On the potential impact of a half-degree warming on cold and warm temperature extremes in mid-latitude North America

Monika J Barcikowska1, Ángel G Muñoz2, Scott J Weaver1, Simone Russo1 and Michael Wehner3
1 Environmental Defense Fund, New York City, United States of America
2 International Research Institute for Climate and Society (IRI), The Earth Institute at Columbia University, Palisades, New York, United States of America
3 Department of Atmospheric and Oceanic Science, University of Maryland, College Park, College Park, MD, United States of America
4 Institute for Environmental Protection and Research (ISPRA), Rome, Italy
5 Lawrence Berkeley National Laboratory, Berkeley, CA, United States of America
E-mail: mjbarcikowska@gmail.com
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Abstract
This study focuses on potential impacts of climate change on the early spring (March–April) temperature and its extremes in the mid-latitudes of North America, discriminated between the 1.5 °C and 2 °C levels of global warming, as projected by a suit of numerical experiments. The results suggest relatively mild seasonal average warming (0.25 °C–1.5 °C), but also an intensification of both warm and cold temperature extremes. The derived changes feature much stronger warming over the West of the United States and weak to no warming to the East, which is congruent with the ventilating effect of the intensified northerly wind over central Canada and the East of the United States. The intensified northerly component of the mid-latitude jet is likely a contributing factor to the derived increased seasonal variability of March–April temperatures over parts of Manitoba and Ontario in Canada, and the Midwest of the United States. The projected changes in temperature extremes agree to some extent with the previous studies: warm extremes intensify especially over southern mid-latitudes, while cold extremes are weakening over the north mid- to high-latitudes. However, high-resolution simulations with the Community Atmospheric Model 5 (CAM5) indicate much sharper spatial gradients, which translate into higher magnitudes and also more complex patterns of changes. Particularly, cold extremes feature not only reductions north of ~45° N latitudes, but also a very strong intensification of cold extremes (by ~4 °C for 20 year return values) in the band 25°–45° N, centered in the Midwest of the United States. While general warming and intensification of the warm extremes may accelerate the arrival of early spring, the intensifying cold extremes may increase the risk of early spring frost damage, and hence may yield a profound impact on the regional agriculture of North America. Combined with reliable information on expected temperature variability at interannual-to-decadal timescales, the background longer-term projections can help inform decision makers in the food security sector.

1. Introduction
Climate variability and change cause profound socio-economic impact, especially when expressed in the form of weather extremes. For example, spring frosts, as experienced in the United States in April 2012 and Europe in April 2016 and 2017, pose a considerable risk to agricultural production, with the potential to cause significant damages to agricultural yields. All three events were preceded with unusually warm temperatures in late winter (Karl et al 2012). This led to accelerated snowmelt and created a ‘false spring’ effect, triggering some plants to blossom too early and leaving them vulnerable to the following frosts (Ault et al 2013). The 2012 frost damage heavily impacted farmers across the Northeast and upper Midwest.
regions of the US, causing in some instances causing total loss (https://usda.gov/media/blog/2016/05/16/spring-climate-trends-changing-northeast; https://freshfruitportal.com/news/2017/08/28/michigan-apple-forecasts-reflects-spring-frost-damage/).

Consistent with the observations, projected future warming is expected to lead to an increase in daily minimum temperatures (Screen 2014), causing an earlier onset of meteorological spring and an earlier bloom for some plants (Feng and Hu 2004, Kunkel et al 2004, Peterson and Abatzoglou 2014, Barichivich et al 2015), prolonging their growing (Christidis et al 2007, McCabe et al 2015). The perspective of increased growth may seem profitable for regional agriculture, thereby tempting farmers to plant earlier or switch to alternative species. However, the negative consequences of an early spring arrival is that an earlier start of growth for plants exposes them to increased frost risk (Bigler and Bugmann 2018, Sgubin et al 2018, Vitasse et al 2018). This was underlined by a probabilistic study of Rigby and Porporato (2008), showing that the risk of spring frost damage to vegetation is equally sensitive to increases in daily temperature variance (which increases frost risk) and to increases in mean temperature (which reduces frost risk).

A remarkable number of the cold spells, occurring recently in mid-latitudes of the North Hemisphere, strengthened the general notion of a future tendency towards more volatile weather as a consequence of interacting signals of anthropogenic warming and natural climate variability. On the contrary, recent research suggests reduced daily temperature variability, observed over most of the northern mid-to-high-latitudes during autumn, winter and spring season (Screen 2014). The author has also shown that, based on CMIP5 models, this tendency could continue in the future.

These two contrasting views on the future weather variability are tied to different mechanisms. The former view relates to the possible link between Arctic amplification and increased winniness of the polar jet stream, implying an intensification of cold weather extremes in the Northern Hemisphere mid-latitudes (Francis and Vavrus 2012). The latter view suggests thermodynamic effects of Arctic Amplification (Screen 2014): the mechanism behind this link is that Arctic Amplification causes high-latitude northerly winds warming much faster than the southerlies, and hence leads to decreased variance of temperature as well as the warming of the cold extremes, especially at the northern mid-latitudes and high-latitudes.

The reduced variance and amplified warming of cold extremes, especially at high latitudes, has been suggested in previous studies using CMIP3 (Kharin et al 2007, Ylhäis and Räisänen 2014), and CMIP5 climate model simulations (Gregory and Mitchell 1995, Collins et al 2013, Kharin et al 2013). Nevertheless, these studies highlight that the uncertainty of cold extremes simulated in the present climate, as well as the inter-model spread in the future projections, is larger than for warm extremes. This is mainly due to poor performance of GCM models in simulating the characteristics of meteorological blocking, (e.g. underestimated frequency and persistence of blocking events, as shown in Anstey et al 2013 and Masato et al 2013) although with improvements when simulated at higher horizontal resolution (~0.25°–0.5°, Schiemann et al 2017). Increased horizontal resolution has also been shown to improve representation of mid-latitude atmospheric circulation, and hence improved climatology of the regional weather and its extremes during cool season (Kitoh and Endo 2016, Barckwoska et al 2018a, 2018b), although some studies (Muñoz et al 2017) do not find a clear improvement in the representation of the atmospheric fields when horizontal resolution is increased. Although the reduced variance of daily temperatures is projected by global climate models during autumn, winter and spring, the amplification of warming cold extremes has been shown for the autumn and winter season. There is a general lack of studies on future projections of temperature extremes in spring.

Meteorological blocking is a predominant weather regime prompting cold conditions in winter and spring (Rex 1950, Carrera et al 2004, Favre and Gershunov 2006, Sillmann et al 2011, Pfahl and Wernli 2012, Brunner et al 2016, Whan et al 2016), as it promotes advection of cold air from polar regions. For example, Carrera et al (2004) and Whan et al (2016) have documented a relationship between the blocking regime over the eastern North Pacific and a cold mean and extremes over the United States. Strong and McCabe (2017) found that the observed timing of the last spring frost over the United States is dynamically linked to a ridge-trough pattern, (i.e. a blocking high system over the eastern North Pacific and a trough over the eastern United States). Croc-Maspoli et al (2007) have documented a decline in winter blocking but an increase in spring blocking, observed over the recent decades. There is a general lack of studies on future projections of blocking activity in spring.

In this research we focus on the future changes projected for early spring in mid-latitudes of North America, using simulations with the Community Atmospheric Model version 5 (CAM5) provided at 0.25° horizontal resolution. Special attention is paid to the changes in warm and cold extremes, due to their significant impact on regional agriculture. The simulations are a part of the Half a degree Additional warming, Prognosis, and Projected Impacts (HAPPI, Mitchell et al 2017) project, designed specifically to address the differential climate response between the Paris Agreement Temperature Levels. Additionally, present climate runs of CAM5 are available at different horizontal resolution, which allows for testing the
sensitivity of the simulated large-scale circulation to the horizontal resolution.

The structure of the study is as follows: section 2 describes data and methodology. Section 3.1 analyzes the representation of large-scale circulation over North America at different spatial resolution, using historical CAM5 simulations. Section 3.2 focuses on the future changes in the mean early spring climate, represented with the high resolution CAM5 simulations. Section 3.3 analyzes future changes in variance and cold and warm extremes, using the high-resolution runs. Section 4 discusses and summarizes the main results.

2. Data and methods

2.1. Data

In order to analyze the effects of the spatial resolution of the model we have used historical runs of CAM5.1 (http://cesm.ucar.edu/models//cam/, last access: April 2019), provided by the C20CC Detection and Attribution Project (http://portal.nersc.gov/c20c//main.html, last access: April 2019). We have compared three simulations for the 1979–2005 period. Each of the three runs is derived at different spatial resolution. The CAM5-1-2 degree run (hereafter CAM5_2deg, Wolski et al 2014), the CAM5-1-1 degree run (hereafter CAM5_1deg, Stone et al 2018) and the CAM5-1-0.25 degree run (hereafter CAM5_0.25deg, Wehner et al 2015) use atmospheric horizontal resolutions of 2.5° × 1.875°, 1.25° × 0.937° and 0.3125° × 0.234°, respectively. These runs use historical values for Green House Gases, ozone, volcanic aerosol, solar forcing. Land use is fixed to the year 1850. The runs do not include changes in nonvolcanic aerosols, and adopt a year-2000-era repeated annual cycle.

The analysis of future climate projections in this study utilizes 10 year time-slice runs of the CAM5.1.2 model (hereafter CAM5.1_2_0.25 deg), the highest available horizontal resolution of the set considered in the study, i.e. 0.25° lat–lon. These runs contribute to the HAPPI project (Mitchell et al 2017), which is designed to quantify the impacts of global warming at the 1.5°C and 2°C levels, in reference to preindustrial conditions (1861–1880). The experiment provides five-member ensembles describing present climate (2006–2015), and the conditions under 1.5°C and 2°C levels of global warming (2106–2115, referred to +1.5°C and +2°C experiments, respectively). Further details on the HAPPI experiment simulations are provided in the supplementary material (SI section 2.1 is available online at stacks.iop.org/ERL/14/124040/mediala)

For the comparison of the simulated and observed climatology of temperature as well as mid-latitude large-scale circulation over North America, we use surface temperature (TAS), zonal and meridional winds at the 700 hpa level in March–April of period 1979–2005. The TAS dataset is provided by the University of Delaware (V4.01), http://climate.geog.udel.edu/~climate/html_pages/README_gcn_ts2.html (last access: April 2019), at 0.5° × 0.5° horizontal resolution. The observed wind components in NCEP Climate Forecast System Reanalysis data were developed by NOAA’s National Centers for Environmental Prediction (Saha et al 2010, https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr (last access: April 2019), at 0.5° × 0.5° horizontal resolution. Analysis of daily surface temperature uses CPC Global Temperature dataset (last access: April 2019), provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://esrl.noaa.gov/psd/ at 0.5° × 0.5° horizontal resolution.

2.2. Methods

The analysis of the future climate projections focuses on the mid-latitudes of North America. The first part of the analysis compares representation of the simulated early spring (March–April) climate at different resolution with the observed one in 1979–2005. For this purpose, we use the three historical simulations, i.e. CAM5_2deg, CAM5_1deg and CAM5_0.25 deg. All the variables from both the simulations and observations were interpolated on a 2.5 × 2.5° horizontal grid.

The analysis of the future climate changes is performed using the five-member ensembles of decadal CAM5.1.2_0.25 deg simulations at their original resolution (0.25° × 0.25°). Analysis of the mean changes is based on the differences computed between two paired samples of March–April seasons. Statistical significance of the derived differences is tested using Wilcoxon signed rank test.

Changes in the waviness of the upper atmospheric flow are analyzed using Meridional Circulation Index (MCI, Francis and Varus 2015), which is the ratio of the meridional (North/South) wind component to the total wind speed: $\text{MCI} = \frac{v}{u^2 + v^2}$.

MCI is equal 0 when the flow is zonal. An increase in MCI indicates that the flow becomes more meridional, and reaches 1 or −1 when the direction of the flow is purely northward or southward, respectively.

The analysis of extreme cold and warm temperatures uses two metrics, i.e. percentiles of the daily temperatures (5th and 95th percentile) sample and 20 year return values (RVs), estimated separately for the +1.5°C and the +2°C experiments. The RVs were estimated by fitting generalized extreme value (GEV) distribution by the method of maximum log likelihood estimation (MLE) (Goles 2001, Smith 2003, Wilks 2006, Gilleland and Katz 2014) to a block (March–April) maximum/minimum in the 50-year sample of ensemble runs. The details of the estimation follow the description in Barcikowska et al
3. Results

3.1. Representation of the simulated present climate in early spring, at different horizontal resolution

In this section, we wish to assess the fidelity of the CAM5 model in simulating the early spring climatology in the mid-latitudes of North America at three different spatial resolutions. Figures 1–2 compare climatologies in the CAM5 historical runs and observations, derived for March–April of 1979–2005.

The comparison of surface temperature (figure 1), indicates that the model plausibly reproduces the meridional temperature gradient over North America. Nevertheless, each simulation exhibits regions with negative and positive biases. The former predominantly covers the Rocky Mountain region, while the latter is concentrated over the central United States. The magnitude of the bias is the most intense (with a local maximum exceeding 3 °C) in the lowest resolution run and it declines with the increased resolution, both in terms of the intensity and spatial extent. In the highest resolution run (in CAM5_0.25 deg) the bias is confined mostly to the northern parts of the Midwest and central Canada (see root-mean-square difference in figure S12(a)).

The temperature bias is manifest also in the climatology of both, cold and warm extremes (5th and 95th percentiles, respectively; figure 2). However, the representation of the warm extremes seems to be more consistent with the observations. The negative bias over the Rocky Mountains is present in both the climatology of 5th and 95th percentiles (cold and warm extremes, respectively) of CAM5_0.25, although for the latter its magnitude is weaker and confined towards northwestern Canada. The positive bias over the Great Plains of North America and the Midwest of the United States is found only in the cold extremes, and its magnitude is comparable with the one found for the seasonal mean (figure 1).

The improvement of the early spring temperature climatology over mid-latitude North America (i.e. the reduction of the warm bias in the central and southern United States), found in the higher resolution simulation (CAM5_0.25 deg), is in congruency with an improved representation of the mid-latitude jet stream transporting the cold and warm air over the continent (see analysis in SI3.1 and figures S11–S13). For example (figure S12), the refined magnitude and the location of the mid-latitude southerlies (the west coast of Canada) and northerlies (central Canada and the Midwest of the United States), which force the jet’s northerly and southerly tilt, is consistent with more accurate (reduced warm bias) temperatures over the Midwest and the southern United States. Hence the improvements found in the CAM5_0.25 deg atmospheric circulation will presumably enable more realistic simulations of weather extremes in North America. The analysis of future projections in this region will be investigated in the following subsection.

3.2. Impacts of global warming at the +1.5 and +2 °C temperature levels: temperature and large-scale atmospheric circulation changes

This section focuses on future changes in the spring climate over eastern North America, associated with the Paris climate agreement temperature targets, i.e. the 1.5 °C and 2 °C global warming. In the following we will present the results of the differentiation between (a) the +1.5 °C future scenario and present climate (~1 °C level of warming), i.e. first half a degree warming, and (b) between the +2° and 1.5 °C future scenarios, i.e. the additional half a degree warming.

The forcing that contributes to the former (i.e. increased SSTs, CO2; see description SI 2.1), differs from the latter (i.e. increased SSTs, CO2 and reduced aerosols; see description SI 2.1). For example, the first half a degree warming is also forced by the reduced concentrations of aerosols, which may amplify warming over regions like North America. Hence, one may expect different or even contrasting responses, as also demonstrated in previous studies analyzing other simulations following the HAPPI design (Barcikowska et al 2018a, 2018b, Li et al 2018, Wehner et al 2018).

Figure 3 shows that the responses to the first half a degree warming and the additional half a degree warming are different, both in terms of the intensity and spatial distribution of warming, and also the atmospheric flow. As expected, the regional impact of the first half a degree warming, is manifest in much stronger warming, compared to the latter (figures 3(b) and (c)). The most intense warming (exceeding 2.5 °C) is featured in the high latitudes and in the northeastern of the United States (up to 2 °C). The warming ceases gradually towards the Southwest of the United States, which features the local minimum of warming (0 °C–0.5 °C). The warming over the Northeast is accompanied with strong southerly anomalies, while the minimum of warming over the Southwest is accompanied with cyclonic anomalies.

The regional impact of the additional half a degree warming is relatively smaller (figure 3(c)), in terms of the magnitude, and of different spatial distribution of the warming. Conversely to the first half a degree warming, the Southwest of the United States features a relatively stronger warming (0.5 °C–1.5 °C), than the regions of the Midwest and eastern parts of the United States (below 0.5 °C). The changes in the former region are also accompanied with an anticyclonic circulation, while the latter is accompanied with the northerly anomalies (figure 3(d)). The northerly anomalies which nearly extend across the whole continent.
continent, are a distinct feature of each spring month, i.e. March, April and May (not shown).

The northerly anomalies over the eastern United States are stretched further northwest, across the Northwest Territories of Canada. These changes are in congruence with the increased SLP and height (figures 4(a) and SI4) over northwestern North America, which translates into the strengthened zonal ridge-trough structure across the mid-latitudes, and hence the intensified northerly flow of polar air across central Canada, the Midwest and eastern parts of the United States.

Figure 1. Time-mean average of the March–April surface temperature (°C) over the period 1979–2005, regridded to a 2° × 2° horizontal grid for the Delaware dataset (0.25° lat–long original resolution), and CAM5 at ~2° (CAM5 2 deg), ~1° (CAM5 1 deg) and ~0.25° (CAM5 0.25 deg) lat–long resolution. Contours show the difference in reference to the observations. Contours denote values −3, −2, 2, 3. Contours for negative values are dashed.
Central Canada and the Midwest are also the regions where the response to the additional half a degree warming is manifest in the seasonal variability of the spring temperatures (figure 4(b)). Analysis of standard deviation in the mid-latitude seasonal temperatures shows mostly increases, which are located in Saskatchewan, Manitoba and the Great Plains (by 10%–35%). The apparent intensification of the northerlies and concomitant advection of cold air can be a viable factor, which contributes to the derived increases in the regional temperature variations by increasing frequency or intensity of cold spring seasons. However, this issue still requires further investigation.

It is also worth noting that the response to the further warming, i.e. derived between the +3 °C and +1.5 °C warming scenario (not shown), also features northerly anomalies extending across North America. However this response pattern is qualitatively different, as it consists of both intensified northerly and westerly components of the jet-stream, and hence may also yield a different impact on the mean and extreme weather. These features highlight that the evolution of the future climate is a nonlinear process, and that the response at different temperature warming can be both quantitatively and qualitatively different. Thereby, one should not assume that the derived climate response, associated with the warming from the +1.5 to +2 °C levels, corresponds with the CMIP5 generation long-term projections.

3.3. Future changes of warm and cold temperature extremes, associated with the increase of the 1.5 °C–2 °C global warming level

In this section, we analyze changes in daily temperature extremes associated with the additional half a degree of global warming between the 1.5 °C and 2 °C temperature levels. We are using two measures of extremes (both cold and warm temperature extremes), i.e. percentiles of the daily data in March–April, and 20 year RV, derived by fitting a GEV distribution to sample with sub-seasonal block (March–April) maxima/minima.

Figures 5(a) and (b) present the response of the warm temperature extremes to the projected half a degree warming. Both the 95th percentile and 20 year RV show a qualitatively similar response, which constitutes an increase of the warm extremes over the

Figure 2. Percentiles 5th (a) and 95th (b) of surface temperature (shaded, °C) for the March–April in CAM5_0.25 deg, regridded to 0.5° × 0.5° horizontal grid, for the period 1979–2005. Contours show a difference in reference to the CPC dataset. Contours denote values −4, −2, 2, 4. Contours for negative values are dashed.
Figure 3. (a) Climatology for surface temperature (shaded, °C), and wind vector (m s$^{-1}$, contours) in the present climate ensemble; Difference between (b) +1.5 °C and present climate ensembles. Contours for negative values are dashed; Difference between +2 °C and +1.5 °C ensembles for (c) temperature (shaded, °C) and wind vector at 500 hPa (m s$^{-1}$) and (d) meridional wind at 500 hPa (shaded, m s$^{-1}$) in March–April. Stippling in (c) and (d) denotes regions where differences are significant at the 10% level.

Figure 4. Difference between the +2 °C and +1.5 °C ensembles for (a) sea level pressure (shaded, hPa), and geopotential height at 500 hPa (m, contours). Contour interval is 5 hPa. Contours for negative values are dashed; and (b) seasonal standard deviation, derived for March–April. Regions with differences significant at the 10% level are shown in figure SI3.
western parts of the United States and Canada, and the southern tier of the United States. The response also shows a relatively weak reduction of the warm extremes in central Canada (Northwest Territories, Saskatchewan, Manitoba) and the northeast region of the United States.

The largest warming of the warm extremes (figures 5(a) and (b)) is concentrated over the southern mid-latitudes (the southern tier of the United States), reaching 1.5 °C and 2.5 °C for 95th and 20 year RVs, respectively. For regions like the Midwest of the United States and eastern Canada the data did not pass the test of the goodness of fit at 5% level, suggesting that the reliability of the GEV approximations (20 year RV) for the warm extremes could be limited in these regions (figure SI5(a)). The approximations of the cold extremes seem to be plausible for most parts of the region (figure SI5(b)).

The changes in the cold extremes show quite a contrasting pattern and stronger magnitudes, with warming confined mostly to the northern mid- and high latitudes (figure 5(d)) and cooling at southern mid-latitudes. Figures 5(c) and (d) shows a sharp meridional contrast between a pronounced increase at 50–80 °N over Canada, and a decrease concentrated over the central United States. The increase is most intense over the western parts of Canada, where the warming exceeds 2 °C, and 4 °C, as defined by 5th percentiles and 20 year RVs, respectively. The decrease over the Midwest of the United States exceeds −1 °C, and −4 °C, as defined by the 5th percentiles, and the 20 year RV, respectively. The cooling of the 20 year cold extremes covers nearly the entirety of the contiguous United States, except the coastal regions. Analysis repeated separately for the months February, March and April shows similar results (not shown), although March features much larger magnitudes of changes (for both warming and cooling of the cold extremes). On the other hand, February features the cooling tendencies of the cold extremes mostly in the southern parts of the Midwest of the United States, while in April these tendencies expand northward and cover also the southern regions of Canada.

Analysis of daily temperature variance (figure 6(b)) shows changes, which highly resemble the spatial pattern derived for the cold extremes (figure 5(d)). The contrast between the warming of the cold extremes at the 50°–80°N latitude band and the cooling of the cold extremes in the southern parts of the mid-latitudes matches well with the regions of the decreased

![Figure 5](image-url). Difference between +2 °C and +1.5 °C ensemble experiments for March–April for (a) 95th percentile of daily temperatures (°C) and (b) 20 year return values for the seasonal maximum of daily temperatures (°C); (c) 5th percentile of daily temperatures (°C); (d) 20 year return values for the seasonal minimum of daily temperatures (°C). Percentiles are derived based on the distribution of all daily values in the given season, while return values are derived based on the block minimum (minimum in March–April). Stippling in (a) and (c) denotes regions where differences are significant at the 10% level. Regions in (b) and (d) where the data passed the Kolmogorov-Smirnov goodness of fit test at the 5% significance level, are shown in figure SI4.
by 5%–10%) and increased (by 5%–15%) variance (figure 6(b)), respectively.

The apparent amplification of the warming cold extremes in the northern mid- to high latitudes, compared to the warm extremes, as well as the reduced land temperature variability in these regions, has been found in the CMIP5 simulations and linked to the thermodynamic effects of the Arctic amplification (Screen 2014).

The cooling of cold extremes and the increased daily temperature variance, found inland of the southern mid-latitudes (in particular central United States), has not been found in previous studies. Our analysis of daily wind deviations suggests the enhanced jet-stream wave amplitude as a plausible explanation for these changes. Figure 6(a) shows changes in Meridional Circulation Index (MCI, figure 6(a)), which represents the contribution of the meridional wind component to the total wind speed. The analysis exhibits mostly negative anomalies of the MCI, which extend through the northwestern and central Canada, and the central United States (with a local minimum in the Midwest). This indicates an increased meridional component of the 500 hPa flow from North to South, which amplifies waviness of the jet-stream. The concept of the enhanced meandering of the jet-stream, which inherently leads to the increased variability and hence more intense extremes, including cold spells, over mid-latitudes, has been proposed by the observational study (Francis and Vavrus 2015). However, CMIP5 models have not been capable of capturing such a response, which could be either associated with the representation of sea ice concentration; stronger forcing, as compared with HAPPI runs; or too low spatial resolution.

4. Discussion and summary

The increasing number and intensification of both hot and cold extremes in recent years lends credence to the notion of more volatile and extreme weather in the future. Some studies support this view through observational analysis (Francis and Vavrus 2015), by proposing a theory of the dynamic impact of Arctic Amplification. That theory suggests that the enhanced waviness of the polar jet-stream causes an intensification of cold extremes in the mid-latitudes. However, another observational study (Screen 2014) as well as most of the CMIP3 and CMIP5 models, suggest rather reduced variance and amplified warming of cold extremes featuring mid- and high-latitudes from autumn to spring. Screen (2014) explained this phenomenon from the thermodynamic perspective, highlighting the impact of Arctic Amplification, i.e. amplified warming of northerlies, which are usually causing an arrival of cold days. Nevertheless, climate models still exhibit substantial uncertainty in simulating daily extremes, particularly for the coldest weather extremes and, associated meso- and large-scale circulation conditions (e.g. Kharin et al 2007, Kharin et al 2013, Schiemann et al 2017).

Future changes in regional mean temperatures as well as temperature variations taken together may have a severe impact on the regional agriculture and food security. In this study we investigate near-term future changes in the mean early spring (March–April) climate as well as the variance and extremes of daily temperature over the United States, provided by the CAM5 model. We analyze the simulations provided by the HAPPI project, designed to address the impact of an additional half a degree warming, between the two Paris temperature targets, i.e. 1.5 °C and 2 °C. The CAM5 simulations describe climate characteristics at relatively high horizontal resolution, i.e. 0.25° lat–lon. This provides a unique opportunity to investigate local-scale weather impacts of the global- or large-scale future climate changes. Moreover, the analysis of an additional set of CAM5 historical simulations, provided at lower horizontal resolution, allows for the
investment of spatial resolution dependence in the context of simulating spring weather.

The first part of our analysis examines the performance of the CAM5 models in reproducing the regional spring climatology (in terms of temperature and large-scale circulation) at different horizontal resolutions. The results of our analysis indicate that increasing the resolution to 0.25° provides a more realistic representation of the temperature, as seen by a reduced positive bias centered in the Midwest of the United States, which is consistent with the improved large-scale circulation. Moreover, the representation of the mid-latitude jet stream, which steers the mean flow of polar air and hence mid-latitude weather systems over North America, are simulated with a more realistic magnitude and location. This will presumably improve fidelity of the simulated future mean and extreme climate characteristics in the mid-latitudes.

Nevertheless, it must also be recognized that simulating the spring weather and climate over the mid-latitudes of North America still poses a challenge even for relatively high-resolution models. This is particularly noteworthy over the central parts of the continent, which features a positive bias in both the simulated mean temperatures and cold extremes.

The second part of our analysis focuses on the simulated mean future changes in the early spring season, associated with the differential half a degree warming between the 1.5 °C and 2 °C warming levels. The results indicate relatively small warming over the northern Midwest and the Northeast of the United States (≈0.25 °C to 0.5 °C) with more intense warming in the Southwest of the United States and in some regions of Canada (≈0.5 °C to 1.25 °C). This finding is also consistent with the observational findings of Kunkel et al (2004), who identified that the frost-free season has increased at a much faster pace over the western parts of the United States than in the eastern parts.

The contrast derived between the relatively intense warming in the Southwest and the weaker warming in the Northeast of the United States, corresponds to the future changes in the large-scale circulation over North America. These changes are manifest primarily in the intensified meridional component of the polar jet-stream across central Canada and the eastern United States, with maxima over the Northwest Territories and the southeastern regions of the Midwest, respectively. An anomalous advection of polar air towards the Midwest and the eastern United States, associated with the intensified northerlies, offsets the radiatively induced warming, which is reflected in the relatively small changes in these regions.

The projected changes in the warm extremes feature increases (up to 2 °C for 20 year RVs) in the Western United States and the west coast of Canada, and some reductions in the areas stretching between the Northwest Territories of Canada and the northern Midwest of the United States. The former regions are not exposed to the changes in the meridional flow, as opposed to the intensified northerlies for the latter regions, which points to an influence of large-scale flow and advection of polar air. This is by no means certain, and requires a more thorough investigation.

The cold extremes feature a meridionally reversed pattern, with warming located mostly in the northern mid-latitudes (up to 4 °C for 20 year RVs) and cooling in the southern mid-latitudes. The ratio of the warming for the cold extremes is remarkably larger than for the warm extremes. The stark warming of the cold extremes in the northern mid- to high latitudes collocated with the decreased standard deviation of daily temperatures. All of these features, has been found in previous CMIP3 and CMIP5 studies and recently (Screen 2014) has been linked to the thermodynamic impact of the Arctic Amplification, causing the northerlies (and associated cold extremes) warming at a faster pace than the southerlies (and associated warm extremes).

On the other hand, the stark cooling of the cold extremes (exceeding −4 °C for 20 year RV) centered in the Midwest of the United States has not been captured by the CMIP-generation studies, which are usually comprised of much lower resolution models, compared to the CAM5_0.25. Bathiany et al (2018), have shown that the southern mid-latitudes feature a large inter-model spread and insignificant changes, being a transition zone between the decreased standard deviation to the north and the increased values to the south, in the March–May season. Hence the sharp spatial gradients featured in our analysis may well be the outcome of the applied much higher resolution and the associated improvement in the spring climatology over North America.

The strong cooling of cold extremes in the southern mid-latitudes, derived in our study, is in congruence with the increased standard deviation of daily temperatures and the increased meridional component of the polar jet-stream across central North America. The latter implies a larger wave amplitude of the jet, which allows to penetrate even more southern regions, bringing there cold air from the north, and making cold days even colder. These results support the concept linking the increased meandering of the polar jet stream with the intensified cold extremes in the early spring (Francis and Vavrus 2015), and prompt future analysis aimed at explaining direct mechanism of the changes in temperature extremes.

Overall, our analysis of the large-scale atmospheric circulation changes associated with the additional half a degree warming from the 1.5 °C to 2 °C global warming levels, translates into much more radical regional changes on weather time-scales. Our study is limited by a relatively small ensemble size. Nonetheless, it demonstrates that average spring temperatures can warm while very extreme cold spring temperatures become colder in future warmer climates.
The projected changes in temperature variations on both seasonal and daily time scales have serious implications for the regional agricultures of North America. The continent-wide mean warming of the early spring season, concomitant with the warm temperature extremes increasing in western North America, will likely accelerate the regional growing season. The amplification of the mean warming over the western United States (exceeding 1 °C), compared to the eastern parts, may also contribute to the zonal contrast in the pace of the lengthening of the frost-free season (Kunkel et al 2004) already observed in recent decades. The future warming in the western United States locally exceeds 1 °C, and is accompanied by a reduced variability of the mean early spring temperatures. The warming tendencies in regions like Manitoba in Canada or the Midwest of the United States may not seem very obvious due to the increased seasonal variations of spring temperatures and the associated weaker predictability of the future seasons in these regions. On the other hand, the changes in the central and southern United States (i.e. the Great Plains) feature an increased daily temperature variability, which translates into more intense warm extremes and cold extremes. The seasonal warming and intensifying warm days may accelerate the blossom season and increase the growth of the plants in these regions. However, the future intensification of the cold extremes may expose plants to an increased risk associated with weather variations such as early spring frost damages.

Our analysis informs policy discussions on taking appropriate action in order to avoid the impacts of the additional half a degree warming overshooting the 1.5 °C temperature target, and to develop relevant measures targeting the mitigation and adaptation initiatives.

The data that support the findings of this study are openly available.

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http://portal.nersc.gov/c20c/data.html

ORCID iDs

Monika J Barcikowska https://orcid.org/0000-0003-1551-3688

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