

Regional climate change projections from NA-CORDEX and their relation to climate sensitivity

Melissa S. Bukovsky¹  · Linda O. Mearns¹

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Abstract

The climate sensitivity of global climate models (GCMs) strongly influences projected climate change due to increased atmospheric carbon dioxide. Reasonably, the climate sensitivity of a GCM may be expected to affect dynamically downscaled projections. However, there has been little examination of the effect of the climate sensitivity of GCMs on regional climate model (RCM) ensembles. Therefore, we present projections of temperature and precipitation from the ensemble of projections produced as a part of the North American branch of the international Coordinated Regional Downscaling Experiment (NA-CORDEX) in the context of their relationship to the climate sensitivity of their parent GCMs. NA-CORDEX simulations were produced at 50-km and 25-km resolutions with multiple RCMs which downscaled multiple GCMs that spanned nearly the full range of climate sensitivity available in the CMIP5 archive. We show that climate sensitivity is a very important source of spread in the NA-CORDEX ensemble, particularly for temperature. Temperature projections correlate with driving GCM climate sensitivity annually and seasonally across North America not only at a continental scale but also at a local-to-regional scale. Importantly, the spread in temperature projections would be reduced if only low, mid, or high climate sensitivity simulations were considered, or if only the ensemble mean were considered. Precipitation projections correlate with climate sensitivity, but only at a continental scale during the cold season, due to the increasing influence of other processes at finer scales. Additionally, it is shown that the RCMs do alter the projection space sampled by their driving GCMs.

Keywords Projections · Climate sensitivity · Uncertainty · Regional climate modeling · North America · CORDEX

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✉ Melissa S. Bukovsky
bukovsky@ucar.edu

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

1 Introduction

This study aims to examine the ensemble of projections produced as a part of the North American branch of the international Coordinated Regional Downscaling Experiment (NA-CORDEX) in the context of their relationship to the climate sensitivity of the global climate models (GCMs) used as forcing for this regional climate model (RCM) ensemble. We present basic projections for the most commonly used variables, near-surface temperature and precipitation, for North America and 30 sub-regions.

NA-CORDEX samples nearly the full range of climate sensitivity found in the Coupled Model Intercomparison Program Phase 5 (CMIP5) archive. Climate sensitivity, a measure of the global mean temperature response to an increase in CO₂, has been shown to be an important source of model uncertainty over large parts of the globe, and not just for near-surface temperature (e.g., Mauritzen et al. 2017). In GCMs, it is often measured in terms of the equilibrium (or “effective”) climate sensitivity (ECS), the global mean near-surface air temperature response to a doubling of CO₂ after equilibrium is reached, or as a GCM’s transient climate response (TCR), the change in global mean temperature at the time CO₂ reaches double its initial concentration while increasing at 1% per year. Here, we focus on examining the spread in the NA-CORDEX projections relative to TCR. Given the timeframe over which TCR is calculated, it is more likely than ECS to explain the spread in GCM temperature changes over the twenty-first century (Knutti et al. 2017), even if it is not the better fit with the CMIP5 GCM projections when compared with ECS in the end (Grose et al. 2018). Also, the distribution of climate sensitivities within the NA-CORDEX ensemble provides natural breaks at low, mid, and high TCR and provides a better allocation of simulations across those categories. We will briefly explore the consequences of this choice.

Why examine the projections from NA-CORDEX in the context of climate sensitivity? We have two main reasons: one being that it is very relevant from a dataset user perspective and the second being that its effect on projection spread has not been examined before with RCM projections (to the best of our knowledge).

Expanding on these points, first, within a given emission scenario, uncertainty in projected changes at a continental and centennial scale is largely due to climate sensitivity, and at smaller spatial scales to regional processes (Grose et al. 2017; Sutton et al. 2015). However, we may not know for a long time what the actual climate sensitivity of the planet is, including whether or not it will fall on the high end, low end, or somewhere in between, given that it encompasses many long-term feedback processes (Mauritzen et al. 2017). Combined with its previously unexplored but assumed effect on the spread in regional climate projections, presenting the projections relative to their driving GCM climate sensitivity should provide a sense of how uncertainty in climate sensitivity affects the RCM projection spread. In addition, it suggests how to leverage that spread if a user cannot apply all of the simulations and must choose only a few. Model spread may be constrained if only a low-, mid-, or high-range TCR subset of simulations is chosen, or if only the ensemble mean is chosen. And, different parts of the spectrum may suggest different levels of impacts and necessary adaptation measures, the credibility of the simulations notwithstanding.

Second, climate sensitivity has often been discussed as an uncertainty that should be spanned when selecting models for downscaling (e.g., Christensen and Christensen 2007; Liang et al. 2008; Evans et al. 2014; Mearns et al. 2015), but RCM results have not yet been examined in this context, despite the fact that some RCM ensembles do exist now that encompass this uncertainty. For instance, in Kjellström et al. (2016), it was concluded that

their single European RCM ensemble did represent the spread in TCR across the CMIP5 ensemble because the GCMs chosen spanned it, but the RCM results were not examined in that context. Similarly, with a limited, early release set of some of the 50 km NA-CORDEX simulations that did span the full range of climate sensitivity in CMIP5, Karmalkar (2018) examined and discussed climate sensitivity, but only explicitly in the context of the driving GCM temperature projections (not the RCM projections). It was concluded that the GCM temperature projections did not scale well with ECS over a set of large sub-continental scale regions for analysis and given a mid-century period of examination only.

In the end, NA-CORDEX is an ensemble of opportunity, with GCMs selected for down-scaling partly based on their country or institute of origin, the quality of a GCM's simulation for a region or an important climate phenomenon, with some coordination among modelers, and with some intention to span GCM climate sensitivity with at least a couple of RCMs, among other potential factors. Therefore, in addition to examining the ensemble's projections in relation to their driving GCM climate sensitivity, we will also briefly compare its projections of North American precipitation and temperature to those from the larger CMIP5 ensemble, to assess the representativeness of the spread at a large scale. Furthermore, we also present a comparison of the NA-CORDEX projection spread relative to climate sensitivity with that from its precursor, the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2012, 2013). CMIP3 climate sensitivity was not well sampled in NARCCAP, and this was a known issue from the start (Mearns et al. 2015). Therefore, it is worth examining what is gained in terms of spread and sampling between the two ensembles. Finally, we note that, in this assessment of NA-CORDEX, we are not assessing the credibility of the simulations in any way. While we encourage in-depth, process-level analysis, it is beyond the scope of this overview of the projections.

2 Simulations and methods

2.1 Simulations

2.1.1 NA-CORDEX

This study includes all of the GCM-driven simulations available in the NA-CORDEX archive as of the time of writing (Mearns et al. 2017) and focuses only on simulations that used Representative Concentration Pathway 8.5 for future projections (RCP8.5; Moss et al. 2010). These simulations come from seven different RCMs (Table 1), forced by seven different CMIP5 GCMs (Table 2), at two different resolutions (25 km and 50 km), for a total of 27 simulations (Table 3). Note that all simulations used ensemble member r1i1p1 of their respective GCM simulations, except for those forced by EC-EARTH. The RCA4 simulation downscaled r12i1p1 of EC-EARTH, while the HIRHAM5 downscaled r3i1p1. As the differences between the two ensemble members are insignificant on the temporal and spatial scales addressed in this analysis (Supplementary Fig. S1), only member r12i1p1 is shown.

While projections using RCPs 4.5 and 2.6 also exist in the NA-CORDEX archive, the number of simulations is much smaller and, therefore, less suitable for this analysis.

The GCMs used to force the RCMs in this ensemble span almost the full range of climate sensitivity in the CMIP5 archive. The CMIP5 TCR ranges from 1.1 to 2.6 °C, with an

Table 1 Regional climate models used in this analysis

Acronym	Model name	Contributing institution(s)	Major reference(s)
1 CanRCM4	Canadian Regional Climate Model version 4	Canadian Centre for Climate Modelling and Analysis (CCCma)	Scinocca et al. 2016
2 HIRHAM5	High-Resolution Limited Area Model with ECHAM physics, version 5	Danish Meteorological Institute (DMI)	Christensen et al. 2007
3 OCRM5	Canadian Regional Climate Model (CRCM) version 5	Ouranos	Zadra et al. 2008 ; Martynov et al. 2013 ; Šeparović et al. 2013
4 QCRM5	Canadian Regional Climate Model (CRCM) version 5	Université du Québec à Montréal (UQAM)	Zadra et al. 2008 ; Martynov et al. 2013 ; Šeparović et al. 2013
5 RCA4	Rosby Centre regional atmospheric model version 4	Swedish Meteorological and Hydrological Institute (SMHI)	Samuelsson et al. 2011
6 RegCM4	Regional Climate Model version 4	Iowa State University and the National Center for Atmospheric Research (NCAR)	Giorgi and Anyah 2012
7 WRF	Weather Research and Forecasting model	University of Arizona and NCAR	Skamarock et al. 2005






























ensemble mean of 1.8 °C, and the ECS ranges from 2.1 to 4.7 °C, with an ensemble mean of 3.2 °C, similar to that of CMIP3 (Flato et al. [2014](#)). In the GCMs downscaled in NA-CORDEX, the TCR (ECS) ranges from 1.3 °C (2.4 °C) to 2.5 °C (4.6 °C), and the average across the 27 NA-CORDEX simulations in Table [3](#) is 2.0 °C (3.5 °C).

The RCM simulations were completed across an approximately 150-year timeslice, from about 1950 to 2100 (start and end years vary some by simulation). Full RCM configurations are available on the NA-CORDEX website (<https://na-cordex.org/rcm-characteristics>). Note that there are two slightly different configurations of the CRCM5 contributed by two different institutions (Table [1](#)). When discussed collectively, when their results are similar, we will refer to the OCRM5 and the QCRM5 as just the CRCM5. Similarly, when referring to the MPI-ESM-LR and the MPI-ESM-MR GCMs collectively, we will refer to just the MPI-ESM.

Table 2 Dynamically downscaled CMIP5 GCMs. The global change column provides the global average, annual mean temperature change from 1951–1999 to 2051–2099

Model	Modeling center	Atmosphere resolution (latitude × longitude)	ECS (°C)	TCR (°C)	Global change (°C)
1 GFDL-ESM2M	National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory	2.0225° × 2.5°	2.4	1.3	2.4
2 EC-EARTH	Swedish Meteorological and Hydrological Institute	1.1215° × 1.1125°	~3.3	2	3.1
3 MPI-ESM-MR	Max Planck Institute for Meteorology	1.8653° × 1.875°	3.4	2	3.2
4 MPI-ESM-LR	Max Planck Institute for Meteorology	1.8653° × 1.875°	3.6	2	3.2
5 CNRM-CM5	Centre National de Recherches Meteorologiques	1.4008° × 1.40625°	3.3	2.1	3.0
6 CanESM2	Canadian Centre for Climate	2.79° × 2.81°	3.7	2.4	4.1
7 HadGEM2-ES	Met Office Hadley Centre	1.25° × 1.875°	4.6	2.5	4.1

Table 3 Full list of simulations, ordered from top-to-bottom first by TCR, then within TCR by ECS, then RCM name, and then by resolution. Horizontal dividing lines denote different TCRs (solid) and within a given TCR, ECS (dashed lines), except within the Ensemble Means, which are grouped together. A different color is assigned for each RCM and resolution. Color and order are used in later box-and-whisker plots

RCM+GCM	Resolution (km)	ECS (°C)	TCR (°C)
 OCRCM5+GFDL-ESM2M	25	2.4	1.3
 RegCM4+GFDL-ESM2M	25	2.4	1.3
 RegCM4+GFDL-ESM2M	50	2.4	1.3
 WRF+GFDL-ESM2M	25	2.4	1.3
 WRF+GFDL-ESM2M	50	2.4	1.3
 HIRHAM5+EC-EARTH	50	3.3	2
 RCA4+EC-EARTH	50	3.3	2
 QCRCM5+MPI-ESM-MR	25	3.4	2
 QCRCM5+MPI-ESM-MR	50	3.4	2
 OCRCM5+MPI-ESM-LR	25	3.6	2
 QCRCM5+MPI-ESM-LR	25	3.6	2
 QCRCM5+MPI-ESM-LR	50	3.6	2
 RegCM4+MPI-ESM-LR	25	3.6	2
 RegCM4+MPI-ESM-LR	50	3.6	2
 WRF+MPI-ESM-LR	25	3.6	2
 WRF+MPI-ESM-LR	50	3.6	2
 Ensemble Mean	25	3.47	2.01
 Ensemble Mean	50	3.53	2.06
 OCRCM5+CNRM-CM5	25	3.3	2.1
 CanRCM4+CanESM2	25	3.7	2.4
 CanRCM4+CanESM2	50	3.7	2.4
 OCRCM5+CanESM2	25	3.7	2.4
 QCRCM5+CanESM2	25	3.7	2.4
 QCRCM5+CanESM2	50	3.7	2.4
 RCA4+CanESM2	50	3.7	2.4
 RegCM4+HadGEM2-ES	25	4.6	2.5
 RegCM4+HadGEM2-ES	50	4.6	2.5
 WRF+HadGEM2-ES	25	4.6	2.5
 WRF+HadGEM2-ES	50	4.6	2.5

2.1.2 NARCCAP

For comparative purposes, we also briefly examine the simulations from NARCCAP (Mearns et al. 2007, 2009), the precursor to NA-CORDEX. These include simulations by six different

RCMs forced by four different CMIP3-era GCMs. Simulations are approximately 30 years long, and the future, mid-century period of simulation uses the A2 SRES scenario (Nakićenović et al. 2000). Of the four GCMs used in NARCCAP, GFDL-CM2.1, HadCM3, CCSM3, and CGCM3.1, the TCR (ECS) ranged from 1.5 to 2.0 °C (2.7 to 3.4 °C). In NARCCAP, each RCM systematically downscaled two of the GCMs for a total of 12 simulations. Additional details can be found in Mearns et al. (2012).

2.2 Methods

In this analysis, we focus on broad timescale annual mean changes, but also include seasonal changes for December–February (DJF, winter), March–May (MAM, spring), June–August (JJA, summer), and September–November (SON, autumn). Mean changes are defined as being from the historical period of 1951–1999 to the future period of 2051–2099. Not all simulations produced years 1950 or 2100, hence the odd start and end years for the analysis. This approximately 50-year period is used for averaging so to better avoid internal variability signals, and because it is more relevant than shorter periods given the timescale over which the feedbacks encompassed by climate sensitivity act. These include feedbacks related to water vapor, clouds, lapse-rate, ice and albedo, and the carbon cycle.

While domain averages are taken over the largest region common to all of the RCMs as defined by latitude/longitude corners, the analysis is completed using the native RCM grids/projections to avoid errors caused by interpolation, particularly in areas of complex orography when examining grid-box level projections across regions; therefore, there are some slight differences in analysis regions. The GCM analysis domains are set using the same latitude/longitude corners, but to provide a better match to the RCM analysis domain given the very different map projections and grids between the RCMs and GCMs, these corners are connected using bounds that follow great circle arcs instead of strict lines of latitude/longitude. Ensemble means for the 25 km and 50 km simulations are produced using the data in the public NA-CORDEX archive that have been interpolated to a common quarter/half-degree latitude/longitude grid, respectively. The GCMs were interpolated to a $1^\circ \times 1^\circ$ latitude \times longitude grid for ensemble averaging. Area averages are grid-cell area-weighted.

For a brief comparison of the NA-CORDEX simulations with those from NARCCAP, the same analysis region is used, but the analysis time period is adjusted to those years available from all of the NARCCAP simulations, namely, 1971–1998 and 2041–2068.

Part of the analysis is completed over sub-regions of North America, as defined in Fig. 1. For more information on these regions, see Bukovsky (2011). Analysis using these regions is only completed for the RCM simulations and not the driving GCMs, as the GCMs are too coarse in resolution. The regional analysis uses box-and-whisker plots that represent values across all of the grid-boxes in a region, where the box ends are defined as the quartiles, the horizontal line in the box is the median, and the whiskers are 3/2 times the interquartile range. As the regions do vary in size, variability in the box-and-whisker plots across regions is likely affected by the number of grid boxes within a region, as well as the amount of orographic variability within a region and the differences in the north-south or east-west extent represented.

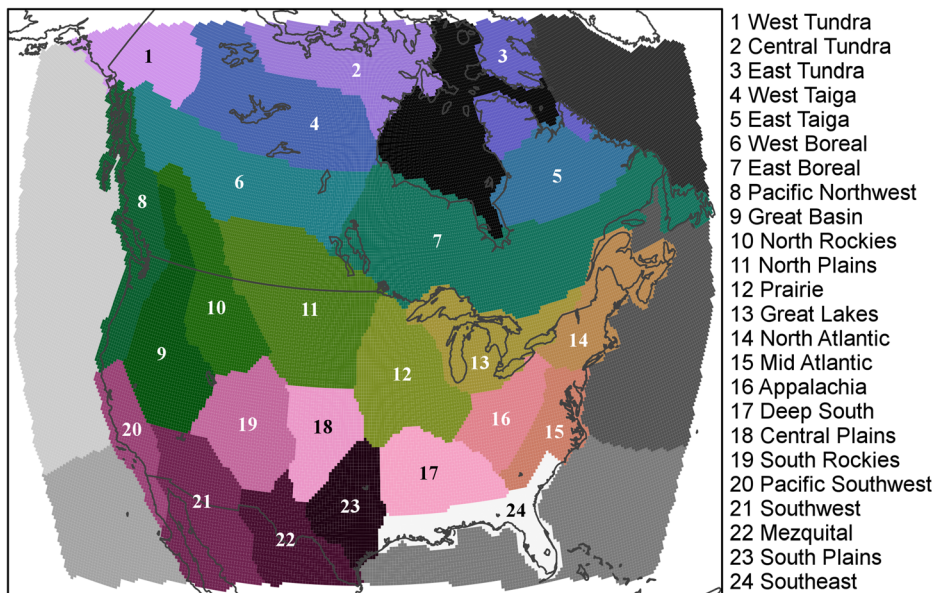


Fig. 1 Regions used in this study

3 Results

3.1 Near-surface temperature

Annually, domain-mean temperature projections from the last half of the twentieth century to the last half of the twenty-first century range from about 2.8 to 5.6 °C in the RCMs and 3.0 to 5.8 °C in the driving GCMs (Fig. 2). These broad changes do vary some seasonally, ranging from 2.6–5.2 °C (2.6–5.0 °C) in the summer to 3.2–6.8 °C (3.6–7.1 °C) in the winter in the RCMs (driving GCMs). There is very little difference between the two resolutions of RCM simulations at these broad space and time scales regardless of season. Consistent with many previous projections of North American temperature, warming is greater in the north than in the south, particularly in the annual mean and in winter, and to some extent in the shoulder seasons (Figs. 3 and 4a; Supplementary Figs. S3–S10). In summer, warming is often greatest over interior western North America, sometimes in conjunction with high warming in the Arctic. The pattern of large-scale seasonal change across the domain is also broadly similar between most RCM simulations and their driving GCMs. Additionally, the ensemble spread in projected warming in any given region generally increases from warmer to cooler regional climates, regardless of season (Figs. 5; Supplementary Figs. S11–S14).

It is clear from Fig. 2 that spanning GCM climate sensitivity in a regional model ensemble is important for capturing that uncertainty and for expanding the ensemble spread in temperature in a representative manner, as the projections across the domain from the RCMs are strongly related to driving GCM TCR. Temperature change is about 1.3 to 2.1 °C per degree of TCR across all seasons in the RCMs and about 2.0 to 2.7 °C per degree of TCR in their driving GCMs, with the greatest rates of change with TCR in winter. The slightly greater rate of warming per degree of TCR in the GCMs is largely due to the HadGEM2-ES consistently projecting somewhat larger increases in domain-mean temperature than its child RCMs, which

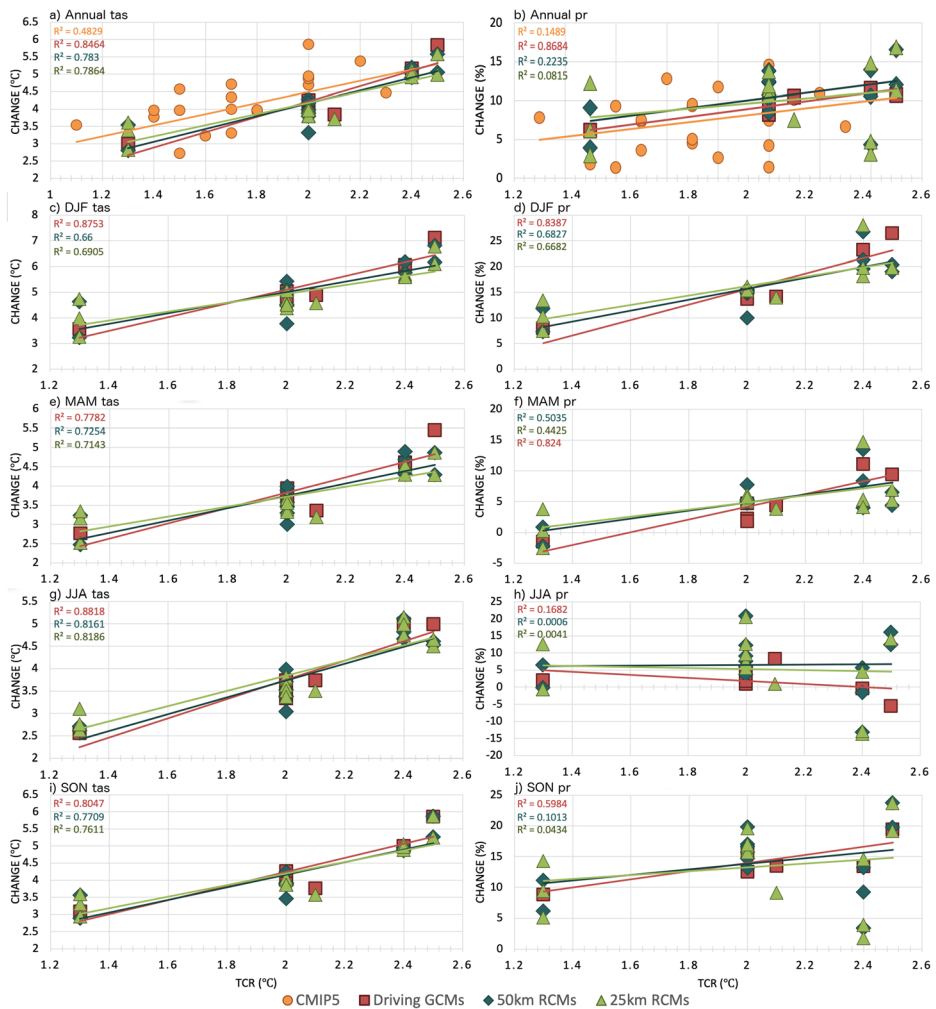


Fig. 2 1951–1999 versus 2051–2099 change in temperature (tas, left column, °C) and percent change in precipitation (pr, right column, %) over the NA-CORDEX domain (illustrated in Figs. 3 and 4) across the year (ANN) and the four seasons (DJF, MAM, JJA, SON) versus TCR (°C), for the 25-km and 50-km NA-CORDEX RCMs, their driving GCMs, and in panels **a** and **b** only, a 28-member CMIP5 ensemble (including the driving GCMs)

may be due to the greater increases in temperature projected in the Arctic in the GCM (c.f. Figs. 3 and 4).

From Fig. 2a, it also appears that, coincidentally, the GCMs downscaled from the CMIP5 set may be on the slightly cooler side of the full range of possible North American warming at any given TCR range. The downscaled GCMs do, however, represent nearly the full range of possible temperature responses across CMIP5. And, also coincidentally, the smaller set of downscaled GCMs have projections for North American annual temperature change that correlate more closely with TCR than the larger CMIP5 ensemble. The coefficient of determination (R^2) value for the full set of 28 CMIP5 simulations in Fig. 2a is on par with that found

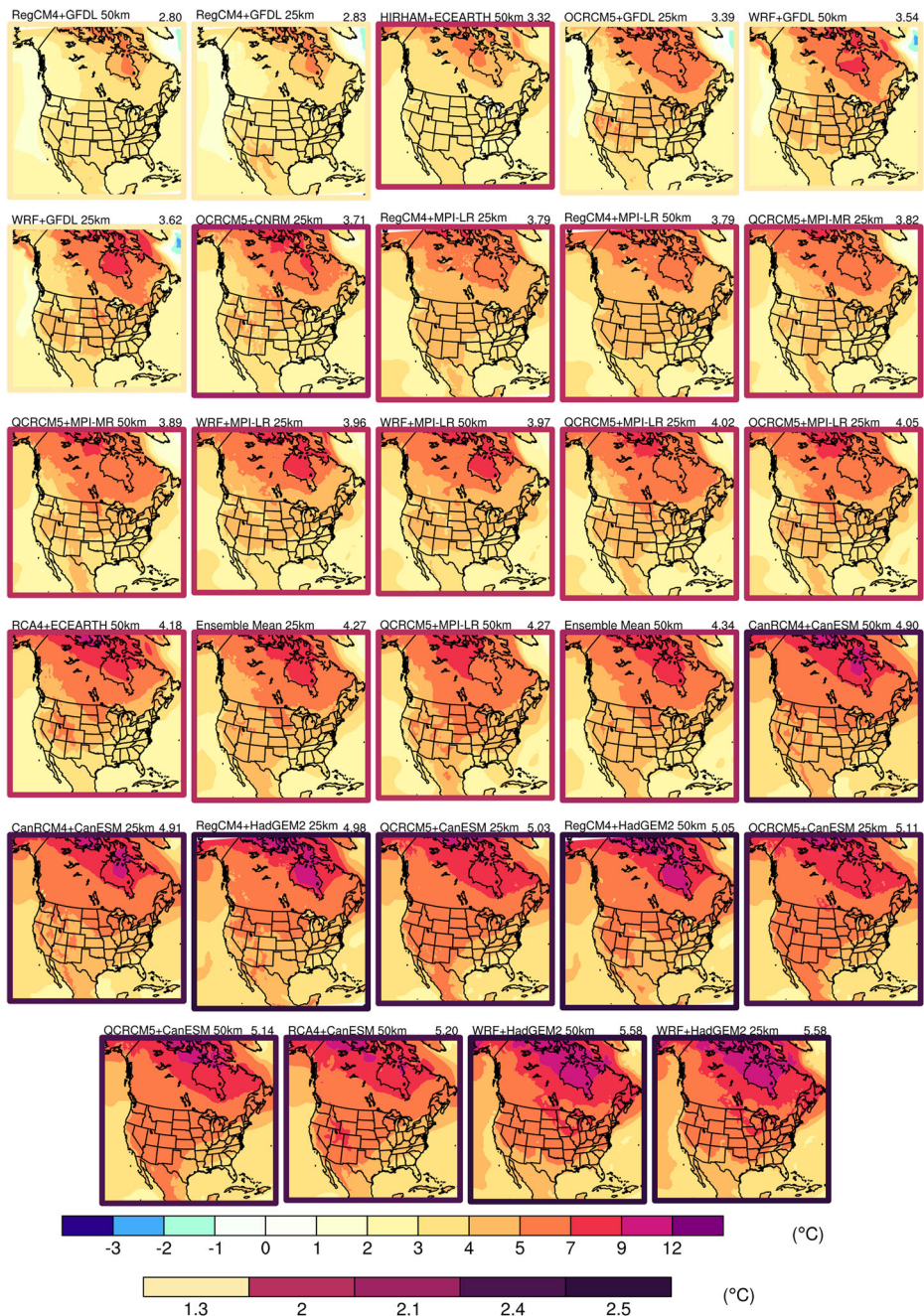


Fig. 3 1951–1999 versus 2051–2099 annual mean change in temperature (top label bar, °C) from the RCM simulations. Panel borders are shaded given the TCR of the driving GCM (bottom label bar, °C). Panels are ordered from left to right and top to bottom by the degree of domain-mean change (given at the upper right of each panel)

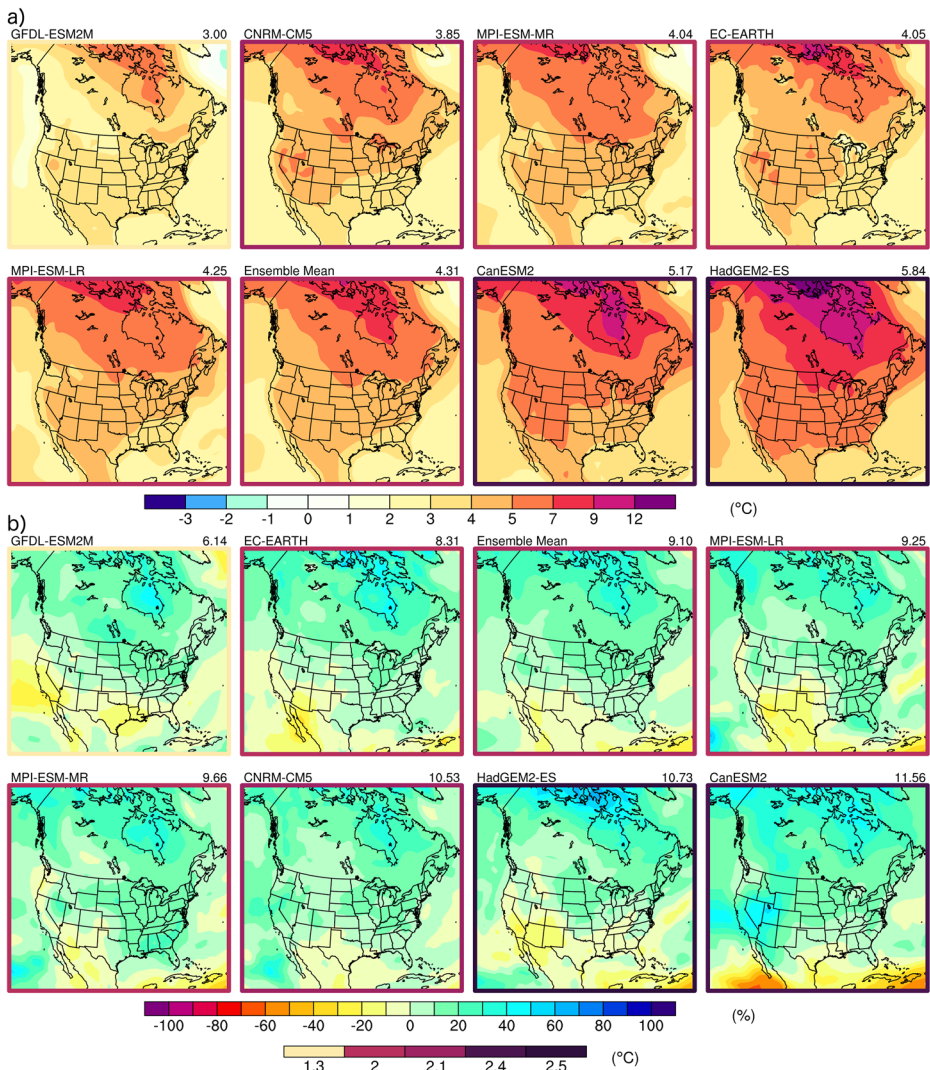


Fig. 4 From the driving GCMs, 1951–1999 versus 2051–2099, **a** annual mean change in temperature (top two rows, °C) and **b** percent change in precipitation (bottom two rows, %). Panel borders are shaded given the TCR of the driving GCM (bottom label bar, °C). Panels are ordered from left to right and top to bottom by the degree of domain-mean change (given at the upper right of each panel)

in Grose et al. (2018) for a 24-member CMIP5, RCP8.5 ensemble over North America (the CMIP5 simulations used here are listed in Supplementary Table S1). Moreover, Grose et al. (2018) found that ECS correlated better with CMIP5 temperature change globally and over North America than TCR, an unexpected result as the analysis timeframe suggested that TCR would be the more relevant metric. However, in the downscaled subset of CMIP5 runs, the temperature change correlations with climate sensitivity are similar for both TCR and ECS. The R^2 values are slightly higher with driving GCMs (by about 0.06) and slightly lower in the 25 km and 50 km RCM sets (by about 0.08 or 0.11, respectively) using ECS compared with

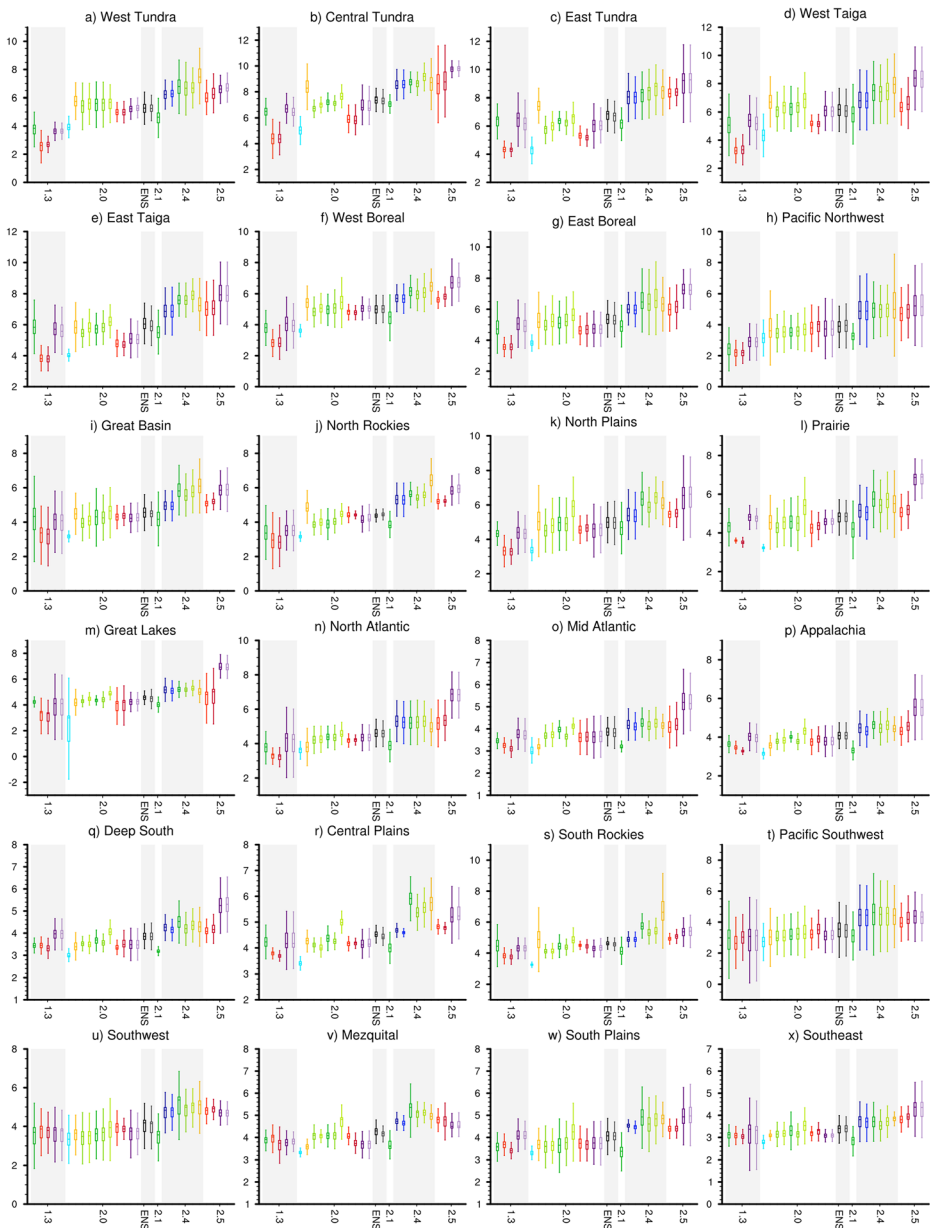


Fig. 5 1951–1999 versus 2051–2099 regional, annual mean change in temperature (y-axis, °C) versus driving GCM TCR (x-axis, °C, groupings by TCR are indicated by alternating gray and white background shading, with the ensemble means in their own group indicated by “ENS”). Each box-and-whisker represents the projection from every grid box in a given region for a different simulation (colored by RCM and resolution, as defined in Table 3)

those given in Fig. 2a using TCR (Supplementary Fig. S2). The better fit of the RCM projected annual mean change with TCR appears to be largely due to the warmer high TCR but mid-

range ECS CanESM2-driven projections relating better to a high TCR than a mid-range ECS over this timeframe.

Overall, RCM temperature projections cluster together like the TCR values in the ensemble, with general low-, mid-, and high-range projections and values. This is generally confirmed in spatial maps of the mean temperature change from all ensemble members, strategically arranged by the degree of change with panel borders colored by TCR, in Figs. 3 and 4a for annual mean change and seasonally in Supplementary Figs. S3–S10. Annual mean temperature changes projected by the lowest TCR GCM, the GFDL-ESM2M, and child RCM simulations, often have the lowest overall temperature increases. However, while the projections from RegCM4+GFDL-ESM2M simulations closely resemble their parent GCM across the domain, the OCRM5 and WRF simulations driven by the GFDL-ESM2M produce more warming over the center of the continent and Arctic compared with the GCM and RegCM4, placing them at the warm end of the low TCR simulations. In winter, the WRF+GFDL-ESM2M simulations in particular are considerably warmer as well, and so much so that they are in the mix with the mid-range TCR simulations (Supplementary Fig. S3). The same is true in the OCRM5 in spring and autumn, but not true in summer (Supplementary Figs. S5, S7, and S9). The HIRHAM5+EC-EARTH simulation produces less annual mean warming by around a degree in many places compared with the corresponding GCM simulations or the RCA4+EC-EARTH simulation, making it the coolest mid-range TCR projection, and comparable with the GFDL-ESM2M-driven simulations in magnitude. While this could be due to the use of different EC-EARTH ensemble members, those differences are small; hence, it is more likely due to the differences in the RCMs (Supplementary Fig. S1).

In the mid-range TCR simulations, the annual mean change in OCRM5+CNRM-CM5 and the GCM itself is slightly less than that in the various MPI-ESM simulations, despite a slightly higher TCR (but lower ECS). This appears to be from less warming in the southern part of the continent. Additionally, the multiple MPI-ESM downscaled simulations (9 total from 4 RCMs) increase the range in the projections over the two GCMs alone by only a few tenths of a degree.

In the high-end TCR simulations, those driven by the CanESM2 and HadGEM2-ES, the additional warming is clearly spread across the domain and not limited to any one region (Figs. 3 and 4a). A notable difference occurs in the OCRM5 simulations versus their CanESM2 driver, as the RCMs spread a high degree of warming further south, projecting more warming than their corresponding GCM over Mexico.

All ensemble mean temperature projections (RCM or GCM) are similar to mid-range TCR simulations, though situated at the high end of the domain-mean change spectrum relative to the other mid-range TCR simulations.

As the RegCM4 and WRF simulations share drivers across the low, mid, and high TCR GCMs, they provide a good sub-sample for intercomparison. Annually, and in almost all seasons (Figs. 3 and 4a; Supplementary Figs. S3–S10), these simulations fully span the NA-CORDEX ensemble spread, with the RegCM4+GFDL-ESM2M always providing the coolest projections and the WRF+HadGEM2-ES always providing the warmest, except in summer where the OCRM5+CanESM2 is warmest. Domain-mean temperature change in WRF is also always warmer than RegCM4. We suspect that this is at least partly due to differences in sea ice treatment between the simulations, as an early WRF+MPI-ESM-LR simulation accidentally completed without sea ice as a lower boundary condition and, instead with sea-surface temperatures assigned using the skin temperature of the atmosphere as in RegCM4, had a temperature change field that was closer spatially and in the domain-mean to that from RegCM4 (not shown). If it was not for that simulation giving us a clue to the cause of this

consistent difference, it could be due to one of many other differences in the configuration of these RCMs, as they otherwise contain few similarities beyond resolution and domain.

While the temperature projections from a domain-mean perspective increase with increasing TCR, this relationship is more subtle to non-existent in some regions/seasons, while it is quite obvious in others. To demonstrate this, near-surface temperature projections for every region (Fig. 1) and RCM simulation are provided in Fig. 5 for annual mean change and Supplementary Figs. S11–S14 for seasonal mean changes. Overall, greater increases in temperature projections with increasing TCR occur in cooler climates. However, even in warmer climates, there is usually a distinct separation between the warmer projections from the high-end TCR simulations (the CanESM2 and HadGEM2-ES forced simulations) and the rest of the simulations, even if there is no distinct separation between the low- and mid-range TCR simulations. Additionally, the mid-range TCR-like ensemble means are not representative of the range of projections from all of the simulations. While a relationship between regional to local temperature projections and TCR of the driving GCM does exist nearly everywhere, there are often outliers and/or interesting RCM- and/or GCM-related effects that become more obvious regionally. The two EC-EARTH-driven simulations, for example, are often very different from each other, and sometimes the other simulations (e.g., Fig. 5b, s), and not just those with a similar mid-range TCR. Additionally, it is clear here that WRF is not only often warmer than the RegCM4; it often has more intra-region spread as well, which is particularly apparent in winter. In summer, a difference by RCM and GCM is also more apparent than in the other seasons, creating an upward trending waviness in the plots from low-to-high TCR, as both flavors of CRCM5 are warmer than RegCM4 and WRF when forced by either flavor of MPI-ESM, and the CanESM2-driven runs are warmer than the HadGEM2-ES-driven runs in many regions. Some of the other RCM outliers that are region- or season-specific, like the HIRHAM5-EC-EARTH over the Great Lakes in any season (Fig. 5m or Supplementary Figs. S11m–S14m), or WRF in winter, particularly in regions like the Southeast (Supplementary Fig. S11x), should be subject to further scrutiny to determine why the projections are strong outliers before use.

3.2 Precipitation

Annually, domain-mean precipitation projections from the last half of the twentieth century to the last half of the twenty-first century range from about 3.0 to 16.9% in the RCMs and 6.1 to 11.6% in their driving GCMs (Fig. 2b). These continental-scale changes do vary considerably, though, seasonally, ranging from –13.4–21.0% (–5.5–8.4%) in summer to 7.3–28.4% (8.0–26.5%) in winter in the RCMs (driving GCMs), with considerably more variation regionally. Generally, the pattern of precipitation change seen in winter and the shoulder seasons across the continent is reflected in the annual mean, with increases in precipitation projected for Canada and most of the USA, with decreases projected in many simulations for Mexico (Figs. 6, 7, and 4b; Supplementary Figs. S15–S26). In winter and especially spring, there is a general agreement for decreases in precipitation over the Southwest, Mezquital, and nearby Pacific Ocean area (Supplementary Figs. S23u, v, and S15). In winter, all RCM simulations except those driven by the GFDL-ESM2M project an increase in precipitation for the eastern slopes of the larger, resolved mountain ranges in western Canada, with no change to decreases in precipitation projected on the western slopes. The same is true across the Western US in all RCM simulations except those driven by the GFDL-ESM2M and CanESM2, and except over California (Supplementary Fig. S15). This is not clearly represented in the coarser resolution

GCM drivers (Supplementary Fig. S16). In summer, there is consistent inconsistency within regions and across the ensemble in the sign of the precipitation projections (Supplementary Figs. S19, S20, and S25). There is a tendency for drying in the Southwest and in the South Rockies in summer, but this is not projected by all of the simulations, particularly the CanESM-driven simulations, which, like their driving GCM, project an odd, strong increase in precipitation that appears to grow out of the Gulf of California (as also discussed in Colorado-Ruiz et al. 2018). Elsewhere, the CanESM-driven simulations often disagree on the sign of precipitation change, with more widespread drying projected by the CRCM5 than the CanRCM4 simulations or the CanESM itself. Furthermore, the RCMs driven by the HadGEM2-ES project much less widespread drying across the USA than their driving GCM in summer. Overall, as with temperature, there is very little difference between the two resolutions of RCM simulations at the space and time scales examined here, regardless of season.

As with temperature, domain average annual, winter, spring, and autumn precipitation change increases with increasing TCR (Fig. 2), but the relationship in the RCMs is not as strong as it is for temperature, except in winter. In winter, the percent increase in precipitation is about 15.0% per degree of TCR in the driving GCMs and 9.2–10.6% per degree of TCR in the RCMs, with R^2 values on par with those for temperature. Outside of winter, the CRCM5+CanESM2 simulations produce less of a domain-mean precipitation increase in the future, mostly due to strong drying in the Southwestern part of the domain than is present in the CanESM2, but exacerbated by the CRCM5s (Figs. 6 and 4b; Supplementary Figs. S15–S22), likely contributing in part to the lower change per degree of TCR and the lower R^2 values outside of winter in Fig. 2. In comparison, the percent change per degree of TCR in the annual average is 4.4 in the driving GCMs and about 2.8–4.3 in the RCMs.

Given Fig. 2b, the GCMs downscaled in NA-CORDEX cover a range that is representative of the full set of CMIP5 projections. And, as with temperature, the smaller set of downscaled GCMs coincidentally correlates better with TCR than the full set.

In general, the examination of Figs. 7 and 4b and Supplementary Figs. S15–S22 suggests that the relationship between continental precipitation change and TCR in Fig. 2 may be coincidental, as it is difficult to spot any region where the relationship appears to hold. However, at the continental-to-global scale, and given the long-term averages, the strong relationship between larger precipitation increases with increasing TCR/temperature in winter, and the weaker relationship in the shoulder seasons, is likely related to the water-holding capacity of the atmosphere in cold weather being less limited as the temperature warms, particularly at latitudes north of about 40°, which make up more than half of the domain (e.g., Trenberth et al. 2007). Outside of the cold season and at sub-continental scales, changes in numerous other processes like circulation, land-atmosphere coupling, or land-ocean temperature contrast, even at the broad space and time-averaged scales used in Fig. 2, are likely in competition, particularly in summer.

Additionally, as Figs. 6 and 4b and Supplementary Figs. S15–S22 suggest, and as Fig. 7 and Figs. S23–S26 confirm, the change versus TCR relationship breaks down completely at the regional-to-local scale. There is no sub-region over which precipitation change is clearly related to TCR. Too many factors are clearly in competition at local-to-regional scales, even in the poleward regions. The effect of the different RCMs combined with the different GCMs (i.e., model uncertainty) more distinctly increases the projection spread across each region than the different TCR levels themselves.

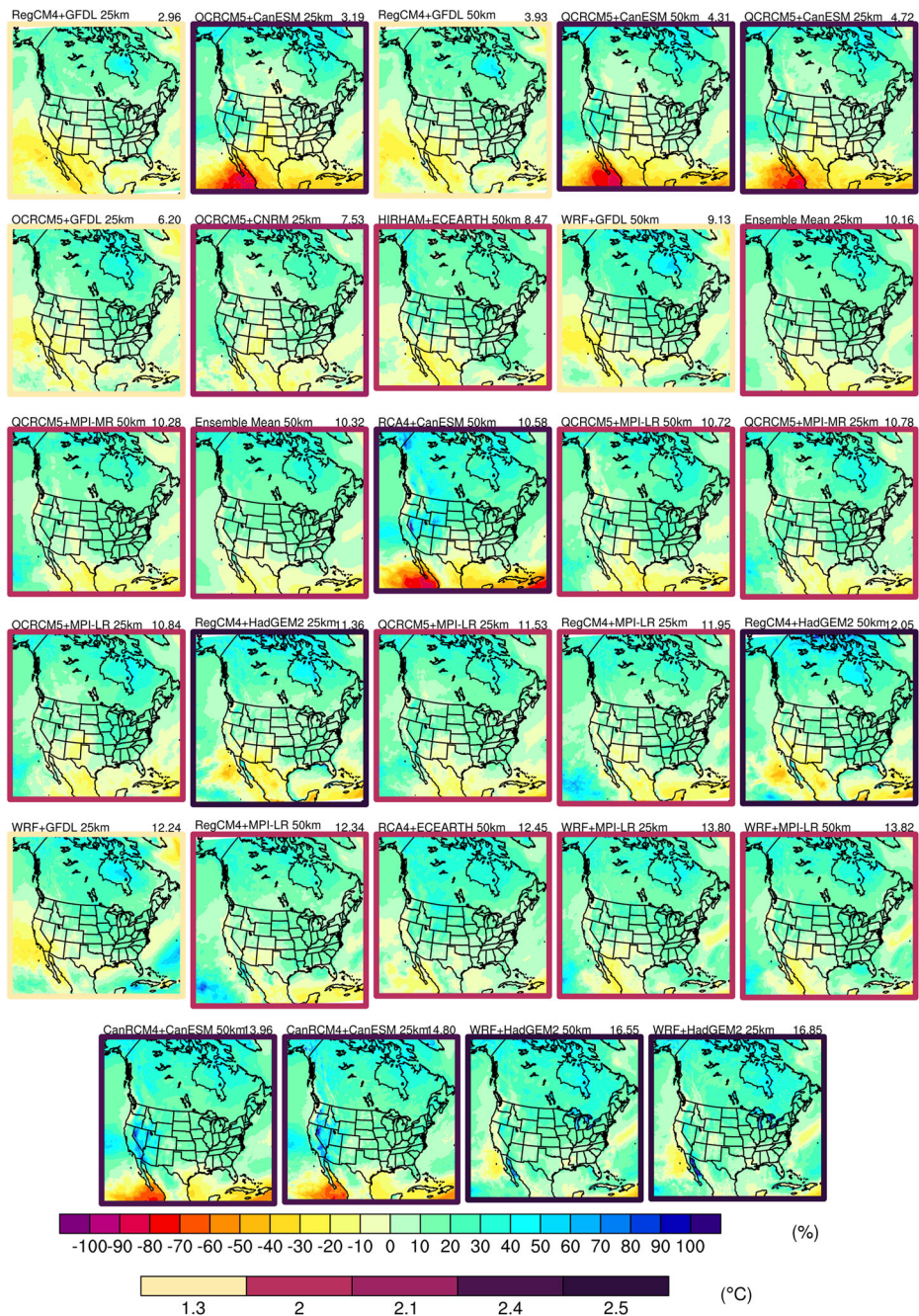


Fig. 6 As in Fig. 3, but for the percent change in annual mean precipitation from the RCMs

The ensemble means in Figs. 4b, 6, and 7 and Supplementary Figs. S15–S26 perform as expected. They generally produce a middle-of-the-road projection regionally or in the full domain-mean, and they diminish any regional maxima/minima projected in the individual simulations.

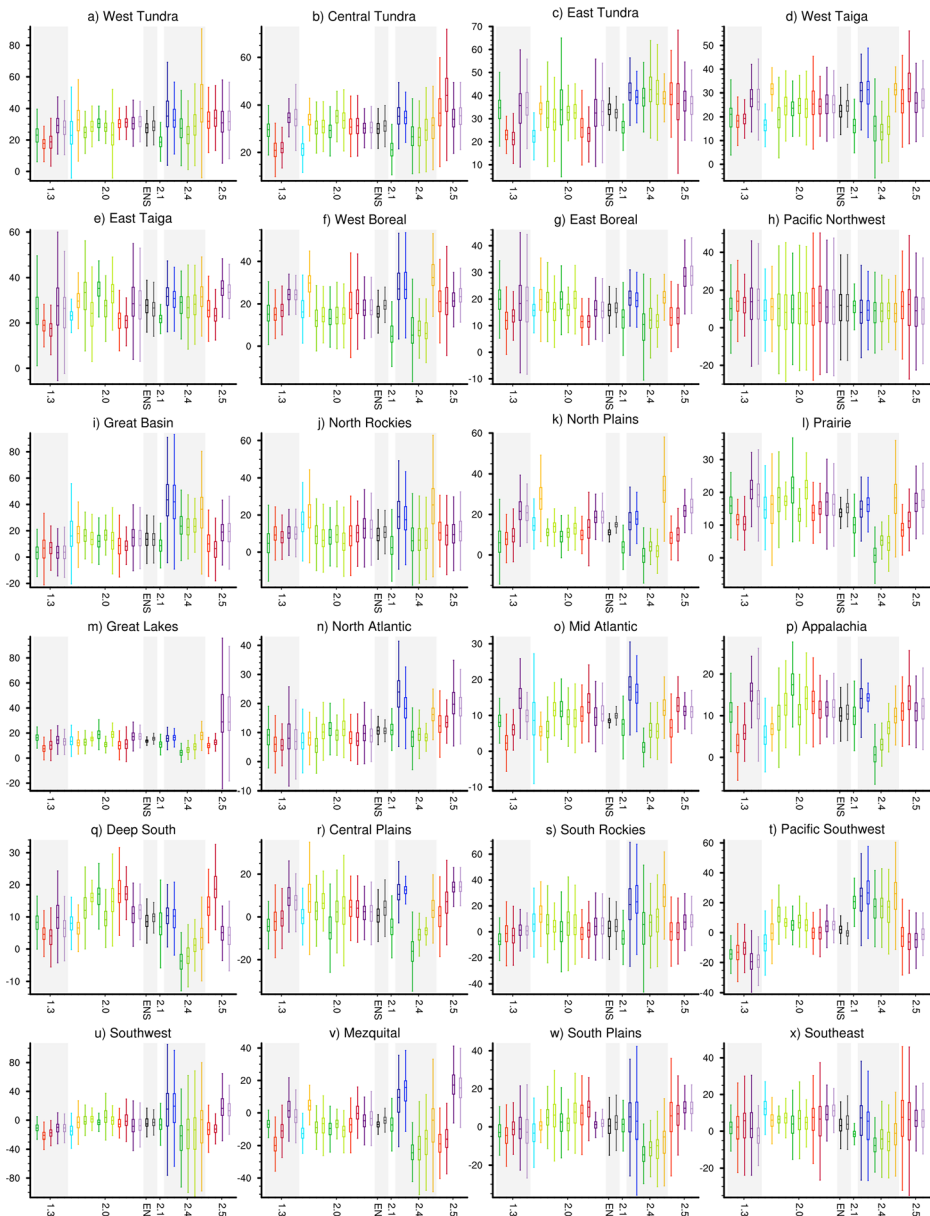


Fig. 7 As in Fig. 5, but for the percent change in annual mean precipitation (y-axis, %)

3.3 NA-CORDEX vs. NARCCAP

For a brief comparison of the projection spread in NA-CORDEX versus that from NARCCAP, annual, domain-mean mid-century projections from the two ensembles are shown in Fig. 8 a and b. While the total number of simulations in each ensemble differs, the narrower range of climate sensitivity sampled across the 12 NARCCAP simulations clearly affects the spread in

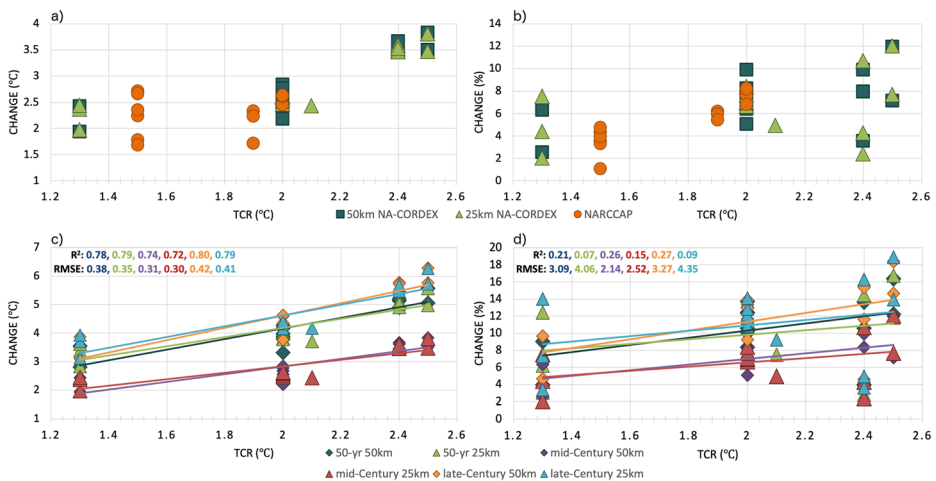


Fig. 8 Top: 1971–1999 versus 2041–2069 annual mean **a** change in temperature (°C) and **b** percent change in precipitation (%) over the full common domain versus TCR (°C) from the NA-CORDEX and NARCCAP RCM simulations. Bottom: comparison of domain-mean, annual **c** change in temperature (°C) and **d** percent change in precipitation (%) projections across different timeslices for the NA-CORDEX RCMs. 50 years (as in Fig. 2): 1951–1999 versus 2051–2099. Mid-century: 1971–1999 versus 2041–2069. Late-century: 1971–1999 versus 2071–2099

their projections. The temperature projection space is greater by about 0.9 °C (or 90%) in the annual mean in the NA-CORDEX ensemble, and this difference is mostly attributable to the addition of the high TCR simulations. In fact, using just 2 RCMs in NA-CORDEX driven by GCMs that span the full range of TCR in CMIP5 provides a greater spread than the 6 RCMs with 4 different GCMs in NARCCAP. The RegCM4+GFDL-ESM2M produces the coolest projection and the WRF+HadGEM2-ES produces the warmest in NA-CORDEX. Similarly, considering just one of those two RCMs at either resolution (RegCM4 or WRF) provides about 0.4–0.6 °C more spread in the annual domain-mean projections than the full NARCCAP ensemble. However, we only mention this to illustrate the effect of climate sensitivity on the ensemble, and we do not advise using only one or two simulations!

Similarly, the spread in the annual mean precipitation projections is greater in NA-CORDEX compared with that in NARCCAP (Fig. 8b), but not to the same extent as with temperature. The NA-CORDEX ensemble projection space is about 2.9% wider though, an increase in spread of about 40% over that from NARCCAP. That spread, again, is mostly attributable to the same 2 RCM simulations (the only two RCMs with simulations that span the full TCR space): RegCM4+GFDL-ESM2M on the low end and WRF+HadGEM2-ES on the high end, although the same spread is almost produced with other RCM+GCM combinations in the case of precipitation.

4 Summary

Temperature and precipitation projections from 27 NA-CORDEX RCM simulations were assessed in the context of the TCR of their driving GCMs. We found that spanning the range of available climate sensitivities in the CMIP5 ensemble is important for producing a representative range of projections in downscaled results. Temperature change does increase with

increasing TCR at a local-to-regional-to-continental scale with increasing fidelity at larger scales, annually and seasonally, in most regions. While precipitation projections do increase in magnitude with increasing TCR annually and in the cold season at a domain-mean scale, this relationship is not maintained at a local-to-regional scale, due to the increasing influence of local-to-regional process changes at those scales. The continental scale relationship between TCR and precipitation agrees with that found in Mauritzen et al. (2017) in the CMIP5 GCMs.

It was also noted that the domain-mean degree of increase in temperature with increasing TCR is similar in the RCMs and their corresponding GCMs. The degree of spread across the domain-mean temperature projections in NA-CORDEX is also very similar to that from their driving GCMs (at about 2.8 °C in the annual mean), but slightly less than the full CMIP5 ensemble (which is about 3.1 °C in the annual mean). The spread in annual domain-mean precipitation projections from NA-CORDEX, however, is greater than that from their driving GCMs (by about 8.5%) and closer to that from the full CMIP5 ensemble but shifted to lower magnitudes of change. Additionally, temperature projections do cluster around the low, mid, and high categories of TCR represented in the NA-CORDEX ensemble. And, the range of spread in the ensemble would be reduced if only considering one category of climate sensitivity, or an ensemble mean. This holds in many regions, not just at the continental scale, and therefore is important to note in choosing simulations for impacts and adaptation studies. This does not, however, apply to precipitation, except in the cold season for the full domain average. However, the ensemble mean does regionally reduce the range of potential changes.

The above conclusions apply even if shorter (e.g., 30-year long) analysis periods or different future timeslices (e.g., mid-twenty-first century or late-twenty-first century) are used. This is summarized in Fig. 8c and d for the RCMs. However, similar spatial projection plots to those contained in this analysis but for the mid-century and late-century periods used in Fig. 8c and d are available for consideration in the NA-CORDEX plot archive (Rendfrey et al. 2018), and regional box-and-whisker plots matching those analyzed herein but for the mid-century and late-century periods used in Fig. 8c and d are available in the Supplementary Material (Figs. S27–S46). While similar when using different timeslices, the degree of increase in temperature change with TCR is slightly greater later in the twenty-first century than in mid-century or in the 50-year mean.

These conclusions are further confirmed by the limited range and clustering of the temperature changes projected by the NARCCAP simulations, which do not sample a broad range of GCM climate sensitivities. There is less spread in annual temperature and precipitation projections from the six different NARCCAP RCMs that use four different GCMs in comparison to just the two NA-CORDEX RCMs that use three GCMs that span low-to-high climate sensitivities. This suggests that sampling across GCM climate sensitivities is very important when creating a representative RCM ensemble. These two RCM examples are not meant to diminish the importance of using a diverse set of RCMs though, as model internal variability becomes more important at smaller spatial scales (Hawkins and Sutton 2009), as suggested herein in the regional projections.

5 Discussion

While the relationship presented between GCM TCR and the RCM projections may not be surprising, we believe this is the first time it has been assessed in an RCM ensemble. We recommend that the sensitivity of RCMs to climate sensitivity be examined in other CORDEX ensembles (e.g., CORDEX-CORE), or in other applicable RCM ensembles, to determine if

there is a generally specific sensitivity to individual RCMs for specific configurations of those RCMs regardless of region. Here, it is interesting that WRF always projects more warming than RegCM4 with the same GCM drivers in a consistent manner, suggesting that a given configuration of an RCM may have a specific, assignable sensitivity as well. However, our sample is not large enough to confirm this. If true, it may be possible to intentionally expand on sampled uncertainty by strategically selecting different RCM+GCM combinations.

Herein, we have also only examined precipitation and temperature projections. But, the relationship between the projection magnitude and climate sensitivity likely applies to other variables. Particularly those that are closely related to temperature, like precipitation intensity or snow, in regions where changes are dominated by temperature change and not precipitation change.

As a caveat to the projection spread in the ensembles examined here, we note that the range of climate sensitivity represented in CMIP5 and therefore in the NA-CORDEX ensemble is less than that judged as “likely” in the 5th IPCC assessment report (IPCC 2013), implying that the range of likely projections may be under-estimated here (Grose et al. 2017). Climate emission/concentration scenario notwithstanding, of course, as it is still likely the most important uncertainty later in the twenty-first century (Hawkins and Sutton 2009).

Finally, in CMIP6, the high-end climate sensitivity in the ensemble has increased outside of the 5th IPCC assessment report’s “likely” range, leading to greater future warming projections in those high-end climate sensitivity simulations (e.g., Gettelman et al. 2019). This has implications for downscaling, as it will similarly increase projections of warming and ensemble spread in any downscaled ensemble that spans the full range of CMIP6 climate sensitivity, among other possible potential effects (e.g., perhaps more unstable simulations towards the end of the twenty-first century), to be discovered in future efforts.

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References

- Bukovsky MS (2011) Masks for the Bukovsky regionalization of North America. www.narccap.ucar.edu/contrib/bukovsky/
- Christensen JH, Christensen OB (2007) A summary of the prudence model projections of changes in European climate by the end of this century. *Clim Chang* 81(1):7–30. <https://doi.org/10.1007/s10584-006-9210-7>
- Christensen OB, Drews M, Christensen JH, Dethloff K, Ketelsen K, Hebestadt I, Rinke A (2007) The HIRHAM regional climate model. Version 5 (beta). Danish Climate Centre, Danish Meteorological Institute. Technical Report, No. 06-17. <http://www.dmi.dk/dmi/tr06-17>
- Colorado-Ruiz G, Cavazos T, Salinas JA, De Grau P, Ayala R (2018) Climate change projections from coupled model intercomparison project phase 5 multi-model weighted ensembles for Mexico, the north American monsoon, and the mid-summer drought region. *Int J Climatol* 38(15):5699–5716. <https://doi.org/10.1002/joc.5773>
- Computational and Information Systems Laboratory (2017) Cheyenne: HPE/SGI ICE XA system. National Center for Atmospheric Research Boulder, CO <https://doi.org/10.5065/D6RX99HX>
- Evans J, Ji F, Lee C, Smith P, Argüeso D, Fita L (2014) Design of a regional climate modelling projection ensemble experiment–NARCLIM. *Geosci Model Dev* 7(2):621–629
- Flato GM, Marotzke J, Abiodun B, Braconnot P, Chou SC, Collens W, Cox P, Driouech F, Emori S, Eyring V, Forest C (2014) Evaluation of climate models. In: *Climate change 2013: the physical science basis. Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, pp. 741–866
- Gettelman A, Hannay C, Bacmeister J, Neale R, Pendergrass A, Danabasoglu G, Lamarque JF, Fasullo J, Bailey D, Lawrence D et al (2019) High climate sensitivity in the community earth system model version 2 (CESM2). *Geophys Res Lett* 46(14):8329–8337. <https://doi.org/10.1029/2019GL083978>
- Giorgi F, Anyah R (2012) Introduction: the road towards RegCM4. *Clim Res* 52:3–6. <https://doi.org/10.3354/cr01089>
- Grose MR, Colman R, Bhend J, Moise AF (2017) Limits to global and Australian temperature change this century based on expert judgment of climate sensitivity. *Clim Dyn* 48(9–10):3325–3339. <https://doi.org/10.1007/s00382-016-3269-2>
- Grose MR, Gregory J, Colman R, Andrews T (2018) What climate sensitivity index is most useful for projections? *Geophys Res Lett* 45(3):1559–1566. <https://doi.org/10.1002/2017GL075742>
- Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. *Bull Am Meteorol Soc* 90(8):1095–1108. <https://doi.org/10.1175/2009bams2607.1>
- IPCC (2013) *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Kamalkar AV (2018) Interpreting results from the NARCCAP and NA-CORDEX ensembles in the context of uncertainty in regional climate change projections. *Bull Am Meteorol Soc* 99(10):2093–2106. <https://doi.org/10.1175/bams-d-17-0127.1>
- Kjellström E, Bärring L, Nikulin G, Nilsson C, Persson G, Strandberg G (2016) Production and use of regional climate model projections – a Swedish perspective on building climate services. *Clim Serv* 2-3:15–29. <https://doi.org/10.1016/j.cliser.2016.06.004>
- Knutti R, Rugenstein MAA, Hegerl GC (2017) Beyond equilibrium climate sensitivity. *Nat Geosci* 10(10):727–736. <https://doi.org/10.1038/ngeo3017>
- Liang XZ, Kunkel KE, Meehl GA, Jones RG, Wang JXL (2008) Regional climate models downscaling analysis of general circulation models present climate biases and propagation into future change projections. *Geophys Res Lett* 35:L08709. <https://doi.org/10.1029/2007GL032849>
- Martynov A, Laprise R, Sushama L, Winger K, Šeparović L, Dugas B (2013) Reanalysis-driven climate simulation over CORDEX North America domain using the Canadian regional climate model, version 5: model performance evaluation. *Clim Dyn* 41(11–12):2973–3005. <https://doi.org/10.1007/s00382-013-1778-9>
- Mauritzen C, Zivkovic T, Veldore V (2017) On the relationship between climate sensitivity and modelling uncertainty. *Tellus A Dyn Meteorol Oceanogr* 69(1):1327765. <https://doi.org/10.1080/16000870.2017.1327765>

- Mearns LO et al. (2007) The North American Regional Climate Change Assessment Program dataset. National Center for Atmospheric Research Climate Data Gateway data portal, Boulder, CO <https://doi.org/10.5065/D6RN35ST>
- Mearns LO, Gutowski WJ, Jones R, Leung LY, McGinnis S, Nunes AMB, Qian Y (2009) A regional climate change assessment program for North America. *EOS* 90:311. <https://doi.org/10.1029/2009EO360002>
- Mearns L, Arritt R, Biner S, Bukovsky MS, McGinnis S, Sain S, Caya D, Correia JJ, Flory D, Gutowski W, Takle ES, Jones R, Leung LR, Moufouma-Okia W, McDaniel L, Nunes A, Qian Y, Roads J, Sloan L, Snyder M (2012) The North American Regional Climate Change Assessment Program: overview of phase I results. *Bull Am Meteorol Soc* 93:1337–1362. <https://doi.org/10.1175/BAMS-D-11-00223.1>
- Mearns LO, Leung LR, Bukovsky MS, McGinnis S, Biner S, Caya D, Arritt RW, Gutowski W, Takle ES, Snyder M, Jones RG, Nunes AMB, Tucker S, Herzmann D, McDaniel L, Sloan L (2013) Climate change projections of the North American Regional Climate Change Assessment Program (NARCCAP). *Clim Chang* 120:965–975. <https://doi.org/10.1007/s10584-013-0831-3>
- Mearns LO, Lettenmaier DP, McGinnis S (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. <https://doi.org/10.1007/s40641-015-0004-8>
- Mearns LO et al. (2017) The NA-CORDEX dataset, version 1.0. NCAR Climate Data Gateway, Boulder, CO. <https://doi.org/10.5065/D6SJ1JCH>
- Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T et al (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463(7282):747–756. <https://doi.org/10.1038/nature08823>
- Nakićenović N et al (2000) Special report on emissions scenarios. Cambridge University Press, Cambridge
- Rendfrey T, Bukovsky MS, McGinnis S (2018) NA-CORDEX visualization collection. UCAR/NCAR. <https://doi.org/10.5065/90ZF-H771>
- Samuelsson P, Jones CG, Willén U, Ullerstig A, Gollvik S, Hansson U, Jansson E, Kjellström C, Nikulin G, Wyser K (2011) The Rossby Centre regional climate model RCA3: model description and performance. *Tellus A Dyn Meteorol Oceanogr* 63(1):4–23. <https://doi.org/10.1111/j.1600-0870.2010.00478.x>
- Scinocca JF, Kharin VV, Jiao Y, Qian MW, Lazare M, Solheim L, Flato GM, Biner S, Desgagne M, Dugas B (2016) Coordinated global and regional climate modeling. *J Clim* 29(1):17–35. <https://doi.org/10.1175/JCLI-D-15-0161.1>
- Šeparović L, Alexandru A, Laprise R, Martynov A, Sushama L, Winger K, Tete K, Valin M (2013) Present climate and climate change over North America as simulated by the fifth-generation Canadian regional climate model. *Clim Dyn* 41(11–12):3167–3201. <https://doi.org/10.1007/s00382-013-1737-5>
- Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG (2005) A description of the advanced research WRF version 2. NCAR Tech. Note NCAR/TN-468+STR
- Sutton R, Suckling E, Hawkins E (2015) What does global mean temperature tell us about local climate? *Phil Trans R Soc A* 373(2054):20140426. <https://doi.org/10.1098/rsta.2014.0426>
- The NCAR Command Language (2019) version 6.6.2. UCAR/NCAR/CISL/TDD Boulder, CO. <https://doi.org/10.5065/D6WD3XH5>
- Trenberth KE, Jones PD, Ambenje P, Bojariu R, Eastering D, Tank AK, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate change 2007: the physical science basis. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Zadra A, Caya D, Côté J, Dugas B, Jones C, Laprise R, Winger K, Caron LP (2008) The next Canadian regional climate model. *Phys Can* 64(2):75–83