A high-resolution climate model for the United States Pacific Northwest, Part II: Mesoscale feedbacks and local responses to climate change

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Abstract

Simulations of future climate scenarios with a high-resolution climate model show markedly different trends in temperature and precipitation over the Pacific Northwest than a global model in which it is nested, apparently due to mesoscale processes not resolved at coarse resolution. Present-day (1990-1999) and future (2020-2029, 2045-2054, and 2090-2099) conditions are simulated at high resolution (15-km grid spacing) using the MM5 model system and forced by ECHAM5 global simulations. Simulations use the IPCC Special Report on Emissions Scenarios (SRES) A2 emissions scenario. The mesoscale simulations produce regional alterations in snow cover, cloudiness, and circulation patterns associated with interactions between large-scale climate change and regional topography and land-water contrasts. These changes substantially alter the temperature and precipitation trends over the region relative to the global model result or statistical downscaling. Warming is significantly amplified in regions where snow cover is lost through snow-albedo feedback. Increased onshore flow in the spring reduces the daytime warming along the coast. Precipitation increases in autumn are amplified over topography due to changes in the large-scale circulation and its interaction with the terrain. The robustness of the modeling results is established through comparisons with the observed and simulated seasonal variability and with statistical downscaling results.
I. Introduction

The Pacific Northwest region of the United States (see map, Figure 1) is characterized by complex terrain and land-water contrasts, which produce strong spatial gradients in the regional climate and in the atmospheric processes controlling that climate. While global simulations indicate large-scale patterns of change associated with natural and anthropogenic climate forcing, they cannot capture the effects of narrow mountain ranges, complex land/water interaction, or regional variations in land-use. A major question in climate science is whether such mesoscale geographical features will significantly alter the local temperature and precipitation trends under climate change. For many resource decisions, information is required at very small scales. For example, Northwest watersheds supplying municipal energy and water are often 50-100 km in horizontal extent with important terrain features at 5-10km scales. Since global model grids can significantly mischaracterize the topography, land use, and land-water boundaries at this scale, any climate response driven by surface interactions (e.g. snow, orographic effects, vegetation effects) may not be reliable. Therefore, methods for producing climate change scenarios that can fully account for such effects are required.

A number of methods, ranging from statistical downscaling to regional climate models, have been applied to bridge the gap between global climate models and local impacts. While statistical methods have been successfully employed in the Pacific Northwest (Salathé, 2003, 2005; Widmann et al., 2003; Wood et al., 2004) and other regions (Giorgi and Mearns, 1999), they generally cannot capture the changes in the climate that result from interactions and feedbacks between the large-scale atmospheric state and mesoscale processes. While regional climate models attempt to simulate such interactions, until recently, such models have not been run at sufficiently fine grid spacing to properly resolve these mechanisms. For example, Wood et al. (2004) compared the results of a climate change simulation downscaled to the Pacific
Northwest using a regional climate model run at 0.5-degree (~50-km) grid spacing and downscaled to 0.125-degree spacing using a statistical method. The regional model and statistical method both produced a uniform warming trend from across the region, with differences of less than a degree Celsius between the two methods. In another study, Duffy et al. (2006) used four regional models, run at 36 to 60-km grid spacing, to simulate climate change over California. The simulations provided little evidence for a substantially different trend in warming in the regional models compared to the global model providing the boundary conditions.

High spatial resolution is essential to simulate mesoscale processes and their interactions with the large scale forcing. Without properly resolving these processes, a regional climate model is unlikely to improve on results from statistical downscaling. The effect of horizontal resolution on regional climate and weather simulations has been discussed extensively in the literature (Achberger et al., 2003; Christensen and Kuhry, 2000; Colle et al., 1999; Colle et al., 2000b; Duffy et al., 2003; Leung and Qian, 2003; Mass et al., 2002). Studies of two years of MM5 mesoscale weather forecasts for the Pacific Northwest (Colle et al., 2000a; Mass et al., 2002) show clear improvements with increasing resolution for precipitation, 10-m wind, 2-m temperature, and sea level pressure when comparing nested grids at 36 and 12 km resolution. Further increasing resolution to 4 km provides more detail and structure (e.g., defining steeper orographic slopes) but has only a limited impact on forecast skill, possibly due to limitations of current verification approaches. To explore model resolution, Leung and Qian (2003) performed a 5-year simulation using NCAR/NCEP reanalyses to provide boundary conditions for simulations on 40-km and 13-km two-way nested grids. They found that, compared to the 40-km nest, the higher resolution nest yields more realistic precipitation patterns and produces more frequent heavy precipitation, which is consistent with observations. To understand the effects of climate change on regions like the Pacific Northwest, resolving mesoscale processes controlling
precipitation, temperature, and winds is critical. Previous studies over the region (Mass et al., 2003) indicate that a model resolution of 15 km or finer is necessary. In Salathé et al. (2007b), we present a regional climate model developed for the Pacific Northwest, USA, and designed to meet these requirements for spatial resolution. This regional model is based on the Pennsylvania State University (PSU)-National Center for Atmospheric Research (NCAR) mesoscale model (MM5) and uses a configuration similar to that used for operational weather forecasting over the region.

To achieve long MM5 simulations, several issues were addressed in Salathé et al. (2007b). Interactions between the atmosphere and land surface are critical to the mesoscale climate response. To improve the simulation of these interactions, we have modified the soil parameterization in MM5 to allow the deepest layer of the soil to respond to climate change, rather than using a prescribed lower boundary condition. At climate time scales, the storage and release of heat deep in the soil can play an important role in the surface energy budget and on snow cover. Another important innovation for climate simulations is the forcing of the outermost nest in the mesoscale model with the global model results using a nudging approach. Nudging has two benefits. First, the mesoscale simulation is forced to better represent the large-scale circulation of the global model, which is assumed to be well resolved, and helps resolve boundary issues between the forcing model and the regional model. Second, the mesoscale simulation is more stable and conserves mass when nudging is used, which allows 10-year continuous simulations (i.e. without periodically reinitializing the mesoscale simulations). Continuous runs allow a much more realistic development of the land surface and its interaction with the atmosphere than mesoscale simulations that are reinitialized periodically, typically every few simulated days.

In this paper, we present results from regional climate model simulations for the Pacific
Northwest using a mesoscale atmospheric model with 15-km grid spacing. We shall illustrate a number of mesoscale effects that produce markedly different climate responses in the mesoscale model compared to the parent global model used to force the regional simulations. In particular, we find amplification of wintertime warming and intensification of autumn precipitation in the mesoscale model relative to the global model. These results may be related to mesoscale processes and feedbacks simulated by the regional model.

II. Model setup

To model the regional climate, we employ a limited-area atmospheric model, MM5, with boundary conditions prescribed by simulations from the ECHAM5 global atmospheric model coupled to the Max Planck Institute ocean model (MPI-OM). ECHAM5 is the fifth-generation general circulation model developed at the European Centre for Medium-Range Weather Forecasts and the Max Planck Institute for Meteorology. The global simulation used in this study was performed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and was forced with the Special Report on Emissions Scenarios (SRES) A2 emissions scenario (Nakicenovic et al., 2000). The A2 scenario entails a relatively aggressive increase in atmospheric carbon dioxide emissions over the next century. ECHAM5 was run at T63 spectral resolution, which corresponds to a horizontal grid spacing of approximately 150 km at mid-latitudes. Model output at 6-hourly intervals was obtained from the CERA WWW Gateway at <http://cera-www.dkrz.de/CERA/index.html>; the data are managed by World Data Center of Climate <http://www.mad.zmaw.de/wdcc/>.

The ECHAM5 model results were compared with other models participating in the IPCC AR4 to assess its performance in simulating 20th Century climate and its projected change in temperature and precipitation for the Pacific Northwest region (Salathé et al., 2007a). While the ECHAM5 simulations shows biases in temperature and precipitation typical of global models,
the annual cycle of both is well reproduced. Furthermore, given its relatively high horizontal and vertical resolution, this model produces realistic synoptic scale patterns over the eastern Pacific and western North America. Many models produce unrealistic cold events over the western U.S., with polar air masses flowing southward and westward from the interior of the continent instead of being blocked by the Rocky Mountains. The ECHAM5 A2 simulation produces far fewer of such unrealistic cold events. In contrast, the NCAR/DOE Parallel Climate Model produced many unphysical cold events, which created an unrealistic cold bias in mesoscale simulations forced by this model (Salathé et al., 2007b).

The Pennsylvania State University (PSU)-National Center for Atmospheric Research (NCAR) mesoscale model MM5 version 3.7 was used as a dynamic regional climate model, and ECHAM5 simulation data was used to provide initial and lateral boundary conditions every six hours. The ECHAM5-driven MM5 configuration will be referred to as “ECHAM5-MM5.” MM5 was developed for mesoscale weather forecasting and has been operating in real-time at the University of Washington (UW) and many other locations for over a decade. It has also been used in regional climate modeling studies (e.g. Leung and Qian, 2003) and in idealized climate sensitivity studies (e.g. Hartmann and Larson, 2002). Details of the configuration used for this study may be found in Salathé et al. (2007b)

High resolution over the Pacific Northwest is achieved by using multiple MM5 nests (Figure 2), with 135 km, 45 km, and 15 km horizontal grid spacing, that are in turn nested within the global model. The outer MM5 domain encompasses nearly the entire North American continent and much of the eastern Pacific Ocean, enabling it to capture synoptic-scale processes that influence Pacific Northwest climate. The second nest covers the western United States and portions of Canada and Mexico, providing higher-resolution simulation of storm systems and monsoon circulations that influence the western United States. The innermost (15-km) domain
covers the entire Columbia River Basin, including southern British Columbia, Washington, Oregon, and Idaho. Regional model runs were completed for the decades 1990-1999, 2020-2029, 2045-2054, and 2090-2099. Ten-year time slices were chosen to strike a balance between selecting a time period long enough to avoid bias due to interannual variability (such as that resulting from ENSO) and short enough to isolate a time period for which global climate change would essentially be static.

This modeling configuration has been verified against observations for simulations forced both by the ECHAM5 climate model and by NCAR/NCEP Reanalysis fields (Salathé et al., 2007b). These results show acceptable performance of the model except for nighttime temperatures, which are too cold in the simulation. This deficiency can be traced to the land-surface model, and corrections have been made in the most recent releases of this model that considerably reduce the bias.

III. Results

We present below the overall features and patterns of change in the ECHAM5-MM5 climate change simulations relative to the base climate. Due to the large interannual climate variability in the Pacific Northwest, we cannot characterize the certainty of the results from these simulations. However, many features appear to be robust and are related to known large-scale forcings. In the following section, we shall discuss in more detail the physical mechanisms responsible for these results.

A. Temperature

Figures 3a-3c show the change in winter (Dec-Jan-Feb) 2-m air temperature simulated by the regional model from the current climate (1990-1999) to the three future decades, 2020-2029 (Fig 3a), 2045-2054 (Fig 3b), and 2090-2099 (Fig 3c). A distinct geographic pattern develops over time in the regional temperature simulation. The model produces amplified warming along
the flanks of the various mountain ranges and across the high plains of eastern Washington, eastern Oregon, and southern Idaho. This pattern is well established in the 2020s and becomes stronger through the simulation, yielding considerable warming in some regions by the 2090s. The dominant features of the warming pattern remain the same in each simulated decade as the warming intensifies. This result suggests that the pattern is not overly affected by interannual variability, but controlled by the climate change forcing from the ECHAM5 model.

For the other seasons of the year, the pattern is again similar for each decade, so only the 2045-2054 results are shown in Figures 3d-3f. For the season March-April-May (Fig 3d), we again find a pattern of amplified warming following the terrain. In this case, however, the amplification is at the highest elevations, following the crest of the Cascade Range. A considerably lower warming rate is simulated along the coast, west of the Cascade Range. For June-July-August (Fig 3e) and September-October-November (Fig 3f), the regional model does not produce significant fine-scale features in the simulated warming. An exception is the large warming rates for the high elevations of the British Columbia Coast Mountains for JJA.

B. Precipitation

Figure 4 compares annual total precipitation from 1990-1999 to the three future 10-year simulations (positive values indicate increased precipitation in the future decade). The mesoscale simulations performed here show no persistent trend in the annual total precipitation pattern over the three decades. There is some similarity in the patterns for 2020-2029 (Fig 4a) and 2045-2054 (Fig 4b), with decreases over southwestern British Columbia and increases over the northern Cascades. However, a very different pattern is simulated for the 2090s, with large decreases along the mountains of Oregon and southcentral Washington and increases along the mainland British Columbia coast. While there is considerable variability in the response over coastal and mountain regions, a small increase in precipitation is consistently found over the inland portion
of the domain. The global climate models used in the IPCC Forth Assessment indicate a relatively weak but robust positive trend over the region (Christensen et al., 2007), which is consistent with the inland trend. The more striking patterns of change are related to mesoscale interactions with the surface that are not captured in global models.

The precipitation change for the 2045-2054 simulation is broken down by season in Figure 5. While DJF shows a decrease in precipitation over the northwest part of the domain, widespread increases are simulated for MAM and SON. The basic geographical distribution and sign of precipitation changes simulated the regional model correspond with the precipitation field simulated by the global model (Fig 6). This result suggests that changes in large-scale storms and moisture flux in the global model play a large role in forcing the precipitation response in the regional model. The regional model shows significant modifications of the large-scale patterns, which reflects the influence of mesoscale processes, which will be discussed below.

IV. Regional Effects on Temperature

A. Snow-albedo feedback

Snow-albedo feedback plays a pivotal role in global climate model simulations (Holland and Bitz, 2003). Global models, however, cannot realistically represent this feedback at regional scales since they do not resolve the slopes and elevations of the regional topography. Previous research with regional models has shown that this feedback may operate at fine spatial scales. Giorgi et al. (1997) report amplified warming with elevation both in observations and in a regional climate model for the Alpine region. Leung and Ghan (1999) show amplified warming in MM5-based simulations for the Pacific Northwest. Duffy et al. (2006) compare snow albedo effects in simulations from several regional models over the southwestern U.S. Amplified warming is seen along the Sierra Nevada Mountains in results from an MM5-based model run at 50-km grid spacing. Three other models, however, do not show a comparable effect, although
these are spectral models, which may have difficulty adequately representing the topography at this spatial resolution.

For the simulations at 15-km resolution presented here, the snow-albedo feedback yields considerable fine-scale spatial structure. Regions of amplified warming, following the terrain, are evident in the regional simulations for DJF (Fig 3a-c) and MAM (Fig 3d). Figure 7a shows the DJF 1990-1999 to 2045-2054 warming in the ECHAM5-MM5 regional simulation minus the warming in the global ECHAM5 model. Positive values indicate more warming in the regional model than the raw global model; negative values indicate less warming. Figure 7b shows the DJF-season loss of snow from 1990-1999 to 2045-2054 as indicated by the reduction in the frequency of days with more than 50% snow cover. Figure 7c shows the change in albedo over the same period. The warming pattern (Fig 3b) clearly matches the loss in snow and the decreased albedo. Local amplification of warming in the mesoscale model relative to the raw global model exceeds 1°C over much of eastern Washington and Oregon and 2°C over the Snake River plain in southern Idaho for the 2040s.

To illustrate the localized differences in the response to climate change over the Pacific Northwest, we select five locations: the Snake River Plain, the Columbia Basin, the Cascade crest, the Cascade western slope, and the Washington coast (see Fig. 1). Figure 8 shows the simulated change in 10-year mean DJF temperature from 1990-1999 to each future decade for the five geographical locations. The warming trend is considerably different at each point, ranging from 2.8 to 5.2 K/century. The regions with the greatest warming have marginal snow cover that responds quickly to warming. The Washington coast, where there is no snow, and the Cascade crest, where snow cover persists under climate change, experience relatively less warming. This variation in the warming trend across the region is comparable to the range in trends from 10 different climate models (Salathé et al., 2007a).
The regions of negative values in Figure 7a indicate a smaller warming signal in the ECHAM5-MM5 simulation, as compared to the raw ECHAM5 simulation. The larger warming in the global model also results from its inability to properly resolve the snow-albedo feedback. Figure 9 shows the warming in the ECHAM5 model from 1990-1999 to 2045-2054, with contour lines indicating the topographic relief for the model. The region of greatest warming lies along the western slopes of the Rocky Mountains, as depicted by the model topography. The global model simulates a large reduction in surface albedo due to snow loss (not shown) in this area. The topography in the ECHAM5 model, however, is substantially different from the true topography, and the region of high elevations in British Columbia, Canada, is in fact a low basin between the Rocky Mountains and Coast Range (Figure 1). Thus, the amplified warming depicted in the raw ECHAM5 model over these regions is spurious, and leads to the larger warming trend in these locations relative to the regional model.

B. Validation of simulated snow-albedo feedback

Confidence in the simulated snow-albedo feedback depends on two conditions: 1) The present-day snow cover must be reasonably captured by the model since the feedback will occur at the margins of the snow-covered area. 2) The change in snow cover and albedo for a given amount of warming must be reasonably captured in order to represent the magnitude of the feedback. Given the mixed results in the literature and uncertainty in the ability to represent present-day snow cover, we shall attempt to validate the snow-albedo feedback in the model by comparing the transition from winter to spring as simulated by the model and as captured by stations observations.

The transition from winter to spring in the Pacific Northwest produces a significant retreat of the snowline along the major mountain ranges and elevated basins. We shall use this change as an analog for climate change to test the model. The difference between the April and
January 10-year monthly mean surface (2-m) air temperature from the 1990-1999 ECHAM5-MM5 simulation is shown in Figure 10a, and indicates a similar spatial pattern to the climate change pattern shown in Figure 3a. To illustrate the role of snow cover in this seasonal change pattern, we compute, at each gridcell, the fraction of days in the decade with 50% or greater snow cover for each calendar month. Figure 10b shows the change in the fractional snow cover from January to April from the 1990-1999 simulation. There is intensified warming at the locations of maximum loss of snow cover, indicating that MM5 simulates a snow-albedo feedback in the transition from January to April, and this feedback helps determine the spatial pattern of warming.

To verify this seasonal warming pattern, we may compare the regional simulation to station observations. The United States Historical Climatology Network (USHCN) (<http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html>) (Karl et al., 1990) includes 113 observing stations in WA, OR, and ID with good coverage of the patterns of warming and snow loss depicted in Figure 10. We compute the 10-year mean (1990-1999) January-to-April temperature change at each station and, in Figure 11, plot this value against the corresponding grid cell value from the MM5 simulation. The model produces a small overestimate of the seasonal warming, but this bias is uniform across all stations, and thus is not related to snow processes. Importantly, the contrast between regions of strong and weak warming corresponds quite well between the model and station network, as indicated by the slope of 0.91 and correlation of 0.82, suggesting the model does not exaggerate warming in areas where there is snow cover in January.

Reproducing the pattern of seasonal change tests many basic elements of the climate system response associated with snow cover. Success in capturing the seasonal warming pattern suggests the model correctly captures the interactions between snow and warming in the seasonal
cycle. Certainly, if a model cannot capture this seasonal pattern of change, one cannot have confidence in the simulated patterns associated with climate change. Furthermore, these observed changes occur on a spatial scale that cannot be depicted in a global model or coarse-resolution regional model.

C. Spring Cloudiness and Diurnal Temperature in spring

For the spring season (Mar-Apr-May), the predominant pattern of temperature change is similar to that in winter, with an intensification of warming over high terrain (Fig 3d). For spring, the intensification moves upslope following the snowline, and maximum warming is found along the crest of the Cascade Range and the higher terrain north of the Snake Plain. Compared to the global climate model or statistical downscaling, which is based only on daily-mean temperature, the regional model reveals a considerably more complex response. Figure 12 shows the difference in simulated MAM warming from 1989-1999 to 2045-2054 between the ECHAM5 global simulation and the ECHAM5-MM5 regional simulation for (Fig 12a) Tmax and (Fig 12b) Tmin. Positive values indicate larger warming in the regional simulation. Along the coastal zone west of the Cascades, the regional model maximum daytime temperatures show considerably less warming than the raw ECHAM5. In the mountains, where snow-albedo feedback is important, the warming is greater for the regional simulation. Nighttime minimum temperatures show greater warming in the regional model than the global model for most of the domain, including the regions that show less warming during daytime.

The greater warming of the continental interior, relative to the oceans, establishes an anomalous on-shore pressure gradient, as can be seen from the 850-hPa height field (change from 1990s to 2050s, Figure 13a). This pressure gradient increases the climatological onshore flow (streamlines in Figure 13b) and cloudiness as indicated by the change in integrated surface to 850-hPa cloud water concentration (Figure 13b); the increase follows the windward slopes of
the terrain, suggesting increased clouds banked against the coastal mountains. The increase in low-level cloudiness derives from two effects. The ECHAM5 global simulation and the 45-km regional domain (not shown) indicate an overall increase in maritime clouds off the US West Coast associated with a strengthening of the Pacific High along the coast. The high shifts eastward in each of the ECHAM5-MM5 future simulations (i.e. 2020-2029, 2045-2054, 2090-2099) relative to the base climate (1990-1999). The increase in maritime cloudiness under the Pacific High likely amplifies the effect of the anomalous on-shore winds on the coastal clouds.

The mechanism for the increased high is not clear, and this result is not seen in all global models (Croke et al., 1999). Nevertheless, the increased onshore flow would itself tend to increase coastal cloudiness, which would have a profound effect on the regional simulation of climate change. Observational studies have shown increased cloudiness over the Southwest US and over land areas worldwide under 20th Century climate change (Croke et al., 1999; Karl et al., 1993). Increased cloudiness reduces the incident solar radiation at the surface, producing a cooling effect during daylight hours. The increased cloudiness also increases downwelling infrared radiation, which produces a warming effect throughout the diurnal cycle. The net result is a decrease in the diurnal range. As in DJF, there is substantial snow loss in the spring, increasing shortwave absorption at the surface. When averaged over all times, the net radiation at the surface shows a slight decrease west of the Cascade crest, indicating that the shortwave cooling is dominant, especially during daylight hours. Over the remainder of the region, the combined effects of decreased albedo and increased downwelling longwave radiation yield a warming effect.

In Figure 14, we show changes in MAM maximum and minimum temperature simulated for the five locations, Snake River Plain, Columbia Basin, Cascade Crest, Cascade western slope, and Washington Coast, over the four decades (following Fig. 8). Figure 14a shows $T_{\text{max}}$ at the
five locations; the lower warming rate for the Washington Coast and Cascade west slope, compared to the rest of the region, is clearly seen and is consistent for all decades. The most rapid warming appears along the Cascade Crest, rather than at mid elevations, as found in winter. The rate of nighttime ($T_{\text{min}}$) warming (Figure 14b) is more uniform across the region, with enhancement at the Cascade Crest late in the century as the snow-albedo effect moves to higher elevations.

V. Regional Effects on Precipitation

The consensus among climate model simulations performed for the IPCC AR4 indicates a modest increase in precipitation over the Pacific Northwest during the months November through January (Christensen et al., 2007; Salathé, 2006), with increases of about 10-15% for 2050-2100 relative to 1950-1999 and approximately half of this enhancement in November. The increase appears to be related to changes in the mid-latitude storm tracks, which move poleward and intensify under climate change (Yin, 2005). At the regional scale, simulations of precipitation over Europe using regional climate models with approximately 50-km resolution (Frei et al., 1998; Frei et al., 2003) show increased precipitation in the winter season. In an earlier study of regional climate simulations for the Pacific Northwest using a 90-km resolution model, Leung and Ghan (1999) showed a considerable enhancement of precipitation over the region. Snyder et al. (2002), using a regional model forced by a simulation using the NCAR Community Climate Model (CCM3), found large increases in precipitation over Northern California under a 2xCO2 experiment. Theses prior studies suggest that there are two influences on precipitation under climate change. The first is related to changes in the large-scale moisture flux and storm patterns, which can be resolved by global modes, and the second relates to mesoscale interactions with the surface orography, which can only be captured in a high-resolution model.
Not all climate models simulate an increase in precipitation, and regional simulations tend to follow the response of the driving model. In simulations using a MM5-based regional climate model with 50-km grid spacing and forced by an ensemble of three Parallel Climate Model (PCM) simulations, Leung *et al.* (2004) found no statistically significant change in precipitation due to climate change over the western US. Compared to a large sample of global models (Salathé *et al.*, 2007a), the PCM produces a relatively small precipitation response, the ECHAM5 yields a moderate increase, and some models produce a considerably larger response than ECHAM5.

As seen in Figures 5 and 6, while there is clear large-scale correspondence between the forcing global model and the regional model, the regional pattern of precipitation changes are considerably different from the global simulation. Here we will discuss the pattern for SON in the 2045-2054 regional simulation, which shows a large increase in precipitation along the full length of the Cascade Range. The mechanisms producing changes in regional scale precipitation are suggested by statistical downscaling results using two empirical methods (Salathé, 2005; Widmann *et al.*, 2003). In both methods, a 1/8-degree gridded dataset based on historic observations (Maurer *et al.*, 2002; Widmann and Bretherton, 2000) is used to develop a scaling factor at 1/8-degree resolution during a 50-year training period, 1950-1999, where the observations and a historic global simulation overlap. Precipitation simulated by the climate model is sampled onto the 1/8-degree grid and the product between this and the empirical scaling factor yields the downscaled precipitation field. In the first method, only the global-model precipitation is used to develop the scaling. In the second method, both global-model precipitation and low-level circulation are used, and the scaling factor is fit during the training period to maintain the observed covariance between sea level pressure and precipitation. The large-scale circulation patterns over the Pacific Northwest control the orographic enhancement of
precipitation on the upwind slopes of the Cascade and Coast Ranges and the rain shadow in eastern Washington and Oregon. Thus, the first method indicates the changes over time in regional precipitation that are captured only by the precipitation field in the model. This result would capture effects due to, for example, changes in the large-scale moisture flux and changes in the frequency and intensity of large-scale storms. The second method includes additional perturbations in regional precipitation caused by changes in the large-scale circulation, which helps account for interactions with the regional topography.

Figure 16a shows the change in precipitation from 1990-1999 to 2045-2054 from the precipitation-only downscaling (the statistical downscaling does not extend over Vancouver Island and western British Columbia). The result in Figure 16a is everywhere the same sign as the change from ECHAM5 in Figure 6d, but the magnitude is scaled in relation to the magnitude of the observed precipitation. With this downscaling applied, the ECHAM5 model predicts modest changes in precipitation over the northern portion of the domain. The second downscaling method indicates a considerably greater precipitation increase that extends farther south along the Cascade Range (Fig 13b). The second downscaling method attempts to relate circulation changes with the regional distribution of precipitation in the present climate. Thus, the large-scale state in the climate change simulation is similar to the large-scale state during times of orographic enhancement in the present climate.

The ECHAM5-MM5 mesoscale simulation (Fig. 13c) shows increases in precipitation generally similar to the second downscaling method (i.e., including the effects of circulation). Contour lines indicate the change in 500-hPa heights, showing a shift in the large-scale circulation to a more on-shore flow. The magnitude of the precipitation increase in the ECHAM5-MM5 simulation is similar to the result for statistical downscaling (Fig 13b), but the region of increased precipitation extends farther south along the full Cascade Range into Oregon.
Similar increases are also seen for the Olympics and the coastal mountains of southern Oregon and Northern California. To the north, there is a decrease over Vancouver Island and the BC Coast Range. These mountain ridges follow a southeast-northwest line as opposed to the north-south line of the ridges in Washington and Oregon. Thus, the circulation shift from the southwest to westerly, which enhances the orographic effect over north-south ridges in WA and OR would have the opposite effect for the northwest-southeast BC ridges. Using observations and MM5 simulations, Leung et al. (2003) have shown that the southwesterly flow associated with El Niño reduce the orographic precipitation along the north-south Cascade Range, despite the increased moisture flux associated with southwesterly flow. In contrast, east of the Cascade Range, rainfall increases during El Niño. The results above suggest that similar interactions between orography and the large-scale flow will also be important under climate change. Statistical downscaling methods may be able to capture some of these effects. However, since the range of conditions simulated in future climate scenarios may not be fully represented by the historic record and since orographic precipitation involves dynamic and thermodynamic processes at very small scales, a regional climate model is a more appropriate tool for capturing these interactions.

VI. Conclusions

We have used high-resolution (15-km) simulations from the MM5 mesoscale model forced by the ECHAM5 global model to explore several mesoscale processes that modify climate change at the local level. In winter and spring, the snow-albedo effect acts at fine spatial scales to determine local warming patterns, with considerable amplification of warming along the margins of the present-day snow pack. In spring, increased on-shore flow is forced by differential heating over land and sea. In the model, this flow results in increased low-level cloudiness along coastal areas, which reduces the daytime warming trend and the diurnal temperature range. During autumn, the ECHAM5 global model shows an increase in the large-
scale precipitation as well as changes in the prevailing circulation patterns. The shift to more onshore flow increases the orographic precipitation along of the north-south ridges of the Cascade Range and parts of the Rockies.

These results give strong evidence that the local response of temperature and precipitation to climate change is influenced by mesoscale processes that are not captured by coarse-resolution global models. While this study is limited to a single scenario from a single global model, this fundamental result depends on clear physical mechanisms that appear to be robust. In particular, snow-albedo feedback enhances warming over regions in which snow pack is lost. we have confidence in the ability of the regional model used here to represent this effect, since it duplicated similar changes that are observed in the annual transition from January to April, when snow-albedo plays an important role in the seasonal cycle. Since the global model does not represent the local topography well, it cannot properly simulate snow-albedo feedback, which leads to areas where the coarse-resolution global model either underestimates or overestimates the warming rate since. Warming in mountainous areas is critical to the climate change impacts on the region due to the importance of the snowpack for regional water resources and ecology. Areas in the Cascade Range show much greater rates of winter and spring warming in the regional model as compared to the global model. These areas contain watersheds that supply municipal water and hydroelectric power to urban areas of Washington and Oregon. Increased winter warming would hasten the loss of snowpack that is essential for storing winter precipitation for summer consumption. On the other hand, reduced wintertime warming rates in the Canadian Rockies would suggest a lesser impact of climate change on the Columbia River, which is a critical source of power and water throughout the western United States. However, since the regional model shows greater warming over much of the Columbia Basin, in particular for the Snake River, a major tributary, the net effects on Columbia flows cannot be estimated
from these results and further research using hydrologic simulations will be required.

For spring, the regional simulations show increased onshore flow and cloud cover. These changes considerably reduce the daytime warming rate relative to the global model, reducing the diurnal range. The reduced warming rate and decrease in solar radiance could have important impacts on air quality and consumptive water use for irrigation (both agricultural and landscape). The magnitude of this effect depends on the cloud representation in the model. The underlying mechanism of increased onshore flow, however, is highly plausible and would itself lead to reduced warming rates -- even if the increase in cloudiness is exaggerated by the model. Blocking by coastal mountain ranges and associated mesoscale effects modulates this mechanism, and thus it cannot be represented in coarse-resolution models.

The response of regional precipitation to climate change is a complex interaction between large-scale storm systems, which are well resolved by global models, and the local terrain, which is not well resolved. Global model consensus of Pacific Northwest climate change indicates an increase in autumn precipitation (Salathé, 2006) and changes in the circulation associated with midlatitude storm tracks (Salathé, 2006; Yin, 2005). Statistical downscaling indicates that the simulated circulation changes should enhance precipitation along the north-south ridges of the Pacific Northwest, but such methods may miss significant features. In fact, the regional model suggests a more widespread increase in precipitation along the Cascade Range extending farther south than indicated by statistical downscaling. Thus, while there is considerable interannual variability in these processes, there is strong evidence that the large-scale circulation patterns will be altered under climate change and that these changes will in turn modify orographic precipitation.

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VII. References


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Figure 1. Geography and topography of the Pacific Northwest.
Figure 2. Mesoscale model domains for the current study. Grid spacing for each domain is: Domain 1, 135 km; Domain 2, 45 km; Domain 3, 15 km.

Figure 3. Simulated seasonal temperature changes (°C) relative to 1989-1999 for a) 2020-2029 DJF b) 2045-2055 DJF c) 2090-2099 DJF d) 2045-2055 MAM e) 2045-2055 JJA f) 2045-2055 JJA
Figure 4. Simulated annual mean precipitation changes (mm/day) relative to 1990-1999 for a) 2020-2029 b) 2045-2055 c) 2090-2099.
Figure 5. Simulated seasonal precipitation changes (mm/day) from 1989-1999 to 2045-2055 from the ECHAM5-MM5 regional model for a) DJF b) MAM c) JJA and d) SON.
Figure 6. Simulated seasonal precipitation changes (mm/day) from 1989-1999 to 2045-2055 from the ECHAM5 global model for a) DJF b) MAM c) JJA and d) SON.
Figure 7. Changes from 1990s to 2050s December-January-February season for a) difference in raw model change and mesoscale model change in 2-m air temperature, b) frequency of 50% snow cover, and c) surface albedo.
Figure 8. Change relative to 1990s at five stations for DJF 2-m air temperature (°C)

Figure 9. 1990s to 2050s change in 2-m air temperature (°C) in raw ECHAM5 model; Contours indicate model terrain.
Figure 10. April minus January 1990s MM5-ECHAM5 simulation a) 2-m air temperature b) Fraction of days with 50% snow cover of grid cell.

Figure 11. Comparison of observed (HCN) and simulated (MM5) change in air temperature from January to April at stations indicated in Fig. 10a.
Figure 12. Difference in simulated MAM changes from 1989-1999 to 2045-2054 between the ECHAM5 global simulation and the ECHAM5-MM5 regional simulation for a) Tmax and b) Tmin (°C). Positive values indicate larger warming in the regional simulation.

Figure 13. Simulated MAM changes from 1989-1999 to 2045-2054 for a) 850-hPa heights (m) b) integrated cloud water (ppmv) and surface wind.
Figure 14. Change relative to 1990s at five stations for MAM 2-m daily a) Tmax b) Tmin (°C).
Figure 15. Change in precipitation (mm/day) for SON season from 1989-1999 to 2045-2054 for a) downscaling with precipitation only b) downscaling with precipitation and sea-level pressure c) regional model.