporadic years that would be considered very cold in coming decades.

b. Precipitation

1) TWENTIETH CENTURY: MODEL AND OBSERVATIONS

Late twentieth-century model bias in precipitation was computed using the Willmott–Matsuura database of monthly total precipitation. The observation-based monthly climatologies for 1950–2005 were first regridded onto the model grid and then average monthly fields were computed over the 56-yr period. Monthly averages were computed over the same period from the model output. Percent difference plots of the model ensemble mean minus the observations are shown for January, April, July, and October in Fig. 12. All model ensemble members show the same general large-scale biases in precipitation, although there are differences in the magnitude and spatial distribution of bias between the model runs. In general, the model has too much rainfall throughout northern Canada and most of the western United States in the fall, winter, and spring (with the exception of the British Columbia coast, which has too little precipitation in the model), and the model has too little precipitation in the southeastern states in the fall, winter, and spring. In the summer, the positive model rainfall bias shifts, such that there is too much rainfall in south-central Canada and the north-central United States. The largest absolute model bias (not shown) is in western North America in the fall and winter, when the model has up to 3 mm day−1 too much total precipitation (precipitation is defined as snow plus rain). These are large, long-standing biases in the CCSM model (e.g., see Collins et al. 2006) that have not shown significant improvement with time. It is likely that increasing the model resolution will help reduce the
bias somewhat (e.g., Gent et al. 2010, 2011), but that improvements in cloud and convective physical parameterizations will also be an important part of the solution.

2) PROJECTED PRECIPITATION CHANGES

The projected percent change in total precipitation for each of the RCPs between the late twentieth and the late twenty-first centuries is shown in Fig. 13. The spatial patterns show certain similarities across all scenarios, with an increase in precipitation over all of Canada and the Southeast United States. There is a smaller decrease in total precipitation over the Southwest United States. These changes are most pronounced in the high emissions (RCP8.5) scenario, where the maximum increase in precipitation is order 30% and the decrease is order 10%. The relative change in seasonal precipitation (especially for drier conditions) is significantly larger than the annual mean change, as can be seen in Fig. 14, which shows the seasonal percent change in precipitation for the high emissions (RCP8.5) scenario. The projections show a widespread summertime drying (with precipitation up to 50% lower than present-day average values) throughout much of southern Canada and the northern United States, while the winter experiences higher precipitation than at present almost everywhere in North America except in the Southwest United States.

In some regions of North America, there is a projected increase in rain but a decrease in snow as temperature increases, such that the precipitation change masks the impact of increasing rainfall. The projected change in rainfall anomaly for different regions in North America is shown in Fig. 15 for all of the RCP scenarios. One striking feature of this plot is the very large variability across the ensemble members for a given scenario in most of North America. This variability is so large that in many regions (e.g., the Southeast United States), the trajectories of each of the individual scenarios are hard to distinguish. In other regions (such as north-central Canada), the variability across the ensemble is very small, and all emissions scenarios have distinct trajectories. The largest projected rainfall anomalies in North America are in northwestern North America (defined here as Alaska and the Yukon Province). The smallest projected change in rainfall is in the Southwest United States.
States (but note that the apparent drying evident in Fig. 13 would not have been apparent if that plot had been made with respect to the 2070–89 mean rather than the 2080–99 mean; in the RCP8.5 scenario, there is a relatively wet period in the Southwest United States immediately prior to the very dry anomaly at the end of the twenty-first century).

As with temperature, precipitation biases exist not just in the mean fields but also in the extremes. The annual number of days for which precipitation is greater than 10 and 20 mm over North America is shown for both the model and observations over the period 1990–99 in Fig. 16. By both of these measures, the model has many more days with very low precipitation than the observations (it can be seen from the inset maps that the small number of days with precipitation above these thresholds tends to occur in central North America). In the precipitation >20 mm category, the observations show a large region of the Southeast United States where rainfall is this high for between 20 and 30 days yr\(^{-1}\), while the model only has 10–15 days yr\(^{-1}\) of high precipitation in this region. The model also shows, in both precipitation categories, a very small number of grid points with a very large number of days at which precipitation exceeds the specified threshold; this is not seen in the observations.

Figure 17 shows the difference in the average number of days per month (January and July) and the difference in the average number of days per month (annual mean fields are shown) between the 10-yr period of 2090 and 2099 and the period of 1990 and 1999 on which rainfall is greater than 0.1, 1, 10, or 50 mm day\(^{-1}\) (results are shown only for the RCP8.5 scenario). The purple shades indicate regions in which the model predicts there will be more days with rainfall above the specified threshold in the late twenty-first century compared with the late twentieth century, and the green shades show regions where less rainfall above the specified threshold is projected. The patterns vary strongly month by month, with some regions having a higher projected number of days with rain above a certain threshold and some having fewer days. As the precipitation threshold is increased, there tends to be fewer days at the end of the twenty-first century relative to the late twentieth century with rainfall below the threshold value. For most of Canada in January, the model projections indicate 3–5 more days
a month in which rainfall is greater than 1 mm day$^{-1}$ in the late twenty-first century as compared with the late twentieth century. However, if the threshold is raised to 10 mm day$^{-1}$, there is very little change apparent in the projections for the same region. For very heavy rain events (>50 mm day$^{-1}$), the model results indicate that some regions on the east and west coasts will experience on average one more day per year with very high precipitation, while the rest of North America shows little change. By contrast, large parts of North America are projected to experience order 10 more days yr$^{-1}$ with precipitation greater than 10 mm day$^{-1}$.

Rather than considering the changes in number of days of rain greater than a specified threshold, it is also possible to assess how projected precipitation changes relative to the mean values in the late twentieth century. Figure 18 shows (for each of nine regions in North America) the average number of days per year for each decade when precipitation is greater than the mean of the $N$ highest daily values over the period 1951–99 (where $N = 10, 100, 500,$ or $1000,$ which corresponds to the mean of the top 0.05%, 0.5%, 2.7%, and 5.5% of daily precipitation values, respectively). The Northeast United States, Southeast United States, and northwestern North America stand out as regions with the largest increases in precipitation over the twenty-first century for all these thresholds, but the distinction between these regions and the rest of North America is more pronounced for the very high precipitation events. The projected precipitation changes relative to the late twentieth-century mean values are relatively modest, with rainfall for $N = 500$ and $N = 1000$ occurring on average 5–10 more days yr$^{-1}$ in the late twenty-first century relative to the present day, and high intensity rainfall ($N = 10$ and $N = 100$ in Fig. 17) occurring 1–2 days yr$^{-1}$ more frequently in the late twenty-first century over much of North America.

The percentage change in precipitation over the whole of North America as a function of rainfall intensity shows remarkably similar behavior across all four emissions scenarios (Fig. 19). By sorting the daily model precipitation from low to high values for both the late twentieth and late twenty-first centuries, and then computing the mean precipitation for each 1% percentile bin over each
20-yr period, the change in precipitation between the late twentieth and twenty-first centuries for each percentile of the distribution can be calculated. Figure 19 shows the percentage change for each percentile of the precipitation distribution for each RCP scenario between the late twentieth and late twenty-first centuries. For the very low precipitation values, even a very small absolute change in rainfall can cause a very large shift in percentage change. For the moderate to high precipitation events, the percentage change is fairly consistent as a function of rainfall intensity for each RCP. For example, in the model, the 50th percentile (which corresponds to 0.4 mm day$^{-1}$ for the late twentieth century and to 0.49 mm day$^{-1}$ for the late twenty-first century in the RCP8.5 scenario), the percent change in precipitation is about 18% (averaged over North America); for the 90th percentile (which has 5.1 mm day$^{-1}$ precipitation for the late twentieth century over North America and 5.9 mm day$^{-1}$ for the late twenty-first century), there is a 15% change. The RCP6.0 and 4.5 scenarios show a percentage change of between 8% and 15% for the 30th percentile and higher bins, while the RCP2.6 scenario shows a change of roughly 5% (top panel, Fig. 19). When the percent precipitation changes in each percentile bin are normalized by the mean temperature change over North America for the same period (bottom panel in Fig. 19), the different scenarios show very similar behavior, especially for the higher percentiles, where the percent precipitation change is roughly 3% K$^{-1}$. These changes observed over North America are slightly larger than the global mean change in the model, which is around 2.5% K$^{-1}$ for this ensemble member. As has
been noted before, this is significantly less than the rate at which global water vapor increases with rising temperature (e.g., Allen and Ingram 2002; Held and Soden 2006). It is of interest to note that, in the model at least, there is no significant upturn at the highest percentiles; that is, the very high precipitation events increase by roughly the same percentage (or less) as the moderate precipitation events. When this percentage is normalized by the mean temperature change, all the scenarios show a very similar response for the high precipitation events. It should be noted that this is the result for a single ensemble member (daily output, which is needed to compute the mean precipitation in each percentile, was saved only for one of the six ensemble members). The ensemble mean response can be expected to be somewhat different, based on the large variability in precipitation patterns observed across the model ensemble members.

c. Snow depth

1) Twentieth Century: Model and Observations

The observed mean snow depth for January–April (JFMA) and the model ensemble snow depth in the late twentieth century are shown in Fig. 20 (top row). The model has too much snow in Alaska, the Rockies, and much of northern Canada relative to observations. Similar model biases to those seen in Fig. 20 are apparent for all winter and spring months.

2) Projected Changes in Snow Depth

The bottom row of Fig. 20 shows the projected late twenty-first-century snow depth for January–April under the RCP8.5 scenario. Despite the model overestimating present-day snow cover, in the U.S. Rocky Mountains snow cover is projected to fall to near-zero values in late
spring by the end of the twenty-first century under a high emissions scenario. Significant reductions in snow depth are apparent for all winter and spring months by the late twenty-first century. Such changes in snow cover could have far-ranging implications, from biodiversity (e.g., Peacock 2011) to economic implications (e.g., Scott and McBoyle 2007).

The way in which snowfall rates are projected to change regionally over North America is shown in Fig. 21. For each of the nine regions, the time series of snowfall anomaly (relative to the 1951–80 mean) is shown for each of the four emissions scenarios. The largest projected reductions in snowfall are in northwestern North America and southwestern Canada. There is virtually no projected change in snowfall rate in north-central Canada. Note that the variability across the ensemble members is very large in some regions, such that there are likely to be years with snowfall rates close to those of the present day until about 2050, even under the high emissions scenario in places of sharp snowfall reduction (such as northwestern North America), and snowfall values close to or higher than those of the present day still occur in many of the other regions through the end of the twenty-first century for all scenarios.

The projected changes in March rainfall, snowfall, and total precipitation are shown in more detail in Fig. 22 for four selected regions under the RCP8.5 scenario. Also shown in this figure are the 50-yr mean trends in each of these fields and the number of days per month above freezing point. In northwestern North America, the projected snowfall decreases through the twenty-first century, with the downward trend becoming significantly larger with time. Rainfall shows the opposite trend in this region, with rain becoming the dominant form of precipitation in this region around 2070. In the Northeast United States, snowfall and rainfall also show opposite trends, but snowfall is always much lower than rainfall. Moreover, snowfall in this region shows a smaller
downward trend at the end than at the beginning of the twenty-first century. In north-central Canada, both snowfall and rainfall increase through the twenty-first century, with trends becoming progressively larger through time. North-central Canada is the only region in North America in which there are zero projected days with March temperatures above zero by 2100 under the high emissions scenario. In the Southwest United States, both rainfall and snowfall are projected to decrease with time, with rainfall only showing a clear downward trend in the second half of the twenty-first century.

3) PROJECTED CHANGES IN HEAVY SNOWFALL

While mean snowfall is projected to decrease over much of North America in the coming decades, this does
not necessarily mean a sharp reduction in the number of days of heavy snowfall in all regions. Figure 23 shows the average number of days per year for which snowfall rate exceeds a specified threshold for different regions under the high emissions scenario. For each region, the threshold value was computed as the mean snowfall for 10% of the days with the highest snowfall during the period 1950–99. In some regions, such as the western United States and the Southeast United States, there is a sharp drop in the number of high snowfall days over the twenty-first century. The drop is more abrupt in some regions than others; for example, in northwestern North America, there is little change between 1990 and 2040, and then a transition to lower values around the middle of the twenty-first century. In southeastern Canada, north-central Canada, and the Midwest United States, there does not appear to be a sharp downward trend in the number of heavy snowfall days. Heavy snowfall (as well as mean snowfall) increases in north-central Canada and shows little trend in southeastern Canada and the Midwest United States.

4. Discussion

Simulated temperature, precipitation, and snow cover still show significant biases relative to present-day observations. Ideally, one would start projections of future climate from a model with a mean state that closely approximated present-day climate. However, without help from data assimilation techniques, freely evolving climate models have not yet reached this point. Therefore, the best that can be done with the current state-of-the-art global climate models is to make the assumption that present-day biases persist into the future, and thus that changes in model fields between the late twentieth and late twenty-first centuries will be in some way meaningful.

CCSM4-simulated temperature changes under the RCP8.5 scenario show spatial patterns that are broadly consistent with previous model simulations (the largest warming in winter occurring in the far north; peak summertime warming occurring in southern Canada and the northern and central United States). The magnitude of the projected warming under the RCP8.5 scenario is somewhat greater than many of the previous projections (summarized, e.g., by Meehl et al. 2007) because the radiative forcing of the RCP8.5 scenario is larger than that of the commonly cited A1B scenario that was widely used in the 2007 Intergovernmental Panel on Climate Change (IPCC) report. The CCSM4 projections indicate that the regions that experience the largest net increases in temperatures are likely not the same as the regions that experience the largest changes in extreme heat. For example, the greatest projected change in the number of hot days per year is in the Southeast United States, while the largest projected reduction in number of frost days is in southern Alaska and inland British Columbia. Model projections show that under a high emissions scenario, temperature extremes are likely to become commonplace over much of the land area of North America, with “5σ–6σ” events covering over 20% of the land area in July by the late twenty-first century.

The amount of moisture in the atmosphere and global mean precipitation are expected to increase as the climate warms (Trenberth 2011). The precipitation changes projected by CCSM4 are in broad agreement with previous model results (as summarized by Meehl et al. 2007), with increased precipitation in the north and drying in the Southwest over the course of the twenty-first century. However, as with temperature, the projected changes under the RCP8.5 high emissions scenario are significantly larger than those of the A1B model ensemble mean, with CCSM4 projections showing a precipitation increase of over 30% in northern Canada by the end of the twenty-first century, compared with about 10%–15% reported for the average change in the AR4 models. The seasonal projections of precipitation change in CCSM4 show much larger changes than in the annual
mean, with wintertime changes of up to 50% in Canada and summertime precipitation decreases that are also order 50% in southern Canada and the northern United States. The projected rainfall anomalies in the Southwest United States show very large variability and decadal oscillations between wetter and drier conditions. The apparent drying that is evident when considering the change between 2080 and 2099 and 1980 and 1999 may not be robust for other periods. It is evident from model intercomparison projects, such as CMIP3 (e.g., Dai 2006), that there are still important differences in simulated precipitation patterns between models. An accurate simulation of precipitation requires an accurate representation of processes, such as cloud microphysics, physics of the planetary boundary layer, convection, as well as the large-scale atmospheric circulation (which will in turn depend critically on factors such as model representation of topography).

The model does show an increase in heavy precipitation events, consistent with previous studies (e.g., Allen and Ingram 2002; Karl and Trenberth 2003), but the magnitude of the projected increase is relatively small. For example, under the high emissions scenario, the projected change in heavy rainfall (>50 mm day\(^{-1}\)) between the late twentieth and late twenty-first centuries is for about 1 more day yr\(^{-1}\) of heavy rainfall in the Southeast United States and on the west coast of North America but little change elsewhere. For all emissions scenarios, the average precipitation change per degree of warming in various percentiles (computed based on sorted daily data over 20-yr periods at the end of the twentieth and twenty-first centuries) is very similar over North America, especially for the higher percentiles, where all scenarios converge to roughly a 3% precipitation increase per degree of warming. Projections of precipitation changes will undoubtedly continue to be refined and improved as both model resolutions and parameterizations improve. Precipitation rate and intensity can change due to a large number of processes, including changes in water vapor content of the atmosphere, changes in cloud cover and type, and atmospheric lapse rates and stability profiles (e.g., Trenberth et al. 2003; Trenberth 2011); it is clear that climate models, including CCSM4, still have much room for improvement in many of these areas.

![Diagram of model ensemble mean snow depth and observed snow depth](image-url)
The projected snow depth changes under the high emissions scenario show a reduction in snow cover by the end of the twenty-first century in almost all parts of North America that are snow covered today. The simulated interannual variability in snowfall shows very strong regional patterns, with some regions showing positive snowfall anomalies relative to the 1951–80 mean into the mid-twenty-first century, even under a strong downward trend in mean snow cover. The relation between projected snowfall and rainfall trends over the twenty-first century also shows strong regional variability over North America. The occurrence of very high snowfall is projected to increase in north-central Canada and shows little trend in southeastern Canada and the Midwest United States. In other regions there is a decrease in the expected frequency of high snowfall events, but such events still persist in all regions through the twenty-first century.

5. Conclusions

Results from a suite of CCSM4 simulations running through 2100, using four different emissions scenarios for the period 2005–2100, have been presented for North America. The model biases in surface air temperature, precipitation, and snow cover, and the projected changes under various emissions scenarios have been discussed. The model results show pronounced spatial and seasonal variability in the magnitude of the projected changes, but that spatial patterns of change show similarities under all the emissions scenarios. The projected changes are far larger under the RCP8.5 scenario than under the RCP6.0,
RCP4.5, or RCP2.6 scenarios. Generally, the projections of the RCP4.5 and RCP6.0 scenarios are very similar in magnitude and in spatial pattern.

Much of the focus of this paper has been on the high emissions (RCP8.5) scenario. This scenario assumes high population growth, fairly low rates of technological change and clean energy development, and high future energy demand (Riahi et al. 2011). Without any form of mitigation in the coming decades, this scenario may be close to earth’s actual greenhouse gas trajectories over the twenty-first century; indeed, emissions data over the past 5 years (Fig. 1) indicate that we are currently on a trajectory closer to the RCP8.5 scenario than to the more moderate scenarios.

The RCP8.5 scenario shows increases in mean temperature and mean precipitation over most of the North America, and a large decrease in spring snow cover over much of the northern United States and Canada. The projected changes for the RCP6.0, RCP4.5, and RCP2.6 scenarios, while more muted in amplitude than changes seen in the RCP8.5 scenario, tend to show a strong spatial similarity in projected changes. The magnitude and spatial pattern of the CCSM4-simulated twenty-first-century changes in temperature over North America are in broad agreement with the multimodel mean changes reported by Christensen et al. 2007 and Karl et al. 2009, although there are important regional and seasonal differences in the CCSM4 projections. Development of the CCSM model continues, with a new atmosphere [Community Atmosphere Model, version 3 (CAM5)] already available as an alternative to the CAM4 atmosphere used in the CCSM4 simulations analyzed herein. Future improvement of large-scale biases in late twentieth-century model temperature and precipitation fields remains as an important development goal.
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Fig. 23. Average number of days per year (a single bar shown for each decade) for various regions in which snowfall exceeds a given threshold, $S_{10}$. Threshold value was computed separately for each state as the mean snowfall for the 10% of days with the highest snowfall over the period 1950–99.


