Amplified warming projections for high altitude regions of the northern hemisphere mid-latitudes from CMIP5 models

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Abstract

We use output from global climate models available from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for three different greenhouse gas emission scenarios to investigate whether the projected warming in mountains by the end of the 21st century is significantly different from that in low elevation regions. To remove the effects of latitudinal variation in warming rates, we focus on seasonal changes in the mid-latitude band of the northern hemisphere between 27.5°N and 40°N, where the two major mountain systems are the Tibetan Plateau/Himalayas in Asia and the Rocky Mountains in the United States. Results from the multi-model ensemble indicate that warming rates in mountains will be enhanced relative to non-mountain regions at the same latitude, particularly during the cold season. The strongest correlations of enhanced warming with elevation are obtained for the daily minimum temperature during winter, with the largest increases found for the Tibetan Plateau/Himalayas. The model projections indicate that this occurs, in part, because of proportionally greater increases in downward longwave radiation at higher elevations in response to increases in water vapor. The mechanisms for enhanced increases in winter and spring maximum temperatures in the Rockies appear to be influenced more by increases in surface absorption of solar radiation owing to a reduced snow cover. Furthermore, the amplification of warming with elevation is greater for a higher greenhouse gas emission scenario.

Keywords: high elevation, mountain, Tibetan Plateau, Himalaya, Rocky Mountains, temperature, surface, minimum, maximum, CMIP5, GCM, warming, amplified, mid-latitude

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1. Introduction

Global scale warming of the land and oceans has occurred during the 20th century, with enhanced rates of warming since the late-1970s (Trenberth et al 2007). This has been attributed to increases in atmospheric greenhouse gas forcing caused by anthropogenic emissions (Hegerl et al 2007). Between 1975 and 2010, land temperatures have increased at a rate of 0.30 °C/decade, which is more than double the rate (0.12 °C/decade) of ocean warming. It has been proposed that mountainous regions would be more sensitive to this global scale climate change than other land at the same
Several studies have suggested that mountain regions have warmed at a greater rate than their low elevation counterparts often with greater increases in the daily minimum temperatures than daily maximum temperatures (Beniston et al 1997, Diaz and Bradley 1997, Liu and Chen 2000, Pederson et al 2010, Qin et al 2009). Although, observations of enhanced warming at higher elevations in recent decades are not found everywhere (e.g., Pepin 2000, Vuille and Bradley 2000), this process may be occurring widely. A recent global study by Ohmura (2012) based on observations from the last 50 to 125 years finds enhanced warming with elevation in about two-thirds of the mountain regions he examined.

Mountain systems are critical to people and ecosystems, and they play a significant role as ‘water towers’ on the landscape. Since more than half of the global rivers have their origins in mountains where they are often dominated by snowmelt runoff (Christensen et al 2007), it is important to understand how climate is changing there in response to increasing levels of atmospheric greenhouse gases. Our understanding of both historical and projected climate change in mountainous regions is quite limited because of the inadequacies extant in our observations and climate models (Rangwala and Miller 2012). In mountain regions, there are generally fewer observing stations which are often located in low lying regions where people live, e.g. valley bottoms, and, therefore, do not adequately capture the representative climate for the whole mountain region. For example, stations used to study climate change in the Tibetan Plateau, where the average altitude is greater than 4000 m, are primarily located in the eastern half of the plateau, which is more inhabited and at lower elevations. Moreover, many of the stations that have been historically used to study climate change on the plateau are outside its eastern boundary where the elevation is below 3000 m (Liu et al 2009).

Global climate models (GCMs) have been used previously to assess the potential for climate change in high elevation regions. Bradley et al (2006) analyzed eight global climate model simulations under a high greenhouse gas emission scenario (SRES A2) and found greater increases in free air temperature with increasing elevation along the entire extent of the American Cordillera, from Alaska to southern Chile, by the end of the 21st century. This led them to argue that such increases in free air temperature could amplify the warming rates at higher elevations in these mountain regions. Using high-resolution (0.5°) climate model projections, Nogués-Bravo et al (2007) found that there would be larger temperature increases in higher northern latitude mountains than in temperate and tropical zones during the 21st century.

In this study, we analyze output from global climate models available from the Coupled Model Intercomparison Project Phase 5 (CMIP5) to address the specific question: are mountains projected to warm at a faster rate than non-mountainous regions? One of the difficulties in answering this question is determining what the warming rates in mountains should be compared to. The global average warming rate is moderated by the ocean, and the northern hemisphere land average is influenced by enhanced warming at high latitudes. To remove some of these influences, we focus on the projected 21st century temperature response in the northern hemisphere mid-latitude band between 27.5 and 40°N where the Tibetan Plateau/Himalayas and Rocky Mountains are located.

2. Methods

We are primarily interested in analyzing the ensemble mean response from all available GCMs from the CMIP5 project. We use the data portal available from the Koninklijk Nederlands Meteorologisch Instituut’s (KNMI) Climate Explorer website (http://climexp.knmi.nl) for this purpose. Additional data were obtained from the Earth System Grid (ESG) website (www.earthsystemgrid.org) to verify the accuracy of the output from the KNMI Climate Explorer website. The multi-model ensemble output at the KNMI website is provided on a 2.5° grid, and we present our analysis at this resolution. We analyze GCM output for three different greenhouse gas emission scenarios—representative concentration pathways (RCPs) 4.5, 6.0 and 8.5—representing middle to high range emission scenarios for which the emission pathways lead to radiative forcings of 4.5, 6.0 and 8.5 W m⁻² in 2100, respectively. The mean atmospheric greenhouse gas concentrations by 2100 for these three scenarios are approximately 650, 850 and 1370 ppm CO₂ equivalent, respectively (Van Vuuren et al 2011).

At the time of this study, the total number of GCM groups available for each of these scenarios were 36, 18 and 32, respectively (see supplementary table S1 available at stacks.iop.org/ERL/8/024040/mmedia for information on these models). Each model group represents the ensemble mean of all its member simulations. We find that the multi-model ensemble seasonal temperature means are consistent with the observed climatology (supplementary figure S22 available at stacks.iop.org/ERL/8/024040/mmedia) and that they have extremely high spatial correlations (>0.99). For most regions globally (>80%), the difference between the multi-model mean and observations is less that 2°C. Errors are generally larger at high latitudes where observations are more limited. And partly for the same reason as well as over-representation of climate observations from lower elevation regions in the observed climatology, high elevation regions such as the Tibetan Plateau and Greenland have a small cold bias in the model ensemble. Additional errors may arise from the differences in elevations for a particular grid cell. Although, errors introduced by such an elevation mismatch could be reduced by interpolating temperatures to a common elevation, we have not done this here because we have assumed that any model errors in temperature introduced by such a mismatch are not changing in time.

We analyze seasonal changes in the daily minimum (Tmin) and maximum (Tmax) temperatures during the 21st century by calculating the changes in their 20 year climatologies between the beginning and end of the century (2081–2100 minus 2006–2025). We choose Tmin and Tmax, instead of mean temperature, because they are affected
differently by different climate drivers. We examine seasonal timescales because the processes affecting the temperature response differ as atmospheric conditions change with season. Since our focus is on the northern hemisphere, seasons are associated with that hemisphere and they are designated as winter (DJF), spring (MAM), summer (JJA), and autumn (SON).

3. Temperature response between 27.5°N and 40°N

Our focus here is on the temperature response during winter in the 27.5°N–40°N latitude band for all three emission scenarios, but first we comment on the temperature response globally. By the end of the 21st century, the multi-model ensemble indicates that there will be enhanced warming at high latitudes and in certain high elevation regions, such as the Tibetan Plateau, with the strongest response occurring in winter and particularly for Tmin (figure 1). The seasonal changes, globally, in Tmin and Tmax for the three different emission scenarios are shown in supplementary figures S1–S6 (available at stacks.iop.org/ERL/8/024040/mmedia). The spatial patterns of these seasonal temperature responses are similar among the different emission scenarios with correlations greater than 0.95 (supplementary table S2 available at stacks.iop.org/ERL/8/024040/mmedia), although the magnitude of warming more than doubles for RCP 8.5 relative to RCP 4.5. The spatial correlations are also high between mid and late century temperature responses among the different scenarios, indicating that spatial warming

Figure 1. Projected 21st century changes (2081–2100 minus 2006–2025 averages, °C) in Tmin and Tmax during winter (DJF) for the RCP 4.5 scenario. The dashed contour line demarcates land surfaces above 4000 m in the models; only the Tibetan Plateau region is identified by this contour. Strongly analogous patterns of temperature responses are found for RCPs 6.0 and 8.5.
patterns do not change with time during the 21st century (supplementary table S3 available at stacks.iop.org/ERL/8/024040/mmedia). We also find inter-model differences in temperature response such that some models strongly agree with the multi-model ensemble mean response, particularly in suggested enhanced wintertime warming in the high elevation regions such as the Tibetan Plateau, while others do not. Examples for some of these models are shown in supplementary figures S23 and S24 (available at stacks.iop.org/ERL/8/024040/mmedia).

To separate out the effects of latitude and altitude, we focus on the one latitude band (27.5°N–40°N) that contains some of the most important high elevation regions on the planet, the Tibetan Plateau/Himalayas and the Rocky Mountains. Figures 2(a) and (b) show how the 21st century changes in Tmin and Tmax during winter correspond to the mean surface elevation within the 27.5°N–40°N latitude band for the three emission scenarios. The temperature responses, as a function of elevation, in both figures are similar for all three scenarios. Although the changes in both Tmin and Tmax are sensitive to elevation, the relationship is stronger for Tmin. The changes in Tmin in the Tibetan Plateau region (80°–100°E) are much greater than for any other region. For Tmax, the increases are generally higher for a much broader region surrounding the Tibetan Plateau between 60° and 120°E. The elevation shown in figure 2 is from the HADGEM2-ES model after it has been horizontally interpolated to the 2.5° KNMI grid. Because individual models in this analysis will have different elevations than shown in the figure, there will be elevation-related differences in absolute temperatures. However, this has a negligible impact on the results shown in figure 2 because the temperatures there are differences between the beginning and end of the 21st century, so any elevational-related bias is removed.

Figure 3 shows a comparison of temperature response for different land regions within the 27.5°N–40°N latitude band for each season. Relative to other regions, the Tibetan Plateau has the largest increases in both Tmin and Tmax for both winter and spring with the exception of the Rocky Mountain region, which has the largest increase in Tmax during spring. Winter warming on the Tibetan Plateau is 40% higher than the global land average within this latitude band. For both winter and spring, the Tibetan Plateau shows greater and statistically significant (p < 0.01) increases in Tmin relative to Tmax. However, for the Rocky Mountains, there are greater increases in Tmax relative to Tmin in all seasons. The Rocky Mountain region also experiences greater warming in all seasons than the regions to their east and west on the North American continent. During summer, the temperature increases are comparable between high elevation regions and the global land average.

Changes in Tmin and Tmax from the six sub-regions (n = 225 grid points), described in figure 3, are plotted as a function of grid cell elevation in figure 4 for the RCP 4.5 scenario. Plots for other scenarios are shown in supplementary figures S25–S28 (available at stacks.iop.org/ERL/8/024040/mmedia). In general, increases in both Tmin and Tmax are enhanced with elevation in all seasons except summer. However, we find the strongest response of increases in Tmin with elevation during winter and spring, and of increases in Tmax during winter.

Table 1 shows the magnitude of temperature response with increasing elevation and the correlation of temperature change with elevation for all land based grid cells within the 27.5°N–40°N latitude band for each season and for each of the three RCP scenarios. Significant correlations are obtained for all seasons except summer, when there is no correlation between temperature response and surface elevation. The highest correlations (r > 0.75) are between Tmin anomalies and elevation during winter and spring. Except for summer, when there is no correlation, the magnitude of the warming response as a function of elevation increases with stronger emission scenarios. For example, the slope for the scatter plot showing increases in Tmin as a function of elevation for RCP 8.5 is more than double that of RCP 4.5.

We have examined several other climate variables and found that during winter, there are relatively greater increases in downward longwave radiation at higher elevations (r > 0.7) that are, in part, driving the enhanced Tmin response in mid-latitudes. Furthermore, the percentage increases in downward longwave radiation during winter are highly correlated (r > 0.9) with percentage increases in specific humidity (supplementary figures S19 and S21 available at stacks.iop.org/ERL/8/024040/mmedia). This relationship is consistent with the hypothesis of enhanced warming at high elevations, particularly in the Tibetan Plateau, caused in part by amplified water vapor feedbacks at these altitudes (Rangwala 2013). The enhanced winter and spring warming over the Rocky Mountain region, however, appears to be

### Table 1: Slope of linear regressions (°C km⁻¹) describing 21st century changes in temperature as a function of surface elevation for each season from three different emission scenarios. These values are calculated for land-only grid points within the 27.5°N–40°N latitude band as described in figure 4. Values in parentheses show correlation (r) between temperature change and elevation for these grid points.

| RCPs | DJF | MAM | JJA | SON |
|------|-----|-----|-----|-----|
| Tmin |     |     |     |     |
| 4.5  | 0.20 (0.74) | 0.16 (0.81) | 0.05 (0.19) | 0.09 (0.65) |
| 6.0  | 0.28 (0.76) | 0.19 (0.77) | 0.04 (0.07) | 0.10 (0.51) |
| 8.5  | 0.50 (0.80) | 0.37 (0.78) | 0.07 (0.00) | 0.19 (0.50) |
| Tmax |     |     |     |     |
| 4.5  | 0.16 (0.68) | 0.12 (0.58) | 0.05 (0.15) | 0.10 (0.60) |
| 6.0  | 0.20 (0.72) | 0.14 (0.53) | 0.06 (0.15) | 0.10 (0.50) |
| 8.5  | 0.36 (0.71) | 0.26 (0.60) | 0.05 (−0.01) | 0.19 (0.56) |
Figure 2. Projected 21st century changes in (a) Tmin and (b) Tmax (solid line) with surface elevation (dashed line) during winter (DJF) for the region within the 27.5°N–40°N latitude band for three different emission scenarios.

associated with increases in the surface absorption of solar radiation, in part, caused by decreases in the surface albedo in response to reduced snow cover (supplementary figures S10 and S11 available at stacks.iop.org/ERL/8/024040/mmedia).

4. Discussion
One of the fundamental questions related to climate change in mountains is whether warming rates in mountains are
enhanced relative to their surrounding lower elevation counterparts at the same latitude. Our analysis of the GCM projections for the 21st century indicates that in particular for the Tibetan Plateau, a region where GCMs have the most realistic representation of elevation, there will be much larger increases in Tmin during winter than for other land regions within the 27.5°N–40°N latitude band. The strongest positive correlations between temperature increases and surface elevation are obtained during winter, followed by spring, and the correlations are higher for Tmin than for Tmax. During summer, we do not see any significant relationship between temperature response and elevation. Furthermore, we find that the amplification of warming with elevation (dTemperature/dElevation) is greater for a higher emission scenario. These results corroborate findings by Liu et al (2009) of amplified increases in Tmin at higher elevations in the Tibetan Plateau during winter and spring in both observations and future model projections. For the North American region, the warming is greater over the Rocky Mountain region in all seasons, and substantially more during spring. In this study, we have not attempted to address the finer scale nature of elevation dependent warming within a mountain region because the existing spatial resolution of GCMs is still too coarse to adequately answer this question.

An important issue in this analysis is the potential impact of comparing surface air temperatures from different models that have different elevations associated with the same horizontally interpolated grid cell. Finer resolution models tend to have higher elevations because they can represent the topography better than coarser resolution models. We believe that this potential elevation mismatch has a negligible impact on our results because our analysis uses temperature differences between the beginning and end of the 21st century, hence removing any elevational bias that might be introduced.

We find that the enhanced Tmin response at high elevations, particularly in the Tibetan Plateau, is caused, in part, by relatively greater increases in downward longwave radiation. These increases in downward longwave radiation appear to be strongly influenced by increases in specific humidity because of the greater sensitivity of downward longwave radiation to changes in specific humidity at high elevations where the atmosphere is usually dry in winter. On the other hand, there is an enhanced response in Tmax at high elevations during winter and spring, particularly in the Rocky Mountain region, which is driven by increases in surface absorption of incoming solar radiation owing to decreases in surface albedo and snow cover.
Figure 4. Projected 21st century seasonal changes in (a) Tmin and (b) Tmax as a function of elevation within the 27.5°N–40°N latitude band for the RCP 4.5 scenario. The scatter plots \( n = 225 \) grid points) include only the six sub-regions (land-only grid points) described in figure 3. ‘m’ is the slope of the regression line in °C km\(^{-1}\).
More extensive analysis is needed to both identify and quantify the mechanisms responsible for the enhanced warming rates, including analysis of the individual model simulations. Among the possibilities are changes in surface albedo, clouds, atmospheric water vapor, atmospheric circulation, and aerosols. There are similarities between certain physical mechanisms associated with enhanced warming rates in mountains and at high latitudes. Both have significant snow and ice at the surface, are very cold in winter, and have generally low concentrations of atmospheric water vapor in winter. The snow/ice-albedo feedback is important in high latitudes, and most mountain studies that discuss this feedback find it to be important there, too (Chen et al. 2003, Giorgi et al. 1997). Furthermore, Chen et al. (2006) find that increasing water vapor in the Arctic could enhance winter warming rates because the sensitivity of downward longwave radiation to water vapor is much greater when the atmosphere is drier, as commonly found in winter. A similar effect is also found in high mountain regions in winter (Rangwala et al. 2010, Ruckstuhl et al. 2007). Furthermore, changes in atmospheric circulation could be an important factor. Li et al. (2012) suggest that a weakening of the Siberian High in winter has been responsible for the enhanced rates of warming in northwest China. There are also indications that increases in cloud cover could contribute to increasing minimum temperatures at higher elevations in the Tibetan Plateau (Duan and Wu 2006, Liu et al. 2009). Changes in aerosols can have an impact and the RCP scenarios tend to reduce aerosols later this century (Bellouin et al. 2011). Lastly, the warming rates projected by climate models for free air temperatures are greater at higher elevations which means that mountains could be warming faster than their lower elevation counterparts simply because their surface is at these higher elevations (Bradley et al. 2006). It’s likely that some combination of these, and other (e.g. Ohmura 2012), factors are coming into play.

In conclusion, our results are robust in showing that the rate of future mid-latitude warming will be enhanced at higher elevations relative to the surrounding landmass at the same latitude, particularly in the colder seasons, regardless of which future greenhouse gas emission scenario is examined here. This is particularly true for regions such as the Tibetan Plateau, where the elevation based forcing can be resolved sufficiently in our current GCMs.

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