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Projected 21st century climate change for wolverine habitats within the contiguous United States

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Abstract

Ensembles of 21st century climate projections made using a state of the art global climate model are analyzed to explore possible changes in spring snow cover and summer air temperature in present-day wolverine habitats in the contiguous United States (US). Projected changes in both snow cover and temperature are presented for a range of future emissions scenarios, and implications for the continued survival of the wolverine in the contiguous US are discussed. It is shown that under a high or medium–low emissions scenario there are likely to be dramatic reductions in spring snow cover in present-day wolverine habitats. Under these scenarios there is also likely to be a concomitant increase in summer-time temperatures, with projected maximum daily August temperatures far above those currently tolerated by the wolverine. It is likely that the wolverine, with its many adaptations for cold weather and deep snow pack, would have great difficulty adapting to such changes. The results of the simulations presented here suggest that the very low numbers of wolverines currently living in the contiguous US will likely further decline in response to the deterioration of their habitat in coming decades.

Keywords: wolverine, climate change

 Online supplementary data available from stacks.iop.org/ERL/6/014007/mmedia

1. Introduction

The question of how changing climate might influence species distributions is both of pressing concern, and, for many species, extremely difficult to quantify. Sutherland *et al* (2009) asked the question ‘Which elements of biodiversity in which locations are most vulnerable to climate change, including extreme events?’ in a list of ‘one hundred questions of importance to the conservation of global biological diversity’. It has also been stated that ‘projections of species’ distribution under global change (climatic and environmental) are of great scientific and societal relevance’ (Dormann 2007).

A number of researchers have chosen to use climate variables as key in projecting future species distributions. An example of this is the study by Thomas *et al* (2004), who predicted the future range of species by using climate change scenarios in combination with statistical relationships between present-day climate and species distributions. There are

clearly problems with applying such a generalized approach (Dormann 2007, Guisan and Thuiller 2005, Fitzpatrick and Hargrove 2009, Van der Putten *et al* 2010). For example, shifting bioclimatic regimes might impact species interactions and the co-existence of species, climate–vegetation interaction might impact species survival, and species may be able to adapt to changing climate, or to migrate to more favorable environments. Despite such issues, there do exist some species for which there does appear to be an obligate relationship with one or more climate variables.

One example of such a species is *Gulo gulo*, the wolverine. The importance of spring snow cover for the wolverine has been widely recognized (Aubry *et al* 2007, Banci 1994, Bjarvall *et al* 1978, Hatler 1989, Inman *et al* 2007, Magoun and Copeland 1998, Persson *et al* 2003, Pulliainen 1968). Copeland *et al* (2010) argue that spring snow cover is not just important, but essential for the wolverine, suggesting that wolverine distribution is defined by an ‘obligate association

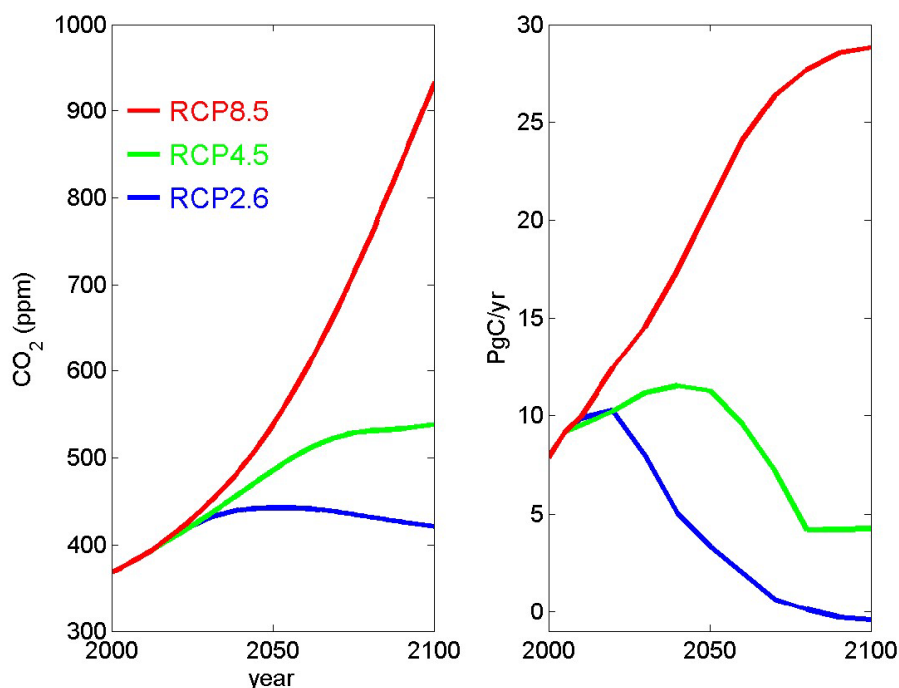


Figure 1. Prescribed concentrations of atmospheric CO₂ (left panel) and CO₂ emissions (right panel) for the three representative concentration projections (RCPs) discussed herein.

with persistent spring snow cover and by an upper limit of thermoneutrality'. If the two climate variables most important in defining the bioclimatic envelope of the wolverine are spring snow cover and summer-time temperature, then it may be possible to use future projections of changing spring snow cover and summer-time temperatures to understand how climate change might impact the wolverine. A persistent snow pack from late winter through late spring is thought to be critical for the reproductive denning success of the wolverine both because of the insulating warmth it provides to the newborn kits, and for the protection afforded against predators. It has also been recognized that wolverines are not found in regions where maximum summer temperatures fall above a threshold value of 22 °C (roughly 72 °F; Copeland *et al* 2010).

The purpose of this study is to evaluate the possibility that future climate change may affect critical spring-time snowpack levels and maximum summer-time temperatures. An ensemble of 20th and 21st century climate simulations from the latest version of the Community Climate System Model (CCSM4; Gent *et al* 2010) are analyzed, with particular emphasis on projected changes in spring snow cover and summer temperatures in present-day wolverine habitats in the contiguous United States. The paper is structured as follows: in section 2, the model and the future emissions scenarios are briefly described. In section 3, the model results are presented. Section 3 is divided into two parts; the first discusses snow cover and the second discusses temperature changes. Because the main results of this paper focus on possible changes in spring-time snow cover, the model is validated against late 20th century data before the 21st century results are discussed. The model results are discussed in section 4, and conclusions presented in section 5.

2. Model description

The Community Climate System model is a general circulation model that includes fully coupled active atmosphere, ocean, sea-ice and land models. Details of the model configuration and simulations can be found in the supplementary material (available at stacks.iop.org/ERL/6/014007/mmedia). Three distinct emissions scenarios (Moss *et al* 2010) were used for the 21st century simulations: a 'low emissions' scenario which will be referred to as RCP2.6; a 'medium-low emissions' scenario (RCP4.5) and a 'high emissions' scenario (RCP8.5). (Note that there also exists a 'medium-high' emissions scenario, but these simulations had not yet been completed at the time of writing this letter.) The atmospheric CO₂ concentration and emissions for each of the three scenarios analyzed here are shown in figure 1. Atmospheric CO₂ in 2010 is about 389 ppm and CO₂ emissions are just under 10 PgC yr⁻¹.

In the low emissions scenario, CO₂ emissions remain close to present-day levels until 2020, and then decline to zero by the early 2080s. Atmospheric CO₂ peaks at just over 440 ppm by 2050 and falls to around 420 ppm by 2100. This low emissions (RCP2.6) scenario seems improbable given current societal trends. In the medium-low emissions scenario, CO₂ emissions peak in 2040 slightly above present-day values, and then show a sharp decline to around 4 PgC yr⁻¹ between 2080 and 2100. CO₂ concentrations in the atmosphere slowly increase to reach a maximum of around 540 ppm by the year 2100. The medium-low emissions scenario (RCP4.5) would require significant international commitment to develop alternative energies and curtail fossil fuel dependence in coming decades. In the high emissions scenario, emissions progressively rise from present-day values to a maximum of

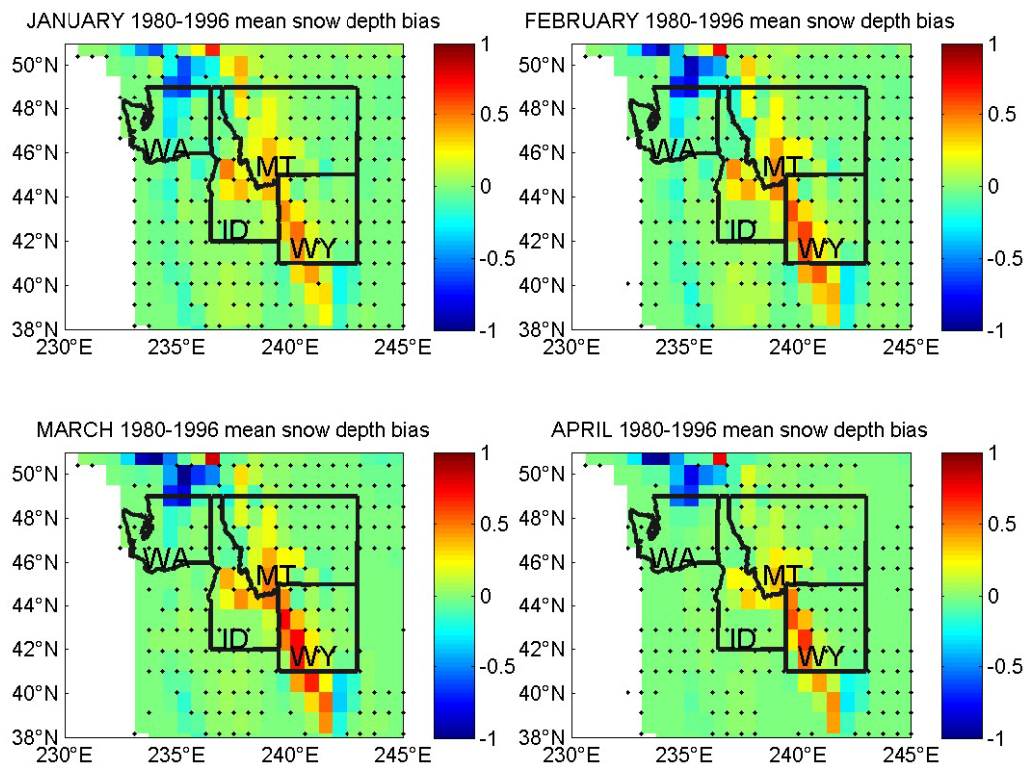


Figure 2. Mean snow depth bias in model in meters (plotted is the ensemble mean model 1980–96 snow depth minus the CMC 1980–96 mean snow depth) for January, February, March and April in the north-west US. Idaho, Montana, Wyoming and Washington State are outlined in black. The CMC data was interpolated onto the model grid, and then variances were computed for each month at each grid point for both model simulated and data-based snow depth. The stippled regions show where the model and observation-based means were identical at a significance level of 0.05 based on the two-sample *t*-test.

around 29 PgC yr^{-1} in 2100 (at which point the emissions curve flattens). Atmospheric CO_2 concentrations in 2100 are slightly above 935 ppm in this scenario. This could be a plausible scenario if no dramatic effectual action is taken to reduce emissions in coming decades.

The discussion in this letter will focus primarily on projected changes in spring snow cover and summer temperature in Idaho, western Montana and western Wyoming under these three emissions scenarios.

3. Model results

3.1. Snow cover

3.1.1. Observations. The observed snow depth for January, February, March and April 2008 (Brown *et al* 2010) is shown in figure S1 (available at stacks.iop.org/ERL/6/014007/mmedia). The persistence of snow well into the spring is evident in isolated regions of the Rocky and Cascade Mountains.

3.1.2. Model bias. The 1980–96 Canadian Meteorological Centre (CMC) Daily Snow Depth Analysis Data (Brown *et al* 2003) is the observational dataset used to assess model skill in representing late 20th century snow depth. The observational data were re-gridded onto the CCSM4 model grid. Using the variance calculated for each month over the 1980–96 time period for both the model and the CMC dataset, a two-sample

t-test was performed to determine where the mean values were significantly different. Figure 2 shows the difference (model minus observations) in snow depth for January, February, March and April over the north-west US; grid points for which the means are statistically identical at a confidence level of 0.05 are stippled, and the states in which wolverines currently live are outlined in black. Throughout much of Idaho, Montana and Wyoming, during the winter months there is no significant model bias in snow depth; there is a small persistent positive model bias (slightly too much snow in the model) in western Wyoming, south-west Montana, and central Idaho. There is a negative model bias in snow depth in northern Washington State.

An alternative way to look at differences in snow depth between model and observations in the late 20th century is to plot the annual cycle averaged over present-day wolverine habitats. Figure 3 shows monthly averaged snow depth spatially averaged over Idaho, western Montana, Washington State, and western Wyoming, for each of the six 20th century ensemble members of the model compared with the CMC 1980–96 data product. It is clear that in Idaho, western Wyoming and western Montana, the model is snow depth is slightly high compared to observations, but for most months, most ensemble members fall within the two-standard-deviation error-bar of the CMC data. For Washington State, the model is biased low, and only two of the six ensemble members fall within the two-standard-deviation error-bar on the observations

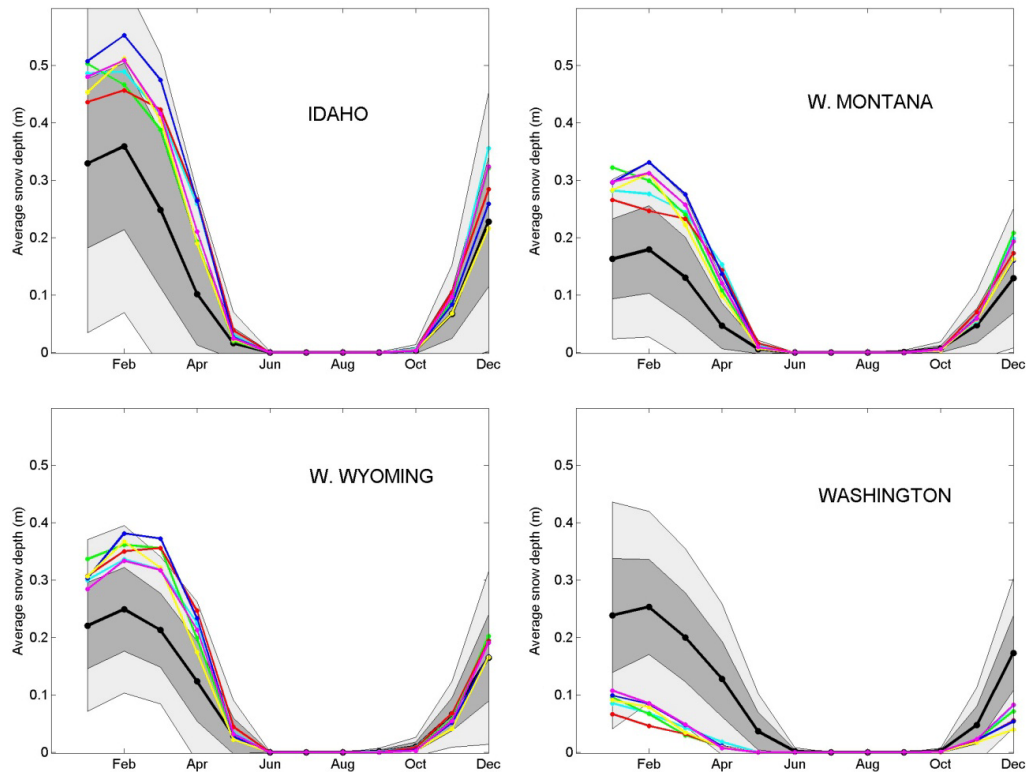


Figure 3. Average snow depth (in meters) by month over the period 1980–96 for four regions: Idaho, Western Montana, Western Wyoming and Washington state. The black line shows the mean based on the CMC 1980–96 observational dataset; the darker shaded region shows the one standard deviation error based on the data, and the lighter shaded region shows the two-standard-deviation error-bar from the data. The colored lines show the average snow depth over 1980–96 for each month for each of the six 20th century ensemble members of CCSM4.

for all months. Because the model has a clear negative bias in Washington State (too little snow compared to observations), it is likely that model projections of changing snow depth in this region will be such that they over-estimate how fast the snow declines with changing climate. In Idaho, Montana, and Wyoming however, there a slight bias towards too much snow in the late 20th century, and it might therefore be expected that projected declines in snow cover will under-estimate actual future changes. For this reason, and also because the large majority of remaining wolverines have been documented in these regions, the remainder of this paper focuses on changes in snow cover and temperature in Idaho, Montana, and Wyoming.

3.1.3. 1850 control and 20th century: model results.

The simulated mean January snow depth in Idaho, western Montana and western Wyoming is shown in figure S2 (available at stacks.iop.org/ERL/6/014007/mmedia). The time-series for the 1300 year duration pre-industrial control run is shown, along with the six 20th century ensemble members and the ensemble mean of the 20th century simulations. The means and standard deviations of snow depth for the 1850 and 20th century runs are very similar (see table S1 available at stacks.iop.org/ERL/6/014007/mmedia for results from western Montana). There is no long-term trend evident in snow depth in any of the regions considered; there is however a downward trend in the late 20th century that is evident in the ensemble mean for all regions in most winter months. It should be noted

that the inter-annual variability is very large for all regions considered, and that the ensemble mean of the 20th century runs masks the large variability seen in the individual ensemble members.

The time-series of spatially averaged snow cover in Idaho over the last three decades is shown in figure S3 (available at stacks.iop.org/ERL/6/014007/mmedia). The model ensemble mean is shown by the heavy black line and the individual ensemble members by the light gray lines. The observed snow cover, derived from the Brown *et al* (2010) CMC dataset, is shown over the period 1999–2009 by the red dots. While most of the observation-based estimates fall below the ensemble mean, they are not inconsistent with the average snow depth predicted by individual ensemble members.

3.1.4. 21st century: model results. The projected changes in mean snow depth over Idaho, western Montana and western Wyoming for the RCP8.5 (high emissions) scenario are shown in figures 4 and 5. Figure 4 shows the six-member model ensemble mean snow depth averaged over western Montana for January, February, March, and April, between 1850 and 2010. For each of these months, there is a clear downward trend in projected snow depth to extremely low values by the year 2100. The April snow cover in particular shows an extremely rapid decline to near-zero values by the latter half of the twenty-first century in western Montana. Similar trends are projected for Idaho and western Wyoming.

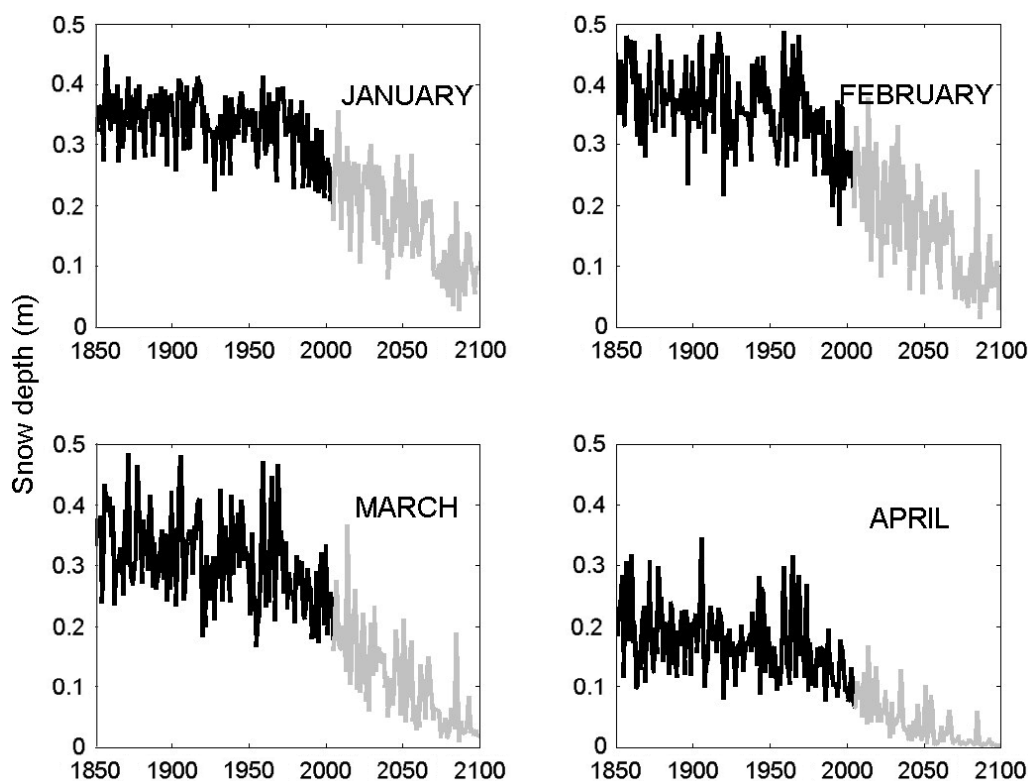


Figure 4. Ensemble mean simulated snow depth averaged over western Montana for the 20th century (black) and 21 century RCP8.5 (high emissions) scenario runs (gray) for the months January, February, March and April.

The projected changes in March snow depth under the high emissions scenario is shown in figure 5. Here the ensemble mean is given by the thick black line and a single ensemble member is shown in gray. The variability in any single ensemble member far surpasses that in the ensemble mean. It should also be noted that a single ensemble member (which is analogous to a realization of the actual climate; the climate is always one particular realization, and not an ensemble mean) shows many more high and low extremes than are evident in the ensemble mean. For example, in both Idaho and western Montana, the ensemble mean falls to low values but does not reach zero in March (figure 4), while the single ensemble member depicted in figure 5 clearly reveals that there will likely be many winters with zero snow by about 2050 in Idaho, western Montana and western Wyoming if we follow a high emissions scenario.

It should also be noted that an individual ensemble member exhibits years of anomalously high winter and spring snow cover, even in the latter half of the 21st century. Idaho, western Montana and western Wyoming all show that some years in the coming decades are likely to have some winters in which snow cover approaches or even surpasses the 20th century mean. This is an important point, and a part of the natural variability in the climate system, even under such strong external forcing as that implicit in the high emissions scenario: in a rapidly warming world in which mean snow depth shows a strong downward trend with time, there will likely still be years in which snow depth is likely to approach or even exceed the 20th century mean.

It is of interest to compare results from the high emissions (RCP8.5) scenario with those from the medium–low emissions (RCP4.5) scenario. Figure S4 (available at stacks.iop.org/ERL/6/014007/mmedia) shows the projected changes in March snow depth in Idaho, western Montana and western Wyoming for the RCP4.5 scenario for both the ensemble mean and for a single ensemble member. In Idaho, the ensemble mean shows that snow cover has fallen to near-zero values by the end of the 21st century in the high emissions scenario (figure 5). By contrast, the ensemble mean is still non-zero in Idaho by the end of the 21st century in the medium–low scenario (figure S4 available at stacks.iop.org/ERL/6/014007/mmedia). However, there are still many years evident in a single ensemble member after 2050 in both these scenarios in which there is zero snow cover. Even with the much more moderate RCP4.5 scenario, there are still likely to be many years of zero or near-zero snow cover in present-day wolverine habitats by the end of the 21st century.

The critical denning period of the female wolverine runs from roughly late February/early March through mid-May. Projected model changes in snow cover under the high emissions scenario between 1 March and 15 May indicate that there is likely to be a dramatic reduction in the number of days of moderate snow cover in current wolverine habitats between now and the end of the 21st century. Figure 6 shows the percentage of days for each model grid box with average snow cover greater than 20 cm between 1 March and 15 May for four decade-long periods: 1890–9; 1990–9; 2050–9 and 2090–9. The 1990–9 period shows that, while there is a

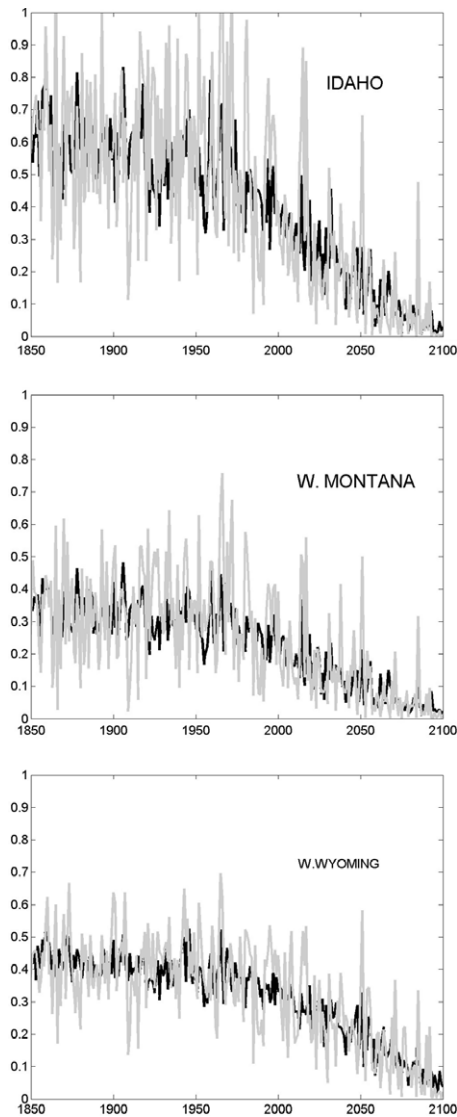


Figure 5. Model simulated snow depth (m) in March from 1850–2100 for Idaho, W Montana, and W Wyoming; years 2005–2100 were obtained under the RCP8.5 scenario. The ensemble mean is shown by the thick black line, and a single ensemble member is shown in gray.

very slight decline in snow cover relative to the pre-industrial state, there is still significant spring snow throughout much of Idaho, Montana and Wyoming. By the middle of the 21st century, however, the percentage of days with moderate snow cover is projected to be much smaller, dropping to zero by the decade 2090–9.

These model projections indicate that, under the high emissions scenario, there will be little or no snow cover persisting into the late spring in present-day wolverine habitats by the middle to late 21st century. Under the medium–low emissions scenario, there are likely to be many years with zero snow cover after 2050 in Idaho, Montana and Wyoming. Under the low emissions scenario, snow cover does not show a dramatic decline between 2050 and 2100 as it does for the other scenarios, but rather equilibrates at a new mean value slightly below the late 20th century mean.

3.2. Surface air temperature

There is evidence that the wolverine is not frequently found in places where the average maximum August temperatures are higher than about 22 °C (roughly 72 °F). Copeland *et al* (2010) suggest that, while average maximum August temperatures are a less effective predictor of wolverine presence than is persistent spring snow cover, there does seem to be evidence that wolverines strongly prefer cooler summer temperatures. We consider projected changes in both monthly mean summer temperatures and in daily maximum summer temperatures in present-day wolverine habitats.

The ensemble mean average August temperatures for the 20th and 21st century model simulations in for Idaho, western Montana and western Wyoming are shown in figure 7. The black line shows the ensemble mean from the 20th century simulations, and the blue, green and red lines show the RCP2.6 (low emissions), RCP4.5 (medium–low emissions) and RCP8.5 (high emissions) scenarios respectively. Regardless of the scenario used for 21st century emissions, there is a sharp rise in projected mean August temperatures for Idaho, western Montana and western Wyoming over the 21st century. It is of interest to note that all three scenarios show a very similar trend out to about 2040 before diverging significantly. There is a strong difference in prescribed emissions for each of these scenarios; CO₂ starts to diverge by around 2030 (figure 1), while methane diverges around 2015 (not shown). It is also worth noting that there are times in the first half of the 21st century when the projected ensemble mean August mean temperature under the very moderate RCP2.6 scenario is actually higher than under the RCP8.5 scenario (one such example is in 2045; in this year the mean August temperature in all three regions considered is actually higher under both the RCP2.6 and RCP4.5 scenarios than under the RCP8.5 scenario). It appears based on these model projections that no matter what happens with regard to emissions over the coming few decades, we have already committed to some warming trend in the next 30 years. The big difference between model runs comes in the latter half of the 21st century when the projected warming from the different scenarios diverges sharply depending on the emissions scenario. Both the low emissions and the medium–low scenarios show an adjustment to a new August mean temperatures some 2–4 °C higher than pre-industrial values by the end of the 21st century, while the high emissions scenario shows a strong linear upward trend in all regions, with an increase in mean August temperatures of roughly 6–8 °C by the end of the 21st century, and no evidence of a flattening of this upward trend.

Another way of looking at projected temperature changes is to consider maximum rather than mean values. Figure 8 shows the average number of days in August with a maximum temperature greater than 32 °C (roughly 90 °F) for the time periods 1890–9, 1990–9, 2050–99 and 2090–9 for the high emissions RCP8.5 scenario. Given that wolverines, with their many adaptations for cold weather and deep snow pack, are rarely found today in regions where daily maximum August temperatures are higher than 22 °C, it is likely that they would have great difficulty adapting to a climatic state where maximum daily August temperatures are above 32 °C for between 20 and 31 days each August.

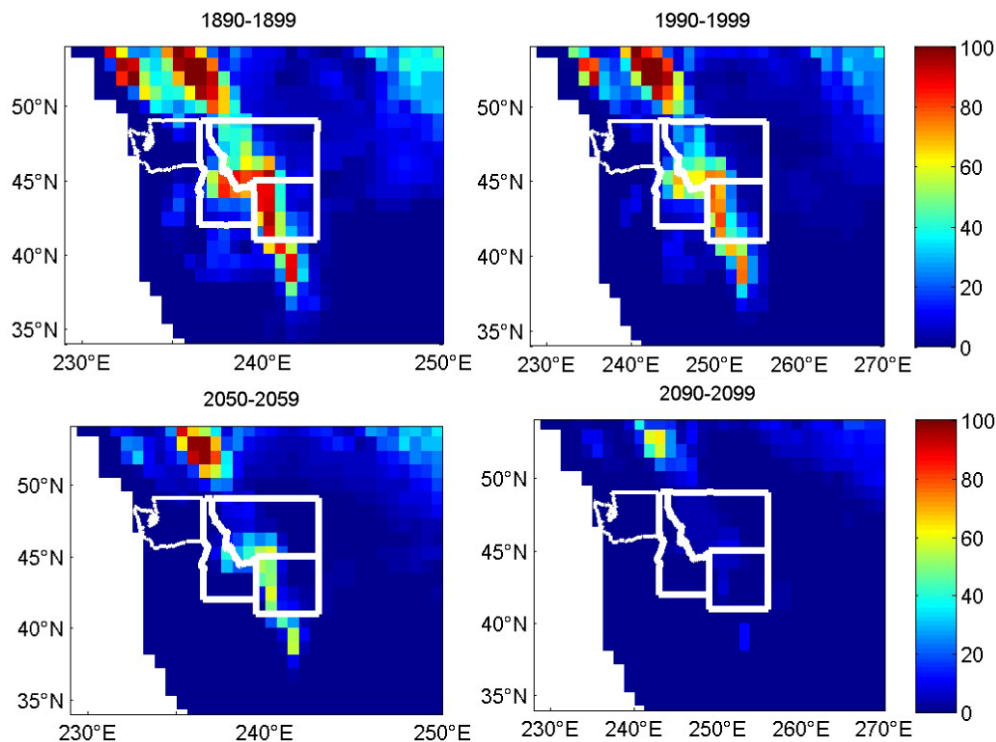


Figure 6. Percentage of days between 1 March and 15 May for which grid points have average snow cover exceeding 20 cm depth. Decadal averages are shown for (a) 1890–9, (b) 1990–9, (c) 2051–60, and (d) 2090–99. Figures computed based on daily snow depth data from 20th century and RCP8.5 simulations.

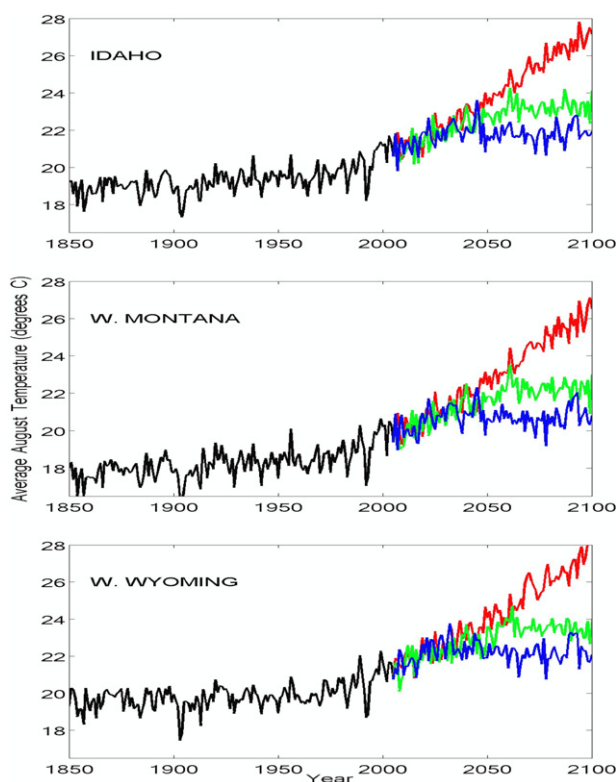


Figure 7. Spatially averaged August mean temperatures (°C) for Idaho, western Montana and western Wyoming. The black line shows the ensemble mean from six 20th century runs; the blue line shows the ensemble mean for the RCP2.6 scenario, the green line for the RCP4.5 scenario and the red line for the RCP8.5 scenario.

4. Discussion

The wolverine is a creature highly adapted to living and reproducing in cold, high-elevation regions which have persistent snow cover for much of the year. The only places wolverines have well-established habitats in the contiguous United States today are north-central Washington, North-central Idaho, western Montana and northwestern Wyoming; a significant contraction in geographic range relative to earlier in the 20th century (Aubry *et al* 2007). There is still debate as to whether the wolverine population has been declining or not in more recent years. Brodie and Post (2010) found a correlation between decline in wolverine harvest and declining average snowpack, and used this to infer a climate-driven decrease in wolverines. McKelvey *et al* (2010) strongly refuted these conclusions and argued that wolverine range in the contiguous US may in fact have been expanding over recent years. Regardless of who is correct, all parties agree that snow cover is widely recognized as a ‘key component of wolverine habitat’, and that the wolverine appears to be restricted to areas ‘represented by the availability and distribution of spring snow cover’ (McKelvey *et al* 2010).

There is no definitive agreement as to the exact number of wolverines alive in the contiguous US today. At one extreme, the estimate of the effective wolverine population in the Rocky Mountains of Montana and Idaho is 35 individuals (Schwartz *et al* 2009). At the other extreme, the US Fish and Wildlife Service estimated around 500 wolverines for the total population in the northern Rocky Mountains (Idaho, Montana and Wyoming).

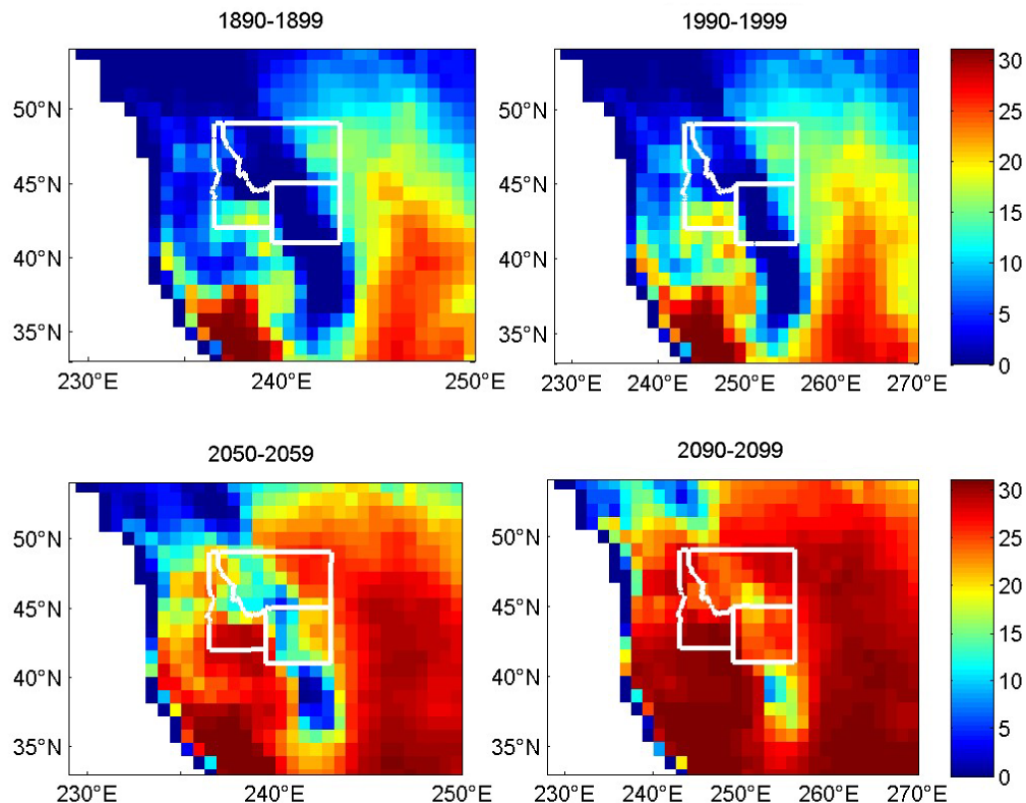


Figure 8. Results from RCP8.5 scenario showing the average number of days in August (north-west US) for which the maximum daily temperature exceeds 32 °C (90 °F) for four decades: 1890–9, 1990–9, 2050–9 and 2090–9. Idaho, Montana and Wyoming are outlined in white.

Based on the projections of temperature and snow cover in the regions of current wolverine habitat in the contiguous US presented herein, it seems likely that the present-day wolverine habitat could undergo dramatic modification in the decades to come. It has been shown in this study that the wolverine faces a potential two-fold threat from future climate change:

- First, under an emissions scenario somewhere between RCP4.5 (medium–low emission) and RCP8.5 (high emissions), spring snow cover is likely to fall to zero or near-zero levels by the middle of the 21st century in present-day wolverine habitats. Individual ensemble members from both the RCP4.5 and RCP8.5 scenarios show multiple years with zero snow cover in Idaho and western Montana in the latter half of the 21st century. It has been proposed that there exists an obligate relationship between wolverines and snow cover, meaning that wolverines will never be found living in a region without persistent spring snow cover.
- Second, maximum daily temperatures in August are likely to show dramatic increases under a high emissions scenario comparable to RCP8.5. The wolverine does not currently tolerate average maximum August temperatures much higher than 22 °C. There are no days in August with have a maximum daily August temperature greater than 32 °C in present-day wolverine habitats. Under the high emissions scenario, it is estimated that the average August

will have between 20 and 31 days in which the maximum temperature is above 32° by the end of the 21st century.

If we follow an emissions scenario between RCP4.5 and RCP8.5, it is likely that the wolverine, faced with the double-threat or rapidly decreasing spring snow cover and rapidly increasing summer temperature, will have lost most of its present-day habitat in the contiguous US by the end of the 21st century. It is possible that the wolverine may continue to thrive in parts of Canada. However, re-location across the border may not be a viable option for the wolverines living in the contiguous US, as it has been shown that dispersal corridors between the northern Rocky Mountains in the US and Canada may be limited (Schwartz *et al* 2009).

5. Conclusions

If indeed it is true that the wolverine cannot survive in regions not characterized by persistent spring snow cover, then the model projections discussed herein provide guidelines for how this critical aspect of their habitat is likely to change under various future emissions scenarios. Based on the model projections presented here, under a high emissions scenario, snow depth will likely decrease by a factor of three to four over Idaho, western Montana, and western Wyoming by the end of the 21st century. Snow cover is likely to drop to near-zero levels by late spring in these regions. Furthermore,

average August temperatures are projected to increase by 6–8 °C over Idaho, western Montana, and western Wyoming under a high emissions scenario (note that this increase is significantly higher than both the projected global mean and US mean changes in temperature).

Under the moderate–low emissions (RCP4.5) scenario, changes are likely to be less extreme, with mean August temperatures increasing by 2–4 °C over pre-industrial values, and snow cover projected to decrease by between a factor of two and three by the late 21st century. However, even under the sharply curtailed emissions required by the RCP4.5 scenario, there are likely to be multiple years seeing zero or near-zero levels of snow cover in the late 21st century over Idaho, western Montana, and western Wyoming.

If dramatic cuts to emissions are made within the next decade (by 2020), and if a low emissions scenario similar to RCP2.6 were to be followed, then projected changes in snow cover and temperature are much more modest. Mean summer temperatures in present-day wolverine habitats under RCP2.6 are projected to rise by only 1–2 °C, and spring snow cover is expected to persist at levels similar to present-day through the end of the 21st century.

Unless the wolverine is able to very rapidly adapt to summer-time temperatures far above anything it currently experiences, and to a spring with little or zero snow cover, it is unlikely that it will continue to survive in the contiguous US under a high or medium–low emissions scenario.

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