ENSO Anomalies over the Western United States: Present and Future Patterns in Regional Climate Simulations

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Abstract

Surface temperature, precipitation, specific humidity and wind anomalies associated with the warm and cold phases of ENSO simulated by WRF and HadRM are examined for the present and future decades. WRF is driven by ECHAM5 and CCSM3, respectively, and HadRM is driven by HadCM3. For the current decades, the ECHAM5-WRF, CCSM3-WRF and HadRM simulations are broadly consistent with the observed warm-dry and cool-wet teleconnection patterns over the Pacific Northwest (PNW) and the Southwest U.S. for warm and cold ENSO. Differences in the regional simulations originate primarily from the respective driving fields. For the future decades, the warm-dry and cold-wet teleconnection patterns in association with ENSO are still represented in ECHAM5-WRF and HadRM. However, there are indications of changes in the ENSO teleconnection patterns in CCSM3-WRF in the future, with wet anomalies dominating in the PNW and the Southwest U.S. for both warm and cold ENSO, in contrast to the canonical patterns of precipitation anomalies. Interaction of anomalous wind flow with local terrain plays a critical role in the generation of anomalous precipitation over the western U.S. Anomalous dry conditions are always associated with anomalous airflow that runs in parallel to local mountains and wet conditions with airflow that runs in perpendicular to local mountains. Future changes in temperature, precipitation and wind associated with the ENSO events in the ECHAM5-WRF and HadRM simulations appear to suggest weakening of teleconnection patterns for warm ENSO but strengthening of teleconnection patterns for cold ENSO.

1. Introduction

The cold season precipitation and temperature anomaly patterns in the western United States associated with the El Niño-Southern Oscillation (ENSO) are well-established (Cayan and Roads 1984; Ropelewski and Halpert 1986; Redmond and Koch 1991; Wallace et al. 1992; Cayan 1996; Mitchell and Blier 1997; Dettinger et al. 1998; Kumar and Hoerling 1998; Pandey et al. 1999) and underlie the skill in seasonal climate prediction for the western U.S. The warm phase of ENSO (i.e., El Niño) is associated with warm-dry weather in the Pacific Northwest (PNW) and cool-wet weather in the Southwest U.S. The cold phase of ENSO (i.e., La Niña) is characterized by cool-wet weather over the PNW and warm-dry weather of the Southwest U.S. These spatially coherent patterns are related to coupled atmosphere-ocean variability in the tropical Pacific that contributes to climate variability in the North Pacific and western United States through the Pacific-North American (PNA) teleconnection pattern (Wallace et al. 1992). ENSO influence on hydrologic and temperature extremes in the western United States have also been reported (Gershunov 1998; Cayan et al. 1999). Thus, ENSO is a critical component to the climate of the western U.S., with important local impacts on ecological and economic systems.

Given this significance of ENSO, it is important to assess how well global and regional models can simulate the large-scale forcings and local anomalies that are observed in the present climate. ENSO anomalies involve interactions between the large-scale forcing and local terrain and therefore present an important test of the ability of regional models to resolve mesoscale processes on long time scales. Leung et al. (2003) analyzed the mesoscale ENSO anomalies over the western U.S. in a 20-year regional climate simulation driven by the NCEP (National Centers for Environmental Prediction)-NCAR (National Center for Atmospheric Research) global reanalysis. They showed that the ENSO-related regional features in precipitation and temperature are well reproduced by the regional model simulations where the interactions of the large-scale circulation with the underlying topography are well represented. It should be noted that the reanalysis data incorporate all the available observations at the time of processing and are considered to best represent the large-scale state of the atmosphere. For climate change studies and climate impacts assessment, it is necessary to examine regional climate model simulations forced by free-running, coupled atmosphere-ocean global climate models, which may not represent ENSO realistically.

In considering future climate change, any shift in the tropical ENSO cycles or in the teleconnection patterns could have significant implications for local climate impacts over the western U.S. Several studies have suggested that climate change could alter the frequency and amplitudes of ENSO events (van Oldenborgh et al. 2005; Müller and Roeckner 2008; Brekke et al. 2008) which would alter climate variability in the western U.S. However, large uncertainties remain in the model-projected changes in ENSO events. For example, using two different versions of the Hadley Centre coupled atmosphere-ocean model (HadCM2 and HadCM3), Collins (2000a, b) found that ENSO becomes more frequent with higher amplitude in HadCM2, but remains about the same in HadCM3. The differences in the model response are apparently related to differences in

the mean climate in the Tropical Pacific region, which could be attributed to subtle changes in the cloud parameterizations used in the two model versions (Williams et al. 2001). Cubasch et al. (2001) and Meehl et al. (2007) further highlighted the uncertainty in projecting future changes in ENSO events through synthesis of results from multiple global climate models in the IPCC third and fourth assessment. Even though the present-day ENSO variability is better simulated in the fourth assessment compared to the third assessment, there is still large inconsistency among model projections of ENSO frequency and amplitude in the future climate. Thus, no clear evidence exists that tropical ENSO variability will change in the future climate (Meehl, et al, 2007). Nevertheless, even in the absence of a shift in the tropical ENSO cycles, the altered mean state of the extra-tropical atmosphere, including shifts in storm track and mid-latitude jet stream locations, could lead to substantially different teleconnection patterns and regional anomalies.

To address these issues, this study examines the WRF (Weather Research and Forecasting) climate model and HadRM (Hadley Centre Regional Model) simulations over the western United States driven by three global climate models. By looking across three sets of global and regional simulations, our goal is to determine how well these simulations capture the ENSO influence on temperature and precipitation in the western U.S., and to assess the level of uncertainty in projecting future changes in hydroclimatic variability associated with ENSO. The paper is organized in the following way. Section 2 gives a brief description of the global and regional models. Examinations of the temperature, precipitation, specific humidity and wind anomalies during the warm and cold phases of ENSO for the current decades (1970 through 1999) and the future decades (2030 through 2059) are presented in Sections 3 and 4, respectively. For the current decades, temperature and precipitation anomalies from both the driving models and the regional models are presented alongside for comparisons. Future changes during the warm and cold phases of ENSO are discussed in Section 5. Major conclusions and discussions are presented in Section 6.

2. Descriptions of Models

2.1 Global Climate Models

Two global climate models, MPI-M (Max Planck Institute for Meteorology) ECHAM5 and NCAR CCSM3 (Community Climate System Model version 3), are used to force the WRF regional model. A version of the Hadley Centre's third generation coupled ocean-atmosphere general circulation model, HadCM3Q0, is used to force HadRM.

The atmospheric component of ECHAM5 is the fifth-generation general circulation model developed at the European Center for Medium-Range Weather Forecasts (ECMWF) and the Max Planck Institute for Meteorology (Roeckner et al. 1999; Roeckner et al. 2003). The ocean component is the Max Planck Institute Ocean Model (MPI-OM) (Marsland et al. 2003). ECHAM5 was run at T63 spectral resolution, which corresponds to a horizontal grid spacing of about $140 \times 210 \text{ km}^2$ at the mid-latitudes, and 32 vertical levels. For the present climate (1970-1999) simulations, we used an ECHAM5 simulation of the 20th century with historical greenhouse gas (GHG) forcing. For the 21st

century (2030-2059) simulations, we used a simulation with the Special Report on Emissions Scenarios (SRES) A1B emissions scenario (Nakicenovic et al. 2000), which assumes a balanced increase in GHG concentrations. ECHAM5 model output at 6-hourly intervals was obtained from the CERA WWW Gateway at <http://cera-www.dkrz.de/CERA/index.html>.

The NCAR CCSM3 consists of the Community Atmospheric Model (CAM), the Parallel Ocean Program (POP), the Community Land Model (CLM), and the Community Sea Ice Model (CSIM) components linked through a coupler that exchanges fluxes and state information among these components (Collins et al. 2006). The atmospheric model was run at a horizontal grid spacing of T85, which corresponds approximately to a grid spacing of $150 \times 150 \text{ km}^2$ at the mid-latitudes. For the present climate simulations, we used one of the ten ensemble CCSM3 simulations of the 20th century with historical GHG forcing. For the 21st century simulations, we used one of the five ensemble simulations with the SRES A2 emissions scenario, which assumes a high population growth and high GHG concentrations. CCSM3 model output at 6-hourly intervals is available through the NCAR mass storage system and the Earth System Grid at <http://www.earthsystemgrid.org>.

HadCM3Q0 is a slightly different version of the standard HadCM3 (Gordon et al. 2000). The atmospheric component of the HadCM3, HadAM3 (Pope et al. 2000), has 19 levels with a horizontal resolution of 2.5° latitude by 3.75° longitude, comparable to a spectral resolution of T42. The oceanic component of the model has 20 levels with a horizontal resolution of $1.25^\circ \times 1.25^\circ$ (Gordon et al. 2000) while the sea-ice component uses a simple thermodynamic scheme including leads and snow-cover. The differences between HadCM3Q0 and HadCM3 lie in that 1) HadCM3Q0 uses flux adjustments to ensure that the SSTs remain close to climatological values during a control period, while allowing SSTs to vary from natural variability and from atmospheric forcings, such as increasing CO_2 and 2) HadCM3Q0 includes an atmospheric sulfur cycle. In this work, we used a single 1950-2100 integration of the HadCM3Q0 to drive HadRM. The external forcing for the future decades is from the SRES A1B emissions scenario. The HadCM3Q0 data are available as part of the PRECIS (Providing REgional Climates for Impacts Studies) package (Jones et al. 2004). In the following, HadCM3Q0 will be referred to as HadCM3 for convenience.

We chose the ensemble simulations of the ECHAM5 and CCSM3 climate models on the basis of the availability of 6-hourly output data that can be used to drive the regional climate models.

2.2 WRF Model

The WRF model is a state-of-the-art, next-generation mesoscale weather system designed for both short-term weather forecasts and long-term climate simulations (<http://www.wrf-model.org>). It is a non-hydrostatic model, with several options for physical parameterizations suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. The physics package includes

microphysics, convective parameterization, planetary boundary layer (PBL), land surface models (LSM), and longwave and shortwave radiation. WRF has been applied extensively in regional climate simulations over the PNW (Leung et al. 2006; Salathé et al. 2009; Qian et al. 2009; Zhang et al. 2009; Dulière et al. 2009).

In this work, the microphysics and convective parameterizations used were the WRF Single-Moment 5-class (WSM5) scheme (Hong et al. 2004) and the Kain-Fritsch scheme (Kain and Fritsch 1993), respectively. The WSM5 microphysics explicitly simulates water vapor, cloud water, rain, cloud ice, and snow. The Kain-Fritsch convective parameterization utilizes a simple cloud model with moist updrafts and downdrafts that includes the effects of detrainment and entrainment. The land-surface model used was the NOAA (NCEP, Oregon State University, Air Force Weather Agency, and Hydrologic Research Lab) LSM (Chen et al. 2001). This is a 4-layer soil temperature and moisture model with canopy moisture and snow cover prediction. It includes root zone, evapotranspiration, soil drainage, and runoff, taking into account vegetation categories, monthly vegetation fraction, and soil texture. The PBL parameterization used was the YSU (Yonsei University) scheme (Hong et al. 2006). This scheme is the updated version of the MRF (Medium-Range Forecast) scheme (Hong and Pan 1996) and includes counter-gradient terms to represent heat and moisture fluxes due to both local and non-local gradients. Atmospheric shortwave and longwave radiation were computed by the NCAR CAM shortwave scheme and longwave scheme (Collins et al. 2004), respectively.

There are minor differences in the WRF model configurations used at the Pacific Northwest National Laboratory for the CCSM3-WRF and at the University of Washington for the ECHAM5-WRF simulations. Firstly, the CCSM3-WRF simulation used the SRES A2 scenario while ECHAM5-WRF used the SRES A1B emissions scenario for future decades. It is expected that the effects of these different emissions scenarios on the model simulations are small because the two emissions scenarios do not begin to diverge until the mid 21st century. Secondly, the ECHAM5-WRF simulation follows the methods of the MM5-based mesoscale climate modeling described in Salathé et al. (2008): (a) Model domains consist of an outermost regional domain at 108-km resolution and a nested domain at 36-km resolution; (b) Nudging is applied to the outermost domain from the forcing fields to prevent possible divergence of the regional model solution from the driving fields; (c) The nested domain is not nudged, allowing the regional model to freely develop fine-scale features; (d) WRF is modified so that deep soil temperatures (~ 8 m depth) vary in accordance with the evolving surface temperature; and (e) Carbon dioxide concentrations are prescribed in accordance with the observed concentrations for the present climate and the projected concentrations under the SRES emissions scenario for future climate. The ECHAM5-WRF model domains are shown in Fig. 1. The CCSM3-WRF uses a single model domain at 20-km resolution with a wider buffer zone for the lateral boundaries to increase the constraints from the global climate simulations (Fig. 1). The relaxation coefficients of the nudging boundary conditions follow a linear-exponential function to smoothly blend the large-scale circulation from the global simulation and the regional simulation. CCSM3-WRF also used the similar approach as ECHAM5-WRF to simulate the deep soil temperature in an

evolving climate with prescribed carbon dioxide concentrations based on the observations and the SRES scenario.

2.3 HadRM Model

HadRM (Jones et al. 2004) is a limited-area, high-resolution version of the atmospheric general circulation model (HadAM3H) developed at the Hadley Centre Met Office. HadRM is a hydrostatic model of the fully primitive equations. It includes dynamical flow, clouds and precipitation, radiative processes, land surface and deep soil.

The latitude-longitude grid is rotated in HadRM so that the equator lies inside the region of interest to obtain quasi-uniform grid box area over that region. The available horizontal resolutions are $0.44^{\circ} \times 0.44^{\circ}$ and $0.22^{\circ} \times 0.22^{\circ}$. For the purpose of this study, we chose the higher resolution which corresponds to a minimum grid spacing of ~ 25 km at the equator of the rotated grid. The HadRM model domain (Fig. 1) covers a large part of the eastern Pacific Ocean and part of Mexico and Canada to better resolve the synoptic weather systems that affect the western U.S. This model domain encompasses entirely the states of Arizona, California, Idaho, Nevada, Oregon, Utah and Washington.

The HadRM simulations were performed using the PRECIS package (Jones et al. 2004). This package also includes software to allow display and processing of the model output data (<http://precis.metoffice.com>). The PRECIS package is flexible, easy to use and computationally inexpensive. It can be applied over any parts of the world to provide detailed climate information for regional climate studies and climate impact assessment.

3. Present Climate

3.1 Observed Anomalies

Figure 2 presents the western U.S. cold season (October to March) anomalies in temperature, precipitation, and snow pack associated with ENSO during the 30-year period of 1970-1999. Temperature and precipitation fields are observations gridded to $1/8$ -degree with corrections for elevation (Maurer et al. 2002). Snow pack anomalies are given by snow water equivalent (SWE) simulated by the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994; Maurer et al. 2002) driven by the observed fields. Figures 2 a, c and e show the anomalies for warm ENSO. Warm ENSO is characterized by warmer, drier conditions in the PNW and cooler, wetter conditions in the southwest U.S. These anomalies result in substantial reductions in mountain snowpack in the Cascades and northern Rockies and modest increases in the Sierra Nevada. There are also important local deviations from this overall pattern, for example, the very small precipitation anomaly in eastern Washington and Oregon, in the lee of the Cascade Range, and the warm anomalies along coastal California. The anomalies for cold ENSO (Figs. 2b, d, and f) are almost exactly the opposite for all parameters.

The surface wind and specific humidity anomalies from the NCEP-NCAR reanalysis (Kalnay et al. 1996) corresponding to the two ENSO phases are shown in Figs. 2g and h, respectively. During El Niño years, a low pressure anomaly is found between 35 and

40°N with associated southwesterly wind anomalies off the California coast and northeasterly wind anomalies off the PNW coast (Fig. 2g). Combined with the warm tropical ocean temperatures, this wind anomaly brings increased moisture to the entire western coast (Fig. 2g). Due to the different flow patterns in the northwest and southwest, however, the increased moisture results in higher precipitation only over the southwest. In the northwest, the strong easterly wind anomaly reduces the orographic enhancement, resulting in reduced precipitation despite the increased atmospheric moisture (Leung et al. 2003a). During La Niña years (Fig. 2h), an anomalous anticyclone occurs between 30 and 35°N with generally opposite wind anomalies to El Niño. Atmospheric moisture is reduced over the region, but increased onshore flow yields increased precipitation over the PNW. Over the southwest, reduced moisture and weaker orographic effects are consistent with the negative precipitation anomalies (Fig. 2d).

3.2 Simulated anomalies

This section compares the ECHAM5-WRF, CCSM3-WRF and HadRM simulated anomalies of surface temperature, precipitation, specific humidity and wind during the warm and cold phases of ENSO for the present climate. The Oceanic Niño Index (ONI) was used to identify El Niño and La Niña events in the tropical Pacific from the driving model (ECHAM5, CCSM3 and HadCM3) SST fields. NOAA (National Oceanic and Atmospheric Administration) has been using ONI for identifying El Niño and La Niña years. ONI is defined as the running 3-month mean SST anomalies for the Nino 3.4 region (i.e., 5°N-5°S, 120°W-170°W). Events are defined as 5 consecutive months at or above the +0.5° anomaly for warm phase and at or below the -0.5° anomaly for cold phase. Figure 3 shows the running 3-month mean SST anomalies for the Nino 3.4 region (ONI) based on ECHAM5, CCSM3 and HadCM3 simulations and observations during 1970-1999. Since ECHAM5, CCSM3 and HadCM3 are free-running global climate models, the simulated ENSO events do not match the observed sequence of ENSO events. Table 1 presents the frequency (defined as the number of occurrence) and intensity (defined as the average of the maximum ONI) of El Niño and La Niña events. The ONI peaks around January in both the observations and simulations (Fig. 3). During 1970-1999, 6 El Niño events with an average intensity of 1.92°C and 6 La Niña events with an average intensity of -1.60°C are indicated in the observations; ECHAM5 shows 7 El Niño events with an intensity of 2.31°C and 8 La Niña events with an intensity of -1.96°C; CCSM3 shows 10 El Niño events with an intensity of 1.56°C and 10 La Niña events with an intensity of -1.54°C; HadCM3 shows 3 El Niño events with an intensity of 2.03°C and 4 La Niña events with an intensity of -1.38°C (Table 1). The ENSO events in ECHAM5 and HadCM3 last for about 1-2 years as in the observations while the ENSO events in CCSM3 last predominantly one year. CCSM3 simulates very frequent ENSO events, with a periodicity of 2 – 3 years compared to the observed 2.5 – 8 years (Fig. 3). Deser et al. (2006) speculated that the overly narrow meridional scale of ENSO in the CCSM3 simulation, which is related to the coupling of the atmosphere and ocean components, may contribute to the excessive high frequency of ENSO.

3.2.1 El Niño Events

Figure 4 shows the surface temperature anomalies for warm ENSO during 1970-1999 based on the global and the regional simulations. The anomalies are computed as the deviations of 6-month (October through March) means for the warm ENSO years from the 30-year averages. Similarities between the regional simulations and the respective global simulations are evident, with the regional simulations maintaining the overall regional patterns from the forcing models. Local deviations in the regional simulations from the global simulations are noted mainly along mountain ranges including the Cascades, the Rocky and the Sierra Nevada Mountains, which are likely related to mesoscale processes such as mountain-valley breeze and snow-albedo feedback (Salathé et al. 2008) or cloud-radiation feedback that are not resolved by the global climate models. Only ECHAM5 and ECHAM5-WRF (Figs. 4a, b) produce the characteristic pattern of warm anomalies in the PNW and cool anomalies in the southwest; however, cool anomalies extend into the northern interior, which is inconsistent with the observations. The regional simulation produces larger anomalies that are more consistent with the observations.

In CCSM3 and CCSM3-WRF (Figs. 4c, d), warm anomalies are noted over the entire western U.S., with larger anomalies in the northwest than the southwest. In contrast, HadCM3 and HadRM show cold anomalies over the entire western and central U.S., with larger anomalies in the southwest than the northwest (Figs. 4e, f). The HadRM simulation shows modest improvement over the forcing simulation, with positive anomalies over the northwestern Washington.

Figure 5 presents the precipitation anomalies based on global and regional simulations as well as the surface specific humidity and wind anomalies in the regional simulations for warm ENSO during 1970-1999. The anomalies in the regional simulations are noticeably stronger than the global simulations over mountainous terrain along the coast and inland where blocking and rain shadow effects have important influence on the magnitude of precipitation (Leung et al. 2003a, b; Mass 2008). Anomalies in ECHAM5 and ECHAM5-WRF (Figs. 5a, b) are in good agreement with the observations. Dry anomalies are simulated over the northwest except for Vancouver Island where wet anomalies are indicated; wet anomalies are simulated over the southwest with stronger anomalies along the coast of California.

As with temperature anomalies, CCSM3 does not produce the characteristic regional precipitation pattern, and the CCSM3-WRF simulations mimic the forcing fields (Figs. 5d, e). Small anomalies are noted over the entire western U.S in the CCSM3 simulations (Fig. 5d). Slightly amplified anomalies are found along the mountains in the CCSM3-WRF simulations (Fig. 5e).

HadCM3 produces a strong characteristic regional pattern of precipitation anomalies, which are amplified in the HadRM simulations (Figs. 5g, h). The anomaly pattern is quite similar to the observations and ECHAM5-WRF simulations although the magnitude is somewhat larger.

Leung et al. (2003a) showed that the shifts in winds associated with ENSO have a strong role in producing the concurrent precipitation anomaly patterns by modulating moisture flux and orographic enhancement. In this case, the spatial patterns of precipitation anomalies are rather consistent with those of surface wind anomalies (Fig. 5) in the regional simulations. The anomalies in specific humidity in ECHAM5-WRF and CCSM3-WRF (Figs. 5c, f) show slightly enhanced moisture along the coast of both the southwest and the northwest. HadRM simulates weak anomalies in specific humidity over the western U.S. (Fig. 5i).

In all three regional simulations, a low pressure anomaly is simulated between 35 and 40°N, as in the reanalysis. As a result, southeasterly wind anomalies prevail along and off the coast of the PNW and southwesterly anomalies off the California coast. In ECHAM5-WRF and HadRM (Figs. 5c, i), anomalous easterly to northeasterly flow is simulated over the northwest interior. In CCSM3-WRF (Fig. 5f), the anomaly wind pattern is much weaker, especially over land areas. As for the reanalysis, these winds, along with warmer temperatures, would tend to increase moisture flux off the west coast. This result is seen in both the ECHAM5-WRF and CCSM3-WRF simulations (Figs. 5c, f). The HadRM simulation (Fig. 5i) shows much weaker moisture anomalies despite realistic wind anomalies. The weakened westerly flow, especially over land, reduces orographic enhancement over the PNW especially in ECHAM5-WRF and HadRM. Thus, the synoptic conditions do not favor orographic precipitation, and negative precipitation anomalies are produced over the northwest.

In contrast, southerly anomalies prevail off the California coast in ECHAM5-WRF and HadRM (Figs. 5c, i), with rather weak southerly anomalies in CCSM3-WRF (Fig. 5f). These wind anomalies turn the winds more perpendicular to the southeast-northwest oriented ridges of southern California and augment orographic precipitation over the southwest.

The wind anomalies in CCSM3-WRF are substantially weaker than in ECHAM5-WRF or HadRM, although they are generally of the same sign. As a result, the large scale precipitation anomaly pattern does not fully emerge. For each model, the strength of the precipitation anomaly is clearly governed by the strength of the wind anomaly, illustrating the dominant role of flow patterns and orographic effects on the simulated precipitation anomalies.

3.2.2 La Niña Events

The spatial patterns of temperature anomalies during La Niña years in ECHAM5, ECHAM5-WRF, HadCM3 and HadRM (Fig. 6) do not match the observed temperature anomalies over the western U.S. (see Fig. 2b). Warm temperature anomalies dominate over the entire domain for both the global and regional models (Figs. 6a, b and 6e, f). The HadRM simulations show larger anomalies over the southwest than the northwest (Fig. 6f). In CCSM3 and CCSM3-WRF, cold anomalies quite similar to the observed anomalies are noted over the western U.S., with larger anomalies in the northwest than the southwest (Figs. 6c, d).

As with the observed fields, precipitation anomalies for cold ENSO (Fig. 7) exhibit generally opposite spatial patterns to those for warm ENSO (Fig. 5). Wet anomalies are noted over the PNW and dry anomalies over the Southwest U.S. in all simulations (Fig. 7). These spatial patterns are generally consistent with the observed patterns for cold ENSO (Fig. 1d), especially for ECHAM5-WRF. Wet anomalies in CCSM3-WRF are too localized over Oregon and do not extend northward along the coastal and interior mountains. The wet anomalies in HadRM are broader in spatial coverage with large wet anomalies extending further north and south than in the observations and ECHAM5-WRF; negative anomalies are restricted to a small region of southern California. As we will see shortly, this difference between ECHAM5-WRF and HadRM is related to the differences in wind anomalies. As in the case for warm ENSO, the magnitude of precipitation anomalies for cold ENSO is larger with more realistic spatial structures in the regional simulations than the global simulations.

For cold ENSO, specific humidity anomalies are rather weak over the entire domain in all the regional simulations (Figs. 7c, f, i). The wind anomalies give some indication of the mechanisms behind the simulated precipitation anomalies. An anticyclonic anomaly is simulated off the coast in both ECHAM5-WRF and CCSM3-WRF (Figs. 7c, f); this pattern is shifted somewhat northward compared to the reanalysis. Consequent northwesterly wind anomalies are simulated off the PNW coast. These anomalies decrease the southerly component and increase the westerly component of the climatological southwesterly flow in this region. The resulting strong westerlies produce enhanced orographic precipitation over the mountains of the PNW and is responsible for the wet precipitation anomalies there in both simulations. The anticyclonic anomaly in ECHAM5-WRF appears to be stronger than in CCSM3-WRF. HadRM simulates strong southerly wind anomalies off the coast of the PNW (Fig. 7i). Orographic effects would not be enhanced along the north-south oriented Cascade and Coastal ranges of Oregon and Washington, but are enhanced along Vancouver Island and the British Columbia coastal mountains. Thus, the mechanisms behind the positive precipitation anomalies in ECHAM5-WRF and HadRM are quite different.

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3.3 Snow Water Equivalent (SWE) Anomaly

Figure 8 shows the SWE anomalies for the warm and cold phases of ENSO during 1970-1999 based on the regional simulations. All simulations show decreases in SWE for warm ENSO (Figs. 8a, b, c) and increases in SWE for cold ENSO over the PNW (Figs. 8d, e, f). This pattern follows the anomalies in the VIC simulation (Figs. 2e, f), but in all cases the simulated anomalies are smaller than observed and restricted to the northern portion of the domain. Given the better match in the geographic extent of precipitation anomalies, this deficiency is likely due to an underestimate of the climatological SWE in the regional models due to poor resolution of the terrain (Salathé et al. 2009). Indeed, it appears that SWE anomalies in CCSM3-WRF are somewhat more localized and larger in magnitude than ECHAM5-WRF, consistent with the finer resolution for CCSM3-WRF (20 km) than ECHAM5-WRF (36 km).

Over the Southwest U.S., slight increases in SWE are indicated in ECHAM5-WRF and CCSM3-WRF for warm ENSO (Figs. 8a, b), consistent with the VIC simulations (Fig. 2e). Large increases in SWE are simulated by HadRM over the Southwest U.S. for warm ENSO (Fig. 8c), which result from the excessive simulated precipitation anomalies (Fig. 5h). For cold ENSO, all simulations show decreases in SWE over the Southwest U.S., although the decreases are larger in CCSM3-WRF and HadRM than ECHAM5-WRF. These anomalous patterns in SWE for cold ENSO are largely consistent with the VIC simulations (Fig. 2f).

3.4 Terrain Effects

To illustrate the importance of the topography on temperature and precipitation anomalies for warm and cold phases of ENSO, we examine cross sections along 47.8°N (across the Olympics and North Cascades over the PNW) and 37.5°N (across the Sierra Nevada and Rockies over the Southwest U.S.). The results are presented in Fig. 9 as anomaly in temperature and percent anomaly in precipitation relative to the climatology. The percent anomaly emphasizes the variation in the climate signal across the region. Considerable deviations in the ECHAM5-WRF (green) and HadRM (red) temperature and precipitation simulations from the respective global simulations are noted around the regional topography, consistent with the observations, while ECHAM5 and HadCM3 show rather smooth pattern across the topography. Differences between the CCSM3-WRF and CCSM3 are rather small across the transects. Of particular note is the modulation of the observed and simulated precipitation anomalies across the Olympics and Cascade mountains (126°W to 114°W). Large negative anomalies are simulated on the western, windward slopes with relatively small anomalies on the lee for warm ENSO (Fig. 9e). By contrast, precipitation anomalies are amplified on the windward slopes and suppressed in the lee for cold ENSO (Fig. 9f). This result shows the importance of orographic effects in producing the PNW anomaly pattern, since changes in thermodynamic factors (temperature and moisture) alone would tend to produce a more constant fractional change in precipitation across the terrain.

The above analyses indicate that the ECHAM5-WRF, CCSM3-WRF and HadRM simulations are broadly consistent with the observed warm-dry and cool-wet teleconnection patterns over the PNW and the Southwest U.S. associated with the El Niño and La Niña events. Differences in the regional simulations originate mainly from the respective large-scale driving fields. Furthermore, interactions of wind flow with local terrain play a critical role in the generation of precipitation over complex terrain such as the PNW and the Southwest U.S.

4. Future Climate

Figure 10 shows the running 3-month mean SST anomalies for the Nino 3.4 region (ONI) based on the ECHAM5, CCSM3 and HadCM3 simulations for 2030-2059. The frequency and intensity of El Niño and La Niña events are presented in Table 1. Compared to the present-day (Fig. 3 and Table 1), changes in the frequency and intensity of ENSO for the future simulations are modest and not consistent among the models.

Future ENSO events in ECHAM5 tend to increase in intensity (future 3.07°C versus current 2.31°C for El Niño events; future -2.59°C versus current -1.96°C for La Niña events) with no significant changes in frequency (future 7 versus current 7 El Niño events; future 10 versus current 8 La Niña events). Future ENSO events in CCSM3 tend to decrease slightly in frequency (future 9 versus current 10 El Niño events; future 7 versus current 10 La Niña events) with no significant changes in intensity. HadCM3 shows a distinct increase in frequency (future 7 versus current 3 El Niño events; future 7 versus current 4 La Niña events) with no significant changes in intensity. As for the case in the present climate, the intensity of ENSO events in CCSM3 and HadCM3 is smaller than in ECHAM5.

4.1 El Niño Events

Figure 11 shows the surface temperature, precipitation, wind and specific humidity anomalies for warm ENSO during 2030-2059 based on the regional simulations. Anomalies are computed from the future (2030-2059) mean state. Warm anomalies are noted over the PNW in all the simulations. Weak anomalies are identified over the Southwest U.S. in ECHAM5-WRF and HadRM (Figs. 11a, g). In CCSM3-WRF, weak warm anomalies are noted over the Southwest U.S (Fig. 11d). For ECHAM5-WRF, the temperature anomaly patterns for the future decades are similar to those of the current decades although the cold anomalies over the Central U.S. are not as strong for the future decades as for the current decades (see Figs. 11 and 4). For CCSM3-WRF, the temperature anomaly patterns for the future decades are also consistent with those of the current decades although differences in spatial location and penetration exist. For HadRM, warm anomalies are simulated over the PNW for the future decades while weak anomalies are simulated for the current decades.

The precipitation anomaly patterns simulated by ECHAM5-WRF and HadRM generally match the El Niño anomalies for the current decades (see Figs. 11 and 5). The ECHAM5-WRF future simulation is overall wetter than the current simulation, and the HadRM anomaly pattern is less pronounced. In CCSM3-WRF, the characteristic El Niño precipitation pattern is again not simulated, with modest wet anomalies over the PNW and weak wet anomalies over the Southwest U.S. These spatial patterns in CCSM3-WRF are different from those for the current decades that show dry anomalies over the PNW. We will show later that changes in surface wind anomalies can explain the simulated changes between the current and future decades.

The surface wind anomalies in ECHAM5-WRF are similar to those for the current decades, with anomalous southeasterly and southwesterly flow off California and Washington (Fig. 11c). Such anomalous flow runs in parallel to the largely north-south oriented Cascade Mountains and is conducive to anomalous dry conditions over the PNW. Over the Southwest U.S., anomalous wet conditions are caused by the blocking and lifting of the anomalous southwesterly flow by the Sierra Nevada mountains. In comparison to the current decades, however, the anomalies are more intense in the southwest of the domain and less intense over the northwest, particularly inland. This difference tends to strengthen the wet precipitation anomaly over California and weaken

the dry anomaly over Oregon and Washington relative to the current decades. HadRM simulates similar flow patterns to those in ECHAM5-WRF except that offshore of California, anomalous southerly flow prevails (Figs. 11c and i). This difference in anomalous flow patterns offshore of California largely explains the differences in the precipitation anomalies over the Southwest U.S. between ECHAM5-WRF and HadRM (Figs. 11b and h) as the anomalous southwesterly flow in ECHAM5-WRF dynamically interacts more with the mainly southeast to northwest oriented mountains than the anomalous southerly flow in HadRM. In CCSM3-WRF, anomalous south-southwesterly flow is simulated offshore of Oregon and Washington, which enhances the southwesterly component in this region; anomalous southerly flow is also simulated offshore of the Vancouver Island and is likely responsible for the wet anomalies in the area (Figs. 11e and f). Off the coast of California, the anomalous southwesterly flow in the CCSM3-WRF simulations splits before reaching the coast: the northern branch blows towards the north and is responsible for the wet anomalies over the northern part of California; the southern branch is deflected to become anomalous northwesterly.

Compared to the current decades (Figs. 11 and 5), moisture anomaly is enhanced over the entire domain in ECHAM5-WRF and CCSM3-WRF with little changes in HadRM.

4.2 La Niña Events

Cold and warm anomalies are noted over the PNW and the Southwest U.S., respectively, for cold ENSO in ECHAM5-WRF (Fig. 12a). These temperature anomalies differ from those of the current decades in which warm anomalies are identified over the entire domain for the current decades (see Figs. 12 and 6). In CCSM3-WRF (Fig. 12d), cold anomalies are the dominant feature over the western U.S. although the cold anomalies over the PNW are slightly larger than those over the Southwest U.S. For the current decades in CCSM3-WRF (Fig. 6d), cold anomalies are noted over the northern part of the PNW with weak anomalies over the Southwest U.S. In HadRM, the PNW and Southwest U.S. correspond to cold and weak anomalies, respectively (Fig. 12g). For the current decades, warm anomalies are noted over the entire domain in the HadRM simulations (Fig. 6f).

Precipitation patterns for cold ENSO show wet anomalies over the PNW and dry anomalies over the Southwest U.S. in ECHAM5-WRF and HadRM (Figs. 12b, h), largely resembling those for the current decades (Fig. 7). In CCSM3-WRF, wet anomalies are noted over the PNW and the northern part of California with weak anomalies over the southern part of California and the rest of Southwest U.S. These precipitation patterns in CCSM3-WRF are also similar to those for the current decades except that dry anomalies are simulated over the northern parts of Washington and the Southwestern U.S. for the current decades (see Figs. 12 and 7).

Weak anomalies in specific humidity are noted over the western U.S. in ECHAM5-WRF and HadRM (Figs. 12c, i), similar to the current decades (Figs. 7c, i). CCSM3-WRF simulates negative anomalies in specific humidity especially over the oceanic areas (Fig. 12f), in contrast to the weak anomalies for the current decades (Fig. 7f). Anomalous

northwesterly flow offshore of the PNW turns into mainly westerly over PNW in ECHAM5-WRF and HadRM (Figs. 12c, i). These anomalous flows would increase the westerly component in the region and thus enhance orographic lifting by the mountains over the PNW. Anomalous northerly to northeasterly flow is noted offshore of California in ECHAM5-WRF and HadRM, and is conducive to anomalous dry conditions over the Southwest U.S. by reducing southwesterly component in the region. These anomalous flow patterns in ECHAM5-WRF and HadRM are nearly the opposite from those for warm ENSO (see Figs. 11 and 12). In CCSM3-WRF (Fig. 12f), anomalous southwesterly flow off the coast of Oregon and California is conducive to anomalous wet conditions over the PNW and the northern part of California as the anomalous flow enhances the southwesterly component in the region. These anomalous flow patterns in CCSM3-WRF for future cold ENSO events bear some resemblance to those for the future warm ENSO (see Figs. 11f and 12f), but differ significantly from those for current cold ENSO events (see Figs. 7f and 12f).

This analysis indicates that in the future decades the warm-dry and cold-wet teleconnection patterns in association with the ENSO events bear much resemblance to those in the current decades in ECHAM5-WRF and HadRM but differ considerably from the current decades in CCSM3-WRF. The reason for the CCSM3-WRF simulated changes in the anomalous patterns between current and future ENSO events is not clear. We noted earlier that the future ENSO events in CCSM3 tend to decrease in frequency when compared to the current decades.

5. Future Changes

In this section, we will examine future changes in the teleconnection patterns associated with ENSO events based on the ECHAM5-WRF and HadRM simulations. We will look at the differences in temperature, precipitation, specific humidity and wind anomalies between the future and current decades. CCSM3-WRF simulates mainly wet anomalies over the PNW and Southwest U.S. for both warm and cold ENSO events in the future, in contrast to the canonical patterns of precipitation anomalies.

Figure 13 shows the difference plots for warm ENSO. Warming on the order of 1-2.5°C and 1.5-3.5°C is noted over the western U.S. in ECHAM5-WRF and HadRM, respectively (Figs. 13a, b), in consistence with the regional warming identified in Leung et al. (2004), Salathé et al. (2008), and Salathé et al. (2009). In ECHAM5-WRF, warming is about 0.5-1°C larger over the Southwest U.S. than the PNW (Fig. 13a). This north-south differential warming in ECHAM5-WRF would help to reduce the southward gradient in temperature for warm ENSO and may help to weaken the teleconnection signals between the PNW and the Southwest U.S. Such a differential warming is not evident in the HadRM simulations (Fig. 13b).

Wet anomalies in precipitation are noted over the PNW and the Southwest U.S. in ECHAM5-WRF for warm ENSO (Fig. 13c). Enhanced local wet anomalies are identified in ECHAM5-WRF along the coast of British Columbia and northern California (Fig. 13c), which are partly related to the anomalous flow that enhances the wind component

running perpendicular to the local mountains and partly related to the increased moisture due to warming (Fig. 13e). Wet and dry anomalies in precipitation are simulated by HadRM over the PNW and the Southwest U.S., respectively, for warm ENSO (Fig. 13d), consistent with the anomalous southwesterly flow off the coast of PNW and northeasterly flow off the coast of California (Fig. 13f). Increased moisture over the entire domain is also simulated in HadRM although not as pronounced as in ECHAM5-WRF (Figs. 13e, f).

During cold ENSO, relatively larger warming is noted over the Southwest U.S. than over the PNW in both models (Figs. 14a, b). This north-south differential warming would help to strengthen the northward temperature gradient for cold ENSO and may help to strengthen the teleconnection signals between the PNW and the Southwest U.S. For precipitation (Figs. 14c, d), dry anomalies are simulated over the Southwest U.S. by both models despite the increased moisture in the area (Figs. 14 e, f); over the U.S. PNW, both models simulate wet anomalies although the wet anomalies are much weaker in the ECHAM5-WRF simulations than in the HadRM simulations. The two models differ over the Vancouver Island and the western British Columbia in that wet anomalies are simulated by ECHAM5-WRF while dry anomalies are simulated by HadRM.

For cold ENSO, anomalous westerly and northerly flow is noted over the PNW and the Southwest U.S., respectively, in the ECHAM5-WRF simulations (Fig. 14e). In the HadRM simulations, anomalous northwesterly to northerly flow is identified over the PNW and Southwest U.S. (Fig. 14f). These anomalous flow patterns are closely related with the precipitation anomalies in that wet (dry) anomalies are located wherever the anomalous flow runs in perpendicular (parallel) to the mountains. As in the case for warm ENSO, increases in moisture are noted over the entire domain in both simulations; the increases are more pronounced in ECHAM5-WRF than in HadRM.

6. Conclusions and Discussions

This paper examines the surface temperature, precipitation, specific humidity and wind anomalies in association with ENSO events for the present and future decades based on the WRF simulations driven by ECHAM5 and CCSM3, and HadRM simulations driven by HadCM3. Major conclusions can be drawn from the analysis in what follows.

For the current decades, the ECHAM5-WRF, CCSM3-WRF and HadRM simulations are broadly consistent with the warm-dry and cool-wet teleconnection patterns over the PNW and the Southwest U.S. associated with the El Niño and La Niña events. Differences in the regional simulations originate primarily from the respective driving fields. While similarities between the regional simulations and the respective driving fields are striking, there are large differences over mountainous areas in which the simulated anomalies in the regional model are localized and amplified, most likely due to mesoscale feedbacks related to the complex orography not resolved by global models.

Interaction of anomalous wind flow with local terrain plays a critical role in the generation of precipitation anomalies over the PNW and the Southwest U.S in association

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with the ENSO events. Anomalous dry conditions are always associated with anomalous airflow that runs in parallel to local mountains, and wet conditions with airflow that runs in perpendicular to local mountains.

For the future decades, the warm-dry and cool-wet teleconnection patterns in association with the ENSO events are still present in ECHAM5-WRF and HadRM. There are indications of changes in the ENSO teleconnection patterns in CCSM3-WRF in the future, with wet anomalies dominating in the PNW and the Southwest U.S. for both warm and cold ENSO events, in contrast to the canonical patterns of precipitation anomalies. There is a tendency for ENSO events in CCSM3 to be fewer in the future. It should be noted that individual ENSO events often deviate from the canonical pattern even in the observed record, and the reason for such departures from the canonical pattern is not well understood. It is possible that changes in the mean state in a warmer climate can lead to more frequent or larger departures from the canonical patterns. This has important implications for seasonal forecasting, as there is still a strong reliance on empirical relationships and canonical anomaly patterns based on the observed contemporary record of ENSO events for ENSO forecasting. More analyses are needed in the future to examine the changes in the mean atmosphere and ocean states, as well as changes in ENSO canonical patterns in SST and changes in teleconnection patterns to determine their potential relationship.

Future changes in temperature, precipitation and wind associated with ENSO events in the ECHAM5-WRF and HadRM simulations suggest weakening of teleconnection patterns for warm ENSO but strengthening of teleconnection patterns for cold ENSO between the PNW and Southwest U.S. This is a complex issue as the future changes occur in concurrence with global and regional warming that also induces changes in the large-scale circulation that influence temperature and precipitation. For example, some studies suggested that global warming may result in a more general El Niño-type average state, when compared to the mean climate of the 20th century (e.g., Collins et al. 2005). The results here compare the future anomalies relative to the future mean state. Thus strength of El Niño anomalies may become smaller as the climate becomes more El-Niño-like, which makes it difficult to distinguish the mean state and the warm phase of ENSO. Furthermore, robustness of our results requires more attention as only one ensemble member of each global climate model simulation is used to investigate changes in teleconnection patterns.

This work clearly shows that the key to improve regional climate simulations lies on improving the large-scale simulations that drive the regional climate models. Consistent with Meehl et al. (2007), this study based on three global models show that large uncertainties remain in projecting future changes in ENSO frequency, magnitude and teleconnection pattern. As ENSO anomalies are amplified at the regional scale due to interactions of large-scale changes and surface orography, uncertainty in projecting temperature and precipitation changes along mountain ranges such as the Cascades and Sierra Nevada may be amplified. Since global climate models at 100-300 km resolution are unable to resolve the terrain effects and mesoscale feedbacks in association with complex terrain, high-resolution climate simulations are needed for climate studies and

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climate change assessment at local and regional scales. This suggests that more research is needed to understand the dynamical/physical mechanism of ENSO changes in a warmer climate, and a larger ensemble may be needed to characterize uncertainty in regional scale response to ENSO in the future.

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References

- Brekke LD, Dettinger MD, Maurer EP, Anderson M (2008) Significance of model credibility in estimating climate project distributions for regional hydroclimatological risk assessments. *Clim Chang* 89:371-394
- Cayan DR (1996) Interannual climate variability and snowpack in the western United States. *J Clim* 9:928-948
- Cayan DR, Roads JO (1984) Local relationships between United States West Coast precipitation and monthly mean circulation parameters. *Mon Weather Rev* 112:1276-1282
- Cayan DR, Redmond KT, Riddle LG (1999) ENSO and hydrologic extremes in the western United States. *J Clim* 12:2881-2893
- Chen F, Dudhia J (2001) Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon Weather Rev* 129:569-585
- Collins M (2000a) The El Niño-Southern Oscillation in the second Hadley Centre coupled model and its response to greenhouse warming. *J Clim* 13(7):1299-1312
- Collins M (2000b) Understanding uncertainties in the response of ENSO to greenhouse warming. *Geophys Res Letts* 27(21):3509-3513
- Collins M and the CMIP modeling group (2005) El Niño or La Niña like climate change? *Clim Dyn* 24:89-104
- Collins W, et al. (2006) The Community Climate System Model version 3 (CCSM3). *J Clim* 19:2122-2143
- Collins WD, Rasch PJ, Boville BA, Hack JJ, McCaa JR, Williamson DL, Kiehl JT, Briegleb B, Bitz C, Lin S-J, Zhang M, Dai Y (2004) Description of the NCAR Community Atmospheric Model (CAM 3.0). NCAR Tech. Note, NCAR/TN-464+STR, 226
- Cubash U, et al. (2001) Projections of future climate change. Chapter 9, Intergovernmental Panel on Climate Change Third Assessment Report, Cambridge University Press, Cambridge, United Kingdom and New York, NY, U.S.A.
- Deser C, Capotondi A, Saravanan R, Phillips AS (2006) Tropical Pacific and Atlantic climate variability in CCSM3. *J Clim* 19:2451-2481
- Dettinger MD, Cayan DR, Diaz HF, Meko DM (1998) North-south precipitation patterns in western North America on interannual-to-decadal timescales. *J Clim* 11:3095-3111

Dulière V, Zhang Y, Mote P, Salathé EP (2009) Extreme precipitations and temperatures over the U.S. Pacific Northwest: a comparison between observations, reanalysis and regional models. *J Clim*, submitted.

Gershunov A (1998) ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: Implications for long-range predictability. *J Clim* 11:3192-3203

Gordon C, Cooper C, Senior CA, Banks HT, Gregory JM, Johns TC, Mitchell JFB, Wood RA (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Clim Dyn* 16:147-168.

Hong SY, Pan HL (1996) Nonlocal boundary layer vertical diffusion in a Medium-Range Forecast Model. *Mon Weather Rev* 124:2322-2339

Hong SY, Dudhia J, Chen SH (2004) A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon Weather Rev* 132:103-120

Hong SY, Noh Y, Dudhia J (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon Weather Rev* 134:2318-2341

Jones RG, Noguer M, Hassel DC, Hudson D, Wilson SS, Jenkins GJ, Mitchell JFB (2004) Generating high resolution climate change scenarios using PRECIS. Met Office Hadley Centre, Exeter, UK, 40 pp.

Kain JS, Fritsch JM (1993) Convective parameterization for mesoscale models: The Kain-Fritsch scheme. In: Emanuel KA and Raymond DJ (eds) *The representation of cumulus convection in numerical models*. Amer Meteor Soc

Kumar A, Hoerling M (1998) Annual cycle of Pacific-North American seasonal predictability associated with different phases of ENSO. *J Clim* 11:3295-3308

Leung LR, Kuo YH, Tribbia J (2006) Research needs and directions of regional climate modeling using WRF and CCSM. *B Am Meteorol Soc* 87:1747-1751

Leung LR, Qian Y, Bian X, Hunt A (2003a) Hydroclimate of the western United States Based on observations and regional climate simulation of 1981-2000. Part II: Mesoscale ENSO anomalies. *J Clim* 16:1912-1928

Leung LR, Qian Y, Han J, Roads JO (2003b) Intercomparison of global reanalyses and regional simulations of cold season water budgets in the western United States. *J Hydrometeor* 4(6):1067-1087

Leung LR, Qian Y, Bian X, Washington WM, Han J, Roads JO (2004) Mid-century ensemble regional climate change scenarios for the Western United States. *Clim Chang* 62:75-113

Liang X, Lettenmaier, DP, Wood E, Burgers, SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J Geophys Res* 99:14415-14428.

Marsland SJ, Haak H, Jungclaus JH, Latif M, Roske F (2003) The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates. *Ocean Model* 5:91-127

Mass, CF (2008) *The Weather of the Pacific Northwest*. University of Washington Press, Seattle & London

Maurer EP, Wood AW, Adam JC, Lettenmaier DP (2002) A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States. *J Clim* 15: 3237-3251.

Meehl GA, et al. (2007) Global climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, U.S.A.

Mitchell TP, Blier W (1997) The variability of wintertime precipitation in the region of California. *J Clim* 10:2261-2276

Muller WA, Roeckner E (2008) ENSO teleconnections in projections of future climate in ECHAM5/MPI-OM. *Clim Dyn* 31:533-549

Nakicenovic N, et al. (2000) *IPCC special report on emissions scenarios*. Cambridge University Press

Pandey GR, Cayan DR, Georgakakos KP (1999) Precipitation structure in the Sierra Nevada of California during Winter. *J Geophys Res* 104:12019-12030

Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3. *Clim Dyn* 16:123-146

Qian Y, Ghan SJ, Leung LR (2009) Downscaling hydroclimate change over Western U.S. based on CAM subgrid scheme and WRF regional climate simulations. *Int J Climatol* doi:10.1002/joc.1928

Redmond KT, Koch RW (1991) Surface climate and streamflow variability in the western United States and their relationship to large scale circulation indices. *Water Resour Res* 27:2381-2399

Roeckner E, Bengtsson L, Feichter J, Lelieveld J, Rodhe H (1999) Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. *J Clim* 12:3004-3032

Roeckner E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kirchner I, Kornbleuh L, Manzini E, Rhodin A, Schlese U, Schulzweida U, Tomkins A (2003) The atmospheric general circulation model ECHAM5, Part I: Model description, Max-Planck-Institute for Meteorology Report No. 349

Ropelewski CF, Halpert MS (1986) North American precipitation and temperature patterns associated with the ENSO. *Mon Weather Rev* 114:2352-2362

Salathé EP, Steed R, Mass CF, Zahn P (2008) A high-resolution climate model for the U.S. Pacific Northwest: Mesoscale feedbacks and local responses to climate change. *J Clim* 21:5708-5726

Salathé EP, Leung RL, Qian Y, Zhang Y (2009) Regional Climate Model Projections for the State of Washington. *Clim Change*, submitted.

Van Oldenborgh GJ, Philip SY, Collins M (2005) El Niño in a changing climate: A multi-model study. *Ocean Sci* 1:81-95

Wallace JM, Smith C, Bretherton CS (1992) Singular value decompositions of wintertime sea surface temperature and 500-mb height anomalies. *J Clim* 5:561-576

Zhang Y, Dulière V, Mote P, Salathé EP (2009) Evaluation of WRF and HadRM mesoscale climate simulations over the United States Pacific Northwest. *J Clim*, in press.

Table 1. Frequency and average intensity (°C) of El Niño and La Niña events for the current decades and future decades based on ONI index

		El Niño Events		La Niña Events	
		Frequency ^a	Intensity ^b	Frequency	Intensity
Current Decades (1970 – 1999)	OBS	6	1.92	6	-1.60
	ECHAM5	7	2.31	8	-1.96
	CCSM3	10	1.56	10	-1.54
	HadCM3	3	2.03	4	-1.38
Future Decades (2030 – 2059)	ECHAM5	7	3.07	10	-2.59
	CCSM3	9	1.37	7	-1.63
	HadCM3	7	1.83	7	-1.54

^a Frequency is the number of events during the period;

^b Intensity is defined as the average of the maximum ONI for all events.

Figure 1. ECHAM5-WRF model domain with one nest (Domain 1, 2), CCSM3-WRF model domain, and HadRM model domain. Shadings represent terrain height (m) for the corresponding model domain. Grid spacing for each domain is: ECHAM5-WRF Domain 1, 108 km; ECHAM5-WRF Domain 2, 36 km; CCSM3-WRF Domain, 20 km; and HadRM Domain, 25 km.

Figure 2. Seasonal (October to March) mean anomalies of (a) (b) observed surface air temperature ($^{\circ}\text{C}$), (c) (d) observed precipitation rate (mm day^{-1}), (e) (f) VIC simulated April 1 snow water equivalent (SWE; mm), and (g) (h) NCEP/NCAR reanalysis surface wind (m s^{-1}) and specific humidity (g kg^{-1}) for the period of 1970-1999. Left and right columns correspond to El Niño and La Niña years, respectively. El Niño and La Niña years were chosen based on NOAA Oceanic Niño Index.

Figure 3. Running 3-month mean SST anomaly for the Nino 3.4 region (5°N-5°S, 120°-170°W) during 1970-1999 constructed from (a) ECHAM5, (b) CCSM3, (c) HadCM3 global climate model simulations for the 20th century, and (d) observations. Dashed lines represent the $\pm 0.5^\circ\text{C}$ reference lines.

Figure 4. Seasonal (October – March) mean surface air temperature ($^{\circ}\text{C}$) anomaly for El Nino years based on (a) raw ECHAM5, (b) ECHAM5-WRF, (c) raw CCSM3, (d) CCSM3-WRF, (e) raw HadCM3, and (f) HadRM simulations for 1970-1999.

Figure 5. Seasonal (October – March) mean precipitation (mm day^{-1}) anomaly for El Niño years based on (a) raw ECHAM5, (b) ECHAM5-WRF, (d) raw CCSM3, (e) CCSM3-WRF, (g) raw HadCM3, (h) HadRM simulations, and mean surface wind (m s^{-1}) and specific humidity (g kg^{-1}) anomaly for El Niño years based on (c) ECHAM5-WRF, (f) CCSM3-WRF, and (i) HadRM simulations for 1970-1999.

Figure 6. Same as Figure 4 except for La Nina years.

Figure 7. Same as Figure 5 except for La Nina years.

Figure 8. April 1 snow water equivalent (SWE) anomaly (mm) for El Niño years based on (a) ECHAM5-WRF, (b) CCSM3-WRF and (c) HadRM simulations, and for La Niña years based on (d) ECHAM5-WRF, (e) CCSM3-WRF and (f) HadRM simulations.

Figure 9. Cross sections showing the observed and simulated 2-m temperature anomaly ($^{\circ}\text{C}$) for (a) El Nino years and (b) La Nina years along 47.8°N , (c) El Nino years and (d) La Nina years along 37.5°N , and the observed and simulated precipitation anomaly (percent) for (e) El Nino years and (f) La Nina years along 47.8°N , (g) El Nino years and (h) La Nina years along 37.5°N . Thick grey lines represent the terrain heights.

Figure 10. Running 3-month mean SST anomaly for the Nino 3.4 region (5°N-5°S, 120°-170°W) during 2030-2059 constructed from (a) ECHAM5, (b) CCSM3, and (c) HadCM3 global climate model simulations for the future decades under the SRES A1B (ECHAM5 and HadCM3) and SRES A2 (CCSM3) scenario. Dashed lines represent the $\pm 0.5^{\circ}\text{C}$ reference lines.

Figure 11. Seasonal (October – March) mean (a) (d) (g) surface air temperature ($^{\circ}\text{C}$), (b) (e) (h) precipitation (mm day^{-1}), and (c) (f) (i) surface wind (m s^{-1}) and specific humidity (g kg^{-1}) anomaly for El Niño years based on ECHAM5-WRF, CCSM3-WRF, and HadRM simulations, respectively, for 2030-2059.

Figure 12. Same as Figure 11 except for La Nina years.

Figure 13. Surface air temperature differences ($^{\circ}\text{C}$) from (a) ECHAM5-WRF and (b) HadRM, precipitation differences (mm day^{-1}) from (c) ECHAM5-WRF and (d) HadRM, surface wind differences (m s^{-1}) and specific humidity differences (g kg^{-1}) from (e) ECHAM5-WRF and (f) HadRM between future and current El Niño years.

Figure 14. Same as Figure 13 but for La Nina years.