A high-resolution climate model for the United States Pacific Northwest, Part I:

Model design and verification

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Abstract

Results from a regional climate model optimized for the United States Pacific Northwest and based on the MM5 mesoscale model is presented. In order to perform long simulations and fully represent the climate system response to climate change forcing, several refinements are made to the MM5 configuration used for weather forecasting over the same domain as the climate model. The resulting model provides higher spatial resolution than previous regional models used to simulate climate change for the United States and thus captures fine-scale mesoscale feedbacks in the climate system. This modeling system is applied to downscale NCAR-NCEP Reanalysis and a global climate model simulation of the 1990s climate. Mesoscale results are validated against station observations covering the simulation domain. A cold bias in the global climate model simulations due to excessively cold arctic outbreaks force a cold bias in the mesoscale simulation for winter months; the simulation forced with reanalysis fields does not show this bias. Nighttime minimum temperatures show a considerable cold bias, which is likely due to deficiencies in the land surface model. The annual cycle of precipitation is captured well for wet stations, but overestimated during the winter (wet) season at arid sites.
I. Introduction

Expanding awareness of the regional impacts of global climate change has led to increased demand for detailed regional climate change scenarios. Global climate models – run with horizontal grid spacing on the order of hundreds of kilometers – capture large-scale atmospheric features and processes, but cannot represent fine-scale atmospheric and surface features that determine climate on regional scales. Various downscaling techniques have been developed to yield higher-resolution regional information based on lower-resolution global climate model output. Statistical downscaling makes use of empirical statistical relationships between large scale predictor fields and small scale fields observed in the past. Since physical processes and feedbacks that may function differently in an altered climate, it is unclear how well such methods can represent future regional trends that are not captured by the global model.

Another approach to climate downscaling, which attempts to capture the effect of such interactions, is to apply a high-resolution, limited-area mesoscale model (or regional climate model) for downscaling the global climate model. The global climate model output is used to initialize the regional model and to update its boundary conditions periodically. The aim of this dynamic downscaling method is to generate realistic regional climate information consistent with the large-scale circulation (which is well-resolved by the global climate model) while giving detailed representations of physical processes at high spatial resolution that can resolve complex topography, land-sea contrasts, and land use (Wang et al., 2004). Recent advances in computational resources have allowed for longer model runs and higher spatial resolution. There
are extensive reviews of these methods in the literature (Fowler et al., 2007; Leung et al., 2004a; Mearns et al., 1999).

The Pacific Northwest presents features that make mesoscale climate modeling particularly appropriate. The terrain of the Pacific Northwest includes complex topography and intricate land-sea contrasts (see Figure 1). These features are not well represented in global climate models, and the resulting small-scale weather phenomena that determine local climate – such as convergence zones, rain shadows, Sound Breezes, and gap flows – are absent from such simulations. Indeed, Mass et al. (2002) found that horizontal model grid spacing coarser than 15 km was unable to properly resolve crucial mesoscale features produced by terrain and surface contrasts in the Northwest. Typical global climate models, with 150-km or greater horizontal grid spacing, do not resolve the topography of Washington – including Puget Sound, the Columbia Basin, and the desert regions East of the Cascade Mountain Range – and therefore cannot properly simulate the characteristic regional circulation or the distribution of precipitation and other fields.

We have implemented a regional climate model optimized for the Pacific Northwest and based on the MM5 mesoscale model configuration that has long been used for real-time numerical weather prediction for the region. In order to perform long simulations and to enable an integrated system response to climate change forcing, we have made several refinements to the real-time MM5 configuration. In this paper, we report on the new features we have implemented for high-resolution regional climate modeling and present validation results for the modeling system. We have applied this modeling system to downscale NCAR-NCEP Reanalysis
and two global climate models for the present climate. Validation is based on comparison to station observations over the domain from the Historical Climate Network. In a second paper (Salathé et al., 2007b), we present results from climate change simulations and examine the mesoscale feedbacks and interactions with the large-scale climate forcing.

II. Model Configuration

The regional climate model we present here is a limited area model, and thus must receive forcing data, *i.e.* initial and boundary conditions, from another source model. First, we summarize these large-scale simulations and follow with a detailed discussion of the regional model configuration.

A. Forcing data

Reanalysis simulations with a general circulation model (GCM) provide excellent forcing grids for validating the regional model. Reanalysis grids are similar to output from free-running climate models in terms of spatial resolution and physical parameterizations. Since observations are assimilated into the simulation, reanalysis fields such as temperature, geopotential heights, and humidity are closely constrained to the actual atmospheric state. Thus, the output fields represent those from an idealized GCM in which the large-scale atmospheric state and its time evolution are well represented on daily, seasonal, and interannual time scales. Regional simulations forced by reanalysis fields help isolate deficiencies in the regional model without the complexity of biases inherited from the forcing model. Here, we use the NCEP/NCAR Reanalysis Project (NNRP) fields (Kalnay et al., 1996) for the 10-year period 1990-1999. Data
are simulated at 6-hourly intervals, 2.5x2.5-degree horizontal resolution (approx. 275 km x 200 km), and 17 pressure levels.

We also present simulations forced by a free-running global climate model, ECHAM5, which is used for climate change simulations in a companion paper (Salathé et al., 2007b). The global model is the fifth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology (ECHAM5) coupled to the Max Planck Institute ocean model (MPI-OM). The simulation used for this study was performed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007) and was forced with observed radiative parameters. ECHAM5 was run at T63 spectral resolution, which corresponds to a horizontal grid spacing of approximately 140x210 km grid spacing at mid-latitudes.

Output from the forcing models were used to provide initial and lateral boundary conditions every six hours for the regional climate model. The global model output was also used to “nudge” the outermost regional model domain, which is discussed in detail below. Regional simulations will be referred to as NNRP-MM5 and ECHAM5-MM5 to indicate the forcing model.

B. Regional Model

The Pennsylvania State University (PSU)-National Center for Atmospheric Research (NCAR) mesoscale model (MM5) Release 3.6 was used as the regional climate model. MM5 was developed for mesoscale weather forecasting and has been operating as such in real-time at the University of Washington (Mass et al., 2003) and many other places for over a decade (Mass and Kuo, 1998) and, more recently, as a tool for regional climate modeling (Leung et al., 2004b).
MM5 is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation (Grell et al., 1993). Parameterizations include Kain-Fritsch convective parameterization (Kain and Fritsch, 1993), Medium Range Forecast model (MRF) planetary boundary layer (PBL) scheme (Hong and Pan, 1996), CCM2 radiation scheme (Hack et al., 1993), and Simple Ice cloud microphysics (Dudhia, 1989).

High regional model resolution is achieved by using multiple MM5 nests at 135 km, 45 km, and 15 km horizontal grid spacing. Figure 2 shows the MM5 nests used in this study. One-way nesting is utilized. That is, the global climate model is run independently first, without updates from the regional model solution; furthermore, information only passes from the outer to inner nests in the mesoscale simulation.

In order to capture the large-scale processes important for Pacific Northwest climate, the outermost MM5 domain encompasses nearly the entire North American continent and much of the eastern Pacific Ocean. The use of such a large outer domain keeps the outer mesoscale boundaries far from the region of study and ensures that weather systems approaching the Pacific Northwest are well represented by the time they reach the region. The second nest covers the western United States and portions of Canada and Mexico, capturing storm systems and Southwest Monsoon circulations that influence the Pacific Northwest. The innermost domain covers the states of Washington, Oregon, and Idaho and the entire Columbia River Basin.

High spatial resolution is critical to success in capturing the essential features of the Pacific Northwest climate, and the 15 km resolution chosen here should be sufficient. Mass et al. (2002) demonstrated, using MM5, that increasing horizontal grid spacing – from 36-km to
12-km grid spacing – improved mesoscale weather forecasts for precipitation, 10-m wind, 2-m air temperature, and sea level pressure in the Pacific Northwest. Similarly, Leung and Qian (2003) showed an improvement in reproducing precipitation patterns over topography when increasing regional model resolution from 40 km to 13 km grid spacing.

1. **Nudging**

As with the MM5-based real-time numerical weather forecasting system used at the University of Washington (Mass et al., 2003), nudging is applied to the outermost regional model domain from the forcing fields. Nudging relaxes the regional model solution for wind, temperature, and moisture towards the driving global climate model solution. The relaxation takes place throughout the interior of the domain and at all vertical levels above the planetary boundary layer. Particularly over large domains, the regional model solution can drift over time from that of the driving global climate model. If we assume that the global climate model reasonably captures synoptic-scale structures and that the goal of the dynamic downscaling system is simply to obtain fine-scale detail for a given large-scale pattern, then the regional model should not modify the large-scale patterns, and such a drift is undesirable.

Other methods to limit this drift rely on using smaller regional model domains (Jones et al., 1995) or periodic (e.g. every 10 days) reinitializations of the simulation (Pan et al., 1999). Since some spin up time is required after each reinitialization, this approach is computationally inefficient. More importantly, however, reinitializing the model interferes with the coupling between the atmosphere and slow varying parameters in the model, such as soil parameters and snow cover, that are the essence of climate system modeling. Von Storch et al. (Von Storch et
showed that nudging was able to keep simulated states close to the driving state at large scales while still generating small-scale features. Nudging allows for larger regional model domains and makes continuous model runs possible while limiting model drift. Figure 3 shows the results of domain-averaged pressure from two short model runs, forced by NCEP-NCAR Reanalysis grids. With nudging (red line), the simulation closely follows the pressure from the large-scale model (green line). Without nudging (blue line), however, the simulation quickly diverges from the forcing field.

The inner two domains are not nudged, allowing the mesoscale model to freely develop atmospheric structures at finer spatial scale. This approach attempts to preserve the large-scale state provided by the global model while generating regional meteorological details on the inner nests.

2. **Soil Parameterization**

Accurate representation of land-atmosphere interactions in climate models is critical to the realistic simulation of energy and water cycles (Wang et al., 2004), which directly influence air temperature, air moisture, and snow dynamics. Snow pack is particularly critical for understanding climate impacts in regions such as the Pacific Northwest where snowmelt plays a central role in regional hydrology. In order to capture these dynamics in the climate system over climate change scales, the soil column must freely interact with the atmosphere. Most climate models, however, prescribe the lower-boundary soil temperature to some climatological value, which restricts the response of the soil column to climate forcing. In the NOAH LSM, the deep
soil temperature is prescribed as a constant climatological value at a depth of 3 meters, which is not sufficiently deep to allow the soil column to realistically respond to climate forcing.

The upper few meters of soil act as a heat reservoir, storing heat in the spring and summer and releasing it in autumn and winter. Heat is transferred through the soil column primarily by conduction, penetrating a few centimeters to perhaps half a meter on daily timescales and to depths as large as 10 meters on annual timescales (De Vries and Afgan, 1975). Observations (Baxter, 1997) and models (Jury et al., 1991) of soil temperature evolution at different soil depths show that soil temperature should be both time-lagged and amplitude-damped at depth with respect to the annual surface soil temperature. In these studies, at a depth of three meters (lower soil boundary in the NOAH LSM), the annual soil temperature cycle is typically time-lagged by 70 days and amplitude-damped to about one-third the amplitude of the surface temperature cycle. A prescribed lower boundary temperature at 3 meters depth may not be problematic for weather forecasting, typically over time scales of days to weeks, since it takes on the order of months for thermal information at depth to reach the surface. For climate simulations over many years, however, this boundary condition would produce deficiencies in the energy budget and accumulate large errors in the surface parameters.

To better represent the soil temperature profile in the mesoscale model, we have implemented a parameterization to specify the 3-m lower boundary soil temperature for the NOAH LSM. The soil temperature at depth follows the variations in the surface skin temperature, but with a phase lag and attenuation that depends on depth. The phase lag and attenuation depend on the frequency of the surface variation, but we shall base our methodology
on the annual cycle. The desired response may be obtained by taking a simple weighted average of the skin temperature over the previous year, where the weighting is adjusted to yield the desired attenuation and phase lag. We choose a weighting function with two terms, the skin temperature averaged over the past year, $\langle T_{\text{skin}} \rangle_{365}$, and the past $n$ days prior to the time of interest, $\langle T_{\text{skin}} \rangle_n$. The soil temperature at any depth is then the weighted average of these two values,

$$T_{\text{soil}} = \alpha \langle T_{\text{skin}} \rangle_{365} + (1 - \alpha) \langle T_{\text{skin}} \rangle_n,$$

where $\alpha$ and $n$ are a function of depth and tuned to produce the desired attenuation and phase lag for the depth of interest. For 3-m depth, we use the published observed values of 30% attenuation and 70 days lag (Baxter, 1997) to obtain $\alpha=0.6$ and $n = 140$ days.

Since good observations of soil temperatures a 3-m depth are not readily available, to test this method, we used surface and 1-m deep soil temperatures observed at Ames Iowa, US (Baxter, 1997). For 1-m depth, we use $\alpha=0.3$ and $n = 46$ days to obtain the observed lag and attenuation. Note that, compared to the values for 3-m depth, a smaller $n$ yields a smaller lag and the smaller $\alpha$ yields less attenuation. In Figure 4, the blue line shows the observed skin temperature and the black line the observed 1-m soil temperature. The weighted mean of the skin temperature yields the red line, which closely captures the form of the observed 1-m soil temperature over four seasonal cycles. Note also how the parameterization effectively removes the high-frequency variations at the surface in accordance with observations.

When applied to the MM5 climate modeling system, this soil temperature parameterization uses surface skin temperatures generated by MM5 and the NOAH LSM to
derive the 3-m soil temperature. For the first year of each decade-long simulation, however, MM5 output is not available, and must be derived from a spin up simulation (i.e. a preliminary simulation not used in the analysis of results, but only to equilibrate model parameters). This spin-up is also required to bring the NOAH LSM soil temperature and moisture fields for the entire soil column into equilibrium with the simulated atmospheric state. Studies (e.g. Cosgrove et al., 2003) have shown that, especially in drier regions, a spin-up period of at least a year is necessary for soil moisture, as the land surface model slowly adjusts soil parameters away from initial values. Thus, the spin-up simulations are initialized at the end of summer (September 1989), when soils are climatologically driest in the Pacific Northwest. For simplicity, we use the same forcing data for the spin-up as for the first year of the actual climate simulation. At initialization, the global forcing model (i.e. NNRP or ECHAM5) is used in Eqn. (1) to compute the lower boundary (3-m) soil temperature. The deep soil temperature parameterization was implemented at each internal time step to avoid biases in temperature that would result from a once-daily algorithm implementation. Initial soil temperatures for all intervening layers (between the surface and three meters) in the NOAH-LSM are linearly interpolated and then allowed to evolve according to the LSM throughout the simulation. Soil moisture is initialized to the climatological values provided in MM5 and then allowed to evolve over the spin-up year according to the LSM. As MM5 surface data became available at each time step, the parameterization was updated at each grid point using the available MM5 output, thereby phasing out the global model data. At the completion of the spin-up year, a complete year of MM5-derived skin temperatures is available for the deep soil parameterization and the soil
temperature and moisture profile has spun up to the atmospheric forcing. Figure 5 illustrates the soil temperature for the surface down to three meters for the spin up and first two years of an MM5 simulation interpolated to the Seattle-Tacoma Airport meteorological station. Due to the gradual phase-in of MM5 data over the spin-up year, a difference between values for the deep (300cm) soil temperature cycle over the first year and subsequent years is noticeable.

This soil temperature parameterization not only yields a deep soil temperature cycle that is realistic – with amplitude that is significantly damped – but also allows for a change in the deep soil temperature pattern over time. That is, whereas the default deep soil annual temperature cycle is the same year after year, this system allows the temperature at three meters to evolve with the rest of the climate system. Thus, when a change in atmospheric radiative forcing occurs and climate change results, the entire soil column will respond accordingly instead of being constrained at depth by the same annual cycle year after year.

III. Cold air outbreaks in forcing models

While nudging enhances model stability and allows for 10-year continuous runs, it assumes that the global model simulates the large-scale flow patterns and synoptic structures appropriately. Although it is generally true that global-scale errors in the driving model will be inherited by the regional model, this is especially true if nudging is employed. A particularly troublesome example for the Pacific Northwest is the simulation of excessive arctic air outbreaks into the Puget Sound lowlands in many global climate models. The terrain resolution in global models is too coarse to capture the details of the Cascade Range and Rocky Mountains, which block cold continental air in the continental interior from reaching the Pacific Northwest. In the
simulation of these events, cold continental air spills across the northwestern U.S. and down the western coast. Figure 6 illustrates a cold outbreak in the ECHAM5 global climate simulation for 12 UTC 21 Feb 1999. Shading indicates 2-m air temperature; white contour lines indicate sea-level pressure in hPa. Frigid conditions, below -20°C, are simulated over Puget Sound, where historic surface temperatures rarely drop below -12°C. While the regional model may modify the propagation of cold air somewhat with its higher-resolution terrain, it cannot correct for it entirely, due in part to the nudging of the regional model towards the global solution. These events are present to some degree in all global models we have examined; however, the ECHAM5 model we use for the primary analyses presented here shows the most realistic synoptic patterns. Figure 7 compares the cumulative frequency of Pacific Northwest mean 2-m air temperature over the 1990-1999 period from four global models, NNRP, ECHAM5, the DOE/NCAR Parallel Climate Model (PCM), and the NCAR Community Climate System Model Version 3 (CCSM3). Both PCM and CCSM3 show unrealistically frequent cold events, with surface temperatures below -10°C 5% of the time compared to 1.2% for NNRP. While the ECHAM5 results are in much better agreement with the NNRP, it still produces substantially too many events between -12 and -5°C.

IV. Model Verification

To evaluate the regional model performance, we present results from two 10-year (September 1989 to August 1999) simulations of the current climate. The first simulation is forced by NCEP-NCAR Reanalysis (NNRP-MM5) and the second forced by the ECHAM5 global climate model (ECHAM5-MM5). The regional model (MM5) is the same for both cases.
Each simulation starts after a one-year spin-up that is not used in the analysis of results. These results are then used to validate the regional model against observations. The NNRP-MM5 simulation is forced by the historical daily weather sequence as represented by the reanalysis data, and represents an idealized case where we can assume minimal bias introduced from the global forcing fields or due to interannual variability. Discrepancies between this simulation and observations would reflect deficiencies in the regional model setup. For the ECHAM5-MM5 simulation, biases in the global simulation are also introduced, although this model performs relatively well for the Pacific Northwest region as compared to other global models (Salathé et al., 2007a). Since the ECHAM5 simulation is from a free-running climate model and the time period is relatively short, interannual variability may lead to differences between the model and observations, but these differences should be within the observed range of variability.

Model evaluation is performed at the station level. Station analysis allows examination of the temporal variability across the seasonal cycle, which helps identify the times of year and the meteorological conditions under which the model skill is low. We present here results for 55 stations across Washington, Oregon, and Idaho. These stations are selected from the Historical Climate Network (HCN) (Karl et al., 1990) such that all are at elevations within 500 feet of the co-located MM5 gridcell.

A. Temperature

A composite annual cycle of daily maximum temperature (Tmax) was obtained for the HCN observations and the ECHAM5-MM5 and NNRP-MM5 simulations at each station location by calculating the 10-year (1990-2000) average Tmax for each calendar month. The
The same analysis is performed for daily minimum temperature ($T_{\text{min}}$). As an example, the seasonal cycle of $T_{\text{max}}$ and $T_{\text{min}}$ is shown for Kennewick, WA (Fig. 8a,b), at Seattle, WA (Fig. 8c,d) and at Wilbur, WA (Fig. 8e,f). Kennewick is located at 118 m elevation in the arid Columbia Basin east of the Cascade Range; Wilbur is at 680 m elevation on the western flank of the Rockies; Seattle is near sea level on Puget Sound. The range of interannual variability in the observed data is indicated by the gray band, which extends one standard deviation above and below the 10-year mean (i.e. including about 68% of the data). This range gives a measure of the significance of the deviation of the model results from the observations. The annual cycle of $T_{\text{max}}$ at Kennewick (Fig. 8a) is well represented by the NNRP-MM5 simulation, with a cold bias of about one standard deviation most of the year. The ECHAM5-MM5 simulation produces a significant cold bias, especially for the winter months, related to excessive cold outbreaks in the ECHAM5 model. For $T_{\text{min}}$ (Fig. 8b), the NNRP-MM5 simulation yields a considerable cold bias for summer months and little bias for winter months. These results suggest there is a deficiency in the MM5 system that results in excessive cooling at night during summer months. For the ECHAM5-MM5 simulation, there is a cold bias throughout the year as the summer cold bias from the MM5 system combines with the winter cold bias from the global model. At Seattle (Figs. 8c, 8d), similar results are found, with $T_{\text{max}}$ well represented in the NNRP-MM5 simulation, but a substantial cold bias for $T_{\text{min}}$. At Wilbur (Figs. 8e, 8f), the results are quite different, with a larger cold bias for $T_{\text{max}}$ and generally insignificant bias in $T_{\text{min}}$. In all cases, the ECHAM5-MM5 simulation produces a cold bias, relative to the NNRP-MM5 simulation, reflecting a cold bias from the ECHAM5 global model. The results for these three stations are
typical across the region, with large cold biases in summer Tmin found at many locations, while many higher-elevation cold stations show better performance.

To summarize all stations and months, Figure 9 shows scatter plots of observed and simulated Tmax (Fig 9a) and Tmin (Fig 9b) for each monthly value from each station; results for the ECHAM5-MM5 simulation are indicated by black dots and the NNRP-MM5 simulation by red dots. Results of regression analysis of the station results are presented in Table 1. Tmax shows a much better correlation and regression coefficient (slope) than Tmin for both simulations, but Tmin produces a slightly smaller overall bias. The ECHAM5-MM5 simulation has a larger cold bias relative to station observations than the NNRP-MM5 simulation, reflecting the additional bias introduced by the free-running climate model relative to reanalysis data. The effect of excessive cold episodes in winter is especially clear in Figure 9b (Tmin), as the ECHAM5-MM5 results yield an increasing bias as observed temperature falls below 0°C.

The low slope for Tmin indicates an increasing cold bias in Tmin in warmer months and locations, which is evident in Fig 9b as the simulated values fall below the 1:1 line above 5°C. To explore the seasonal aspect of this behavior, we compute the seasonal cycle of the temperature bias by averaging the bias over all stations for each calendar month. The result for Tmax and Tmin from each simulation is shown in Figure 10. For the NNRP-MM5 simulation, the bias in Tmax is relatively constant over the year, fluctuating around the mean of -1.9°C. Tmin, however, shows a strong seasonality, with little bias in winter months and a considerable bias in summer that exceeds the bias in Tmax. The results for the ECHAM5-MM5 simulation are more complex due to the additional bias inherited from the global model. The cold outbreaks in
winter add to the biases seen in the NNRP-MM5 simulation, increasing the bias in winter months.

B. Precipitation

We evaluate precipitation at each station in a similar manner, by computing the annual cycle of the observed and simulated precipitation. Fig. 11 shows the observed and simulated total precipitation at the Forks, WA (Fig. 11a), located along the Pacific Coast of the Olympic Peninsula and at Ritzville, WA (Fig 11b) located in the arid Columbia Basin; as for Fig 8, shading indicates the range of interannual variability as one standard deviation above and below the mean. The NNRP-MM5 and ECHAM5-MM5 simulations represent precipitation at Forks, WA, quite well. This station is on the windward slopes of the Olympic Mountains, and receives very high precipitation amounts, especially in winter. The good model performance at this station is characteristic of other very wet station in the simulation domain. At Ritzville, WA, however, both simulations produce significantly too much precipitation in winter months while the dry season is well represented. A similar large wet bias is seen at most dry stations in the domain.

Figure 12 shows the observed and simulated precipitation for all stations and months, and results of linear regression are shown in Table 1. There is strong correlation, better than 90%, between observations and both simulations. An overall wet bias is evident, and appears to be greatest for months and stations of moderate precipitation, consistent with the wet bias for the rainy season at dry stations. The seasonal characteristic of this bias is illustrated in Figure 13, which shows the percent difference between observed and simulated precipitation averaged over
all stations for each month. For summer months, there is a small dry bias in both simulations. For winter months, there is a substantial wet bias, due to the excess precipitation simulated for dry stations. Since the bias is expressed as a percent of the station mean, the wet bias at dry stations contributes substantially to the domain-average bias despite accounting for a small amount of the domain-total precipitation.

V. Summary

We have presented here a configuration of the MM5 mesoscale atmospheric model suitable for multi-year simulations at high spatial resolution. We have run this model for decadal simulations using nested grids at 135, 45, and 15-km grid spacing and forced by two global atmospheric simulations. The configuration of the model follows that used for real-time weather forecasting over the same region of the Pacific Northwest with several important changes necessary for climate simulations. First, a full land surface model, the NOAH LSM, is employed to simulate land-surface interactions, especially snow cover. The LSM is modified so soil temperatures vary at the lower boundary in accordance with the evolving climatological surface temperature. To allow long simulations that conserve mass and preserve the large-scale circulation of the forcing model, we employ nudging of the interior of the outermost domain. The inner domains are not nudged, allowing the mesoscale model to freely develop the smaller scale atmospheric state.

The use of nudging makes the regional simulations especially susceptible to deficiencies in the large-scale simulation used to force the regional model. In particular, unrealistic cold outbreaks are inherited from the forcing model in the current configuration. We are
experimenting with the boundaries of the regional model domains to help modify these events as
they pass into the model domains. If the 45-km domain is extended sufficiently far north, then
the natural blocking process could be captured in the regional model, preventing the cold
episodes in the mesoscale simulation.

To verify the climate simulation, we have compared two simulations for the 1990s
against station observations. The simulations use identical regional model configurations with
different large-scale forcing fields, a reanalysis simulation (NNRP) and a free-running climate
model (ECHAM5). We compare the observed and simulated annual cycle of daily maximum
temperature, daily minimum temperature, and precipitation between the simulations and
observations at three observing stations. Daily maximum (daytime) temperatures are reasonably
represented by both the NNRP-MM5 and ECHAM5-MM5 simulations throughout the year
despite a cold bias. The ECHAM5-MM5 simulation shows a more significant cold bias for
winter months due to occasional unrealistic cold outbreaks in the ECHAM5 simulation; this bias
is not seen in the NNRP-based simulation since the forcing data does a better job depicting these
events. For daily minimum (night time) temperatures, however, the regional model introduces a
considerable cold bias at many stations during summer. Simulations using a recently updated
version of the NOAH LSM appear to mitigate this problem at some stations, which suggests the
deficiency is related to the depiction of land-atmosphere interactions in the model. Since the new
NOAH LSM does not reduce the overall bias, however, further work will be needed to resolve
this issue. For precipitation, correspondence between simulations and observations is good for
stations with high annual precipitation, but is overestimated during the rainy season at arid sites.
Overall, there is a substantial wet bias in the precipitation, although the regional and seasonal contrasts are well represented.

Of the biases discussed above, the cold nighttime temperatures are the most problematic, and are likely related to the land-surface model. Otherwise, the simulation yields a realistic depiction of the spatial and seasonal structure of Pacific Northwest climate. Thus, the model should provide meaningful insight into fine-scale interactions within the climate system and their response to climate change. Simulations have been performed for three future decades, forced by an SRES A2 scenario simulation of the ECHAM5 global model. The results show important interactions among snow cover, cloudiness, and circulation that are critical to the regional response to climate change. These processes yield changes in temperature and precipitation over the 21st Century that vary considerably across the region and that could not be inferred from the global climate model simulation alone. These results and their analysis are the subject of a companion paper (Salathé et al., 2007b).

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VI. References


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VII. Figures

Figure 1. Complex terrain and land-water contrast in the Pacific Northwest.
Figure 2. Mesoscale model domains for the current study. Grid spacing for each domain is:

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Fig. 4. Soil temperature observations and deep soil temperature estimation using parameterization described in text.
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Fig 6. Cold outbreak in ECHAM5 global climate simulation for 12 UTC 21 Feb 1999. Shading indicates 2-m air temperature; white contour lines indicate sea-level pressure in mb.
Figure 7. Cumulative distribution of surface air temperatures below -5°C averaged over the Pacific Northwest, indicating the frequency of cold events in NCEP/NCAR Reanalysis (black) and three global climate models: ECHAM5 (red), PCM (green), and CCSM (blue). Note that a frequency of 0.1 at -5°C for NNRP implies temperatures fall below -5°C on 10% of the days.
Fig 8 Annual cycle of temperatures from station observations and MM5 simulations at Kennewick, WA, for (a) Tmax (b) Tmin; at Seattle WA for (c) Tmax (d) Tmin; and Wilbur WA for (e) Tmax and (f) Tmin. Shading indicates one standard deviation of the observed interannual variability.
Fig 9 Scatter plot of observed and simulated 10-year monthly-mean (a) daily maximum temperature and (b) daily minimum temperature for 55 stations in the MM5 simulation domain.

Fig 10 Annual cycle of bias between observed and simulated temperatures averaged over all 55 stations.
Fig 11 Annual cycle of daily precipitation from station observations and MM5 simulations at a) Forks, WA, and b) Ritzville, WA. Note different scales.

Fig 12 Scatter plot of observed and simulated precipitation for 55 stations in the MM5 simulation domain.
Fig 13 Annual cycle of bias between observed and simulated precipitation, expressed as a percent of the observed precipitation, and averaged over all 55 stations.
VIII. Tables

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<td>NNRP–MM5 Tmax</td>
<td>0.98</td>
<td>0.96</td>
<td>-1.86°C</td>
</tr>
<tr>
<td>ECHAM5–MM5 Tmax</td>
<td>0.97</td>
<td>1.00</td>
<td>-3.41°C</td>
</tr>
<tr>
<td>NNRP–MM5 Tmin</td>
<td>0.92</td>
<td>0.78</td>
<td>-1.25°C</td>
</tr>
<tr>
<td>ECHAM5–MM5 Tmin</td>
<td>0.93</td>
<td>0.88</td>
<td>-2.73°C</td>
</tr>
<tr>
<td>ECHAM5–MM5 Pcp</td>
<td>0.91</td>
<td>0.89</td>
<td>0.069 mm/day</td>
</tr>
<tr>
<td>NNRP–MM5 Pcp</td>
<td>0.92</td>
<td>0.95</td>
<td>0.076 mm/day</td>
</tr>
</tbody>
</table>

*Table 1. Regression analysis for station results*