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Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models

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[1] We find a consistent and statistically significant increase in the intensity of future extreme winter precipitation events over the western United States, as simulated by an ensemble of regional climate models (RCMs) driven by IPCC AR4 global climate models (GCMs). All eight simulations analyzed in this work consistently show an increase in the intensity of extreme winter precipitation with the multi-model mean projecting an area-averaged 12.6% increase in 20-year return period and 14.4% increase in 50-year return period daily precipitation. In contrast with extreme precipitation, the multi-model ensemble shows a decrease in mean winter precipitation of approximately 7.5% in the southwestern US, while the interior west shows less statistically robust increases. **Citation:** Dominguez, F., E. Rivera, D. P. Lettenmaier, and C. L. Castro (2012), Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models, *Geophys. Res. Lett.*, *39*, L05803, doi:10.1029/2011GL050762.

1. Introduction

[2] It has been hypothesized that climate change will drive changes in the intensity and frequency of intense precipitation events due primarily to changes in atmospheric moisture content [*Trenberth et al.*, 2003; *Emori and Brown*, 2005]. Increased atmospheric moisture content arises because warmer atmospheric temperatures allow the air to hold more moisture following the Clausius-Clapeyron relation [*Trenberth et al.*, 2003; *Meehl et al.*, 2007]. The rates of change of mean and extreme precipitation are different because changes in the mean are constrained by the surface energy budgets, while the intensity of individual extreme precipitation events can change proportionately to the moisture content [*Trenberth*, 1999; *Allen and Ingram*, 2002]. In particular, changes in mean precipitation in the western United States (US) will be dominated by the likely widening of the tropical belt [*Seidel et al.*, 2008] and the poleward shift of the westerly winds [*Archer and Caldeira*, 2008]. On the other hand, extreme rainfall events are driven by water vapor content, moist-adiabatic lapse rate, upward wind velocity, small scale dynamics, cloud microphysics, temperature when precipitation extremes occur and orientation of the storm tracks relative to topography [*Trenberth et al.*, 2003; *Lenderink and Van Meijgaard*, 2008; *O'Gorman and Schneider*, 2009; *Leung and Qian*, 2009; *Sugiyama et al.*, 2010]. In fact, observations show that hourly precipitation extremes can increase with rising temperatures at higher levels than those predicted by the Clausius-Clapeyron relation [*Lenderink and Van Meijgaard*, 2008], although the scaling is not constant over temperature and varies with event duration [*Hardwick Jones et al.*, 2010]. Observational records show an increase in the amount and frequency of intense precipitation events over the US [*Easterling et al.*, 2000; *Groisman et al.*, 2001]. In some regions such as the Southwestern US, mean precipitation is expected to decrease, while the frequency of extreme rainfall events is expected to increase [*Emori and Brown*, 2005; *Meehl et al.*, 2007]. The higher probability of extreme precipitation events has important consequences for water management systems, which rely on the probability of occurrence of future extreme events. It is increasingly evident that under a changing climate the probability distributions of precipitation that are used for water infrastructure design are likely to be different from those estimated from the historical record due to the non-stationarity of the climate system, and hence the design criteria must change accordingly [*Milly et al.*, 2008].

[3] In this respect, global climate model (GCM) projections consistently predict a generalized shift toward more intense and frequent extreme precipitation events in the future [*Kharin and Zwiers*, 2005; *Kharin et al.*, 2007; *Groisman et al.*, 2005; *Sun et al.*, 2007; *Tebaldi et al.*, 2006]. The changes in extreme precipitation simulated by the GCMs are larger than the change in mean precipitation [*Kharin and Zwiers*, 2000, 2005], and the signal of change in extremes has been found to be larger than that of natural climate variability [*Hegerl et al.*, 2004], consequently, these changes may be attributed at least in part to human-induced increases in greenhouse gases [*Min et al.*, 2011; *Zhang et al.*, 2007]. However, GCMs generally do not realistically represent precipitation due to their coarse spatial resolution and physical parameterizations, especially in complex terrain. Higher spatial resolution, improved representation of orography and land-surface heterogeneity, and hence a better representation of precipitation, are most practically achieved with the use of regional climate models (RCMs), as GCMs are presently too computationally expensive for multi-decade climate change projection-type integrations with equivalent resolution. RCMs generally better capture mean and extreme precipitation at the regional scale [*Diffenbaugh et al.*, 2005; *Leung and Qian*, 2009]. We refer to the process of using RCMs forced at their lateral boundaries by GCMs as "dynamical downscaling". Two large multi-institutional

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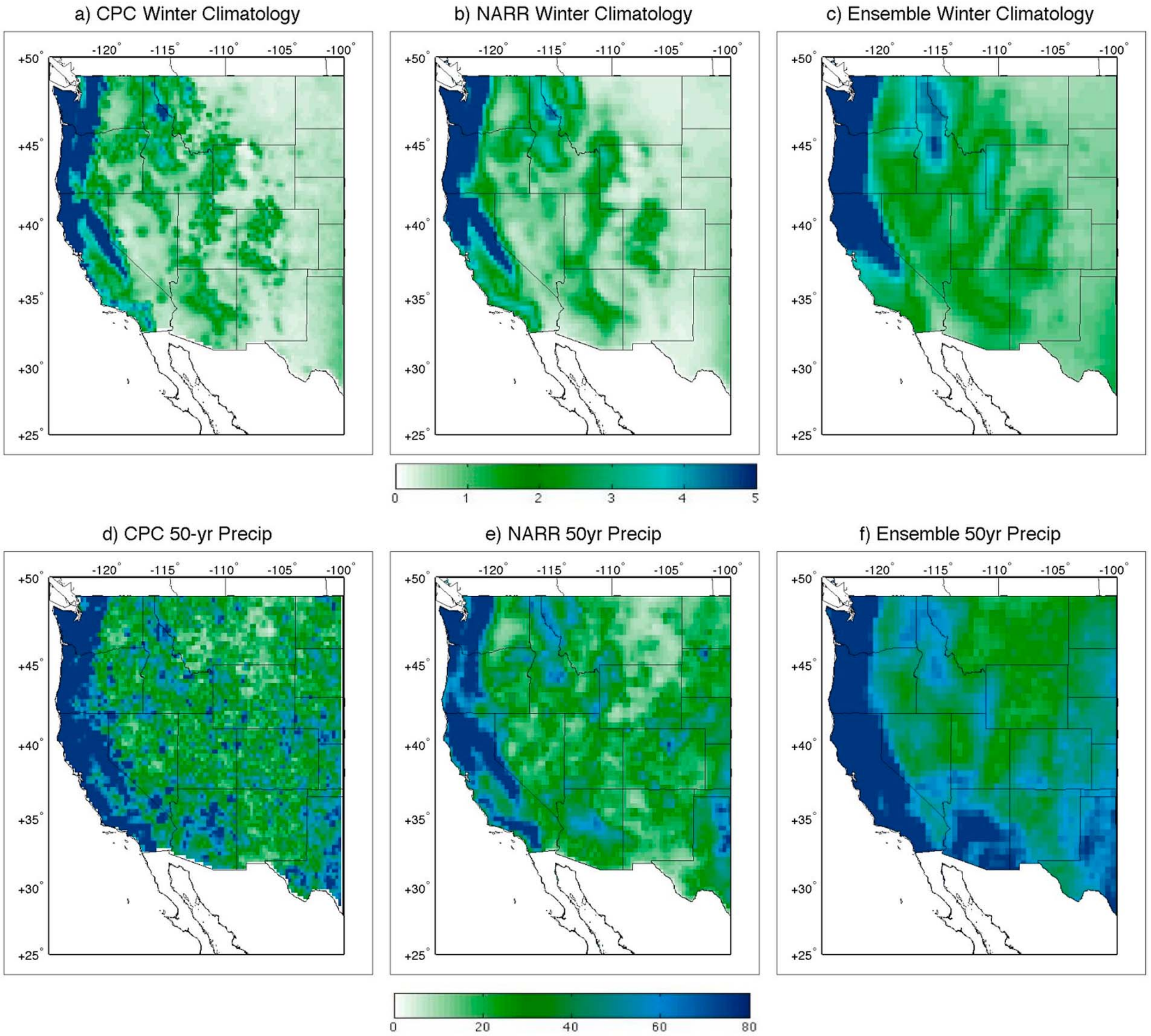

Figure 1. Winter 1979–1999 Precipitation Climatology (mm/day) for (a) CPC precipitation, (b) NARR precipitation, and (c) multi-model ensemble of eight downscaled simulations. And 50-yr return period precipitation for (d) CPC precipitation, (e) NARR precipitation, and (f) multi-model ensemble of eight downscaled simulations.

dynamical downscaling efforts, the 'North American Regional Climate Change Assessment Program' (NARCCAP) [*Mearns et al.*, 2009] and 'Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects (PRUDENCE) [*Christensen et al.*, 2007] have analyzed extreme precipitation in North America and Europe, respectively, using time-slice experiments. The RCMs participating in NARCCAP, driven by historical National Center for Environmental Prediction-Department of Energy (NCEP-DOE) Reanalysis II data [*Kanamitsu et al.*, 2002], show a realistic representation of the frequency and intensity of cool season extreme events when compared to observations [*Gutowski et al.*, 2010]. NARCCAP models show very similar geographical representation of extreme events when compared against one another in the historical period [*Schliep et al.*, 2010], however an analysis of NARCCAP future extremes has not been published to date. Using extreme value analysis on the PRUDENCE ensemble, [*Fowler et al.*, 2007] find an increase in the magnitude of short and long duration extreme precipitation over Europe, and a strong sensitivity to the driving GCM. Particularly over the United Kingdom, PRUDENCE shows increases in projected extreme precipitation in every season except summer [*Fowler and Ekstroem*, 2009].

[4] In this work, we evaluate future extreme precipitation events over the Western US as projected by eight different dynamically downscaled simulations for the historical period (1968–1999) and the future period (2038–2070). Our goal is to provide estimates of changes in future extreme precipitation useful for engineering design of water management structures.

2. Materials and Methods

2.1. Simulations

[5] The driving GCM future projections for the eight downscaled simulations were all generated using the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment A2 scenario, which is characterized by slow economic growth and ever-increasing population [*Intergovernmental*

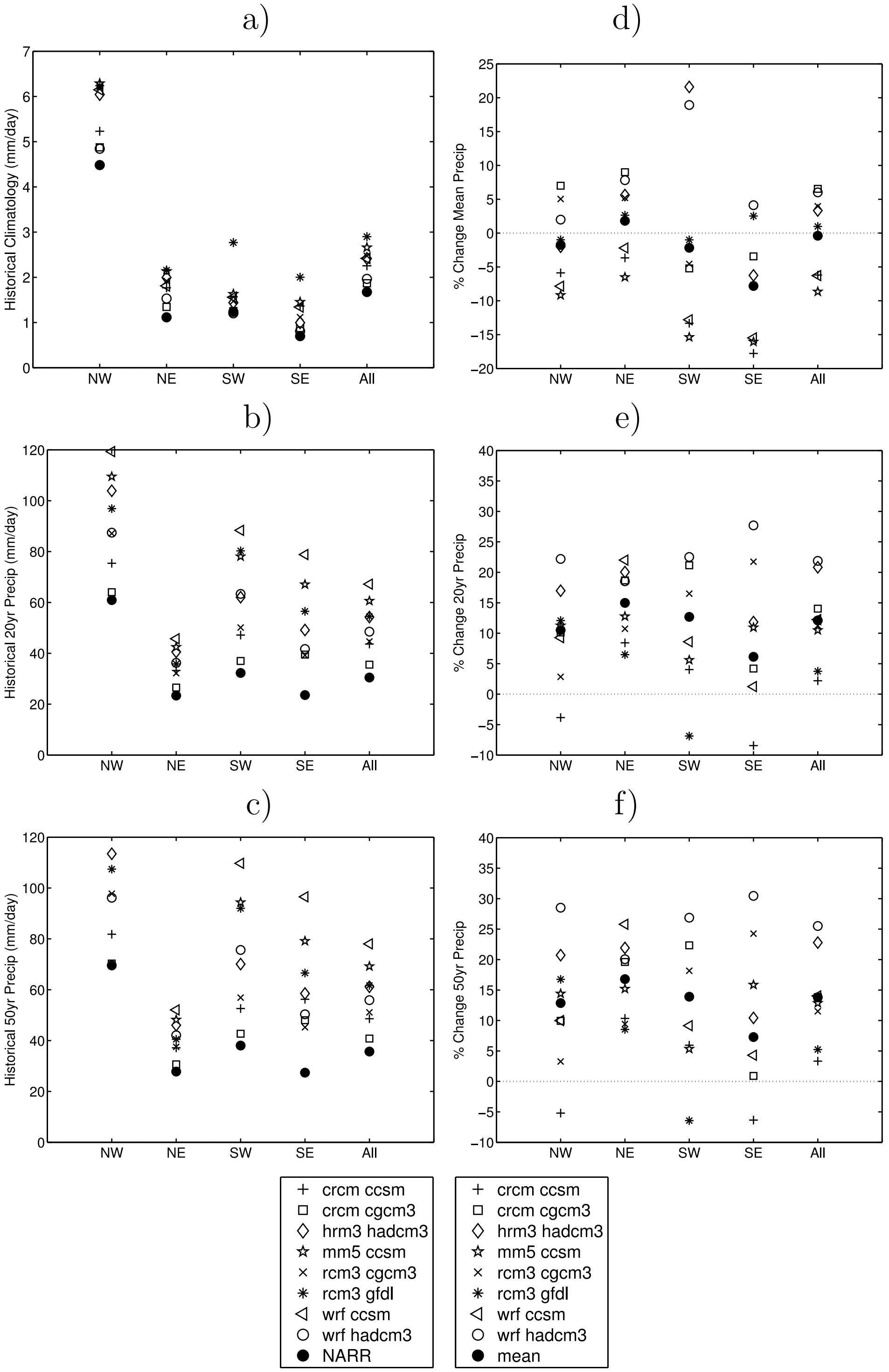

Figure 2. Area-averaged (a) mean, (b) 20-year return period, and (c) 50-year return period winter precipitation for the historical period (1979–1999) for the eight downscaled simulations and the NARR (1979–1999) (solid black circle) for the four sub regions and the entire region. Percent change of (d) mean, (e) 20-year return period, and (f) 50-year return period winter precipitation between the future (2038–2070) and the historical period (1968–1999) for the eight downscaled simulations and multi-model mean.

Panel on Climate Change (*IPCC*), 2007]. Seven of the downscaled simulations come from the NARCCAP multi-institutional effort and one simulation was produced independently by the authors at the University of Arizona, for a total of eight simulations with different RCM-GCM combinations (Table S1 in the auxiliary material).[1] Details of the downscaled simulations are provided in section S1 of

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL050762.

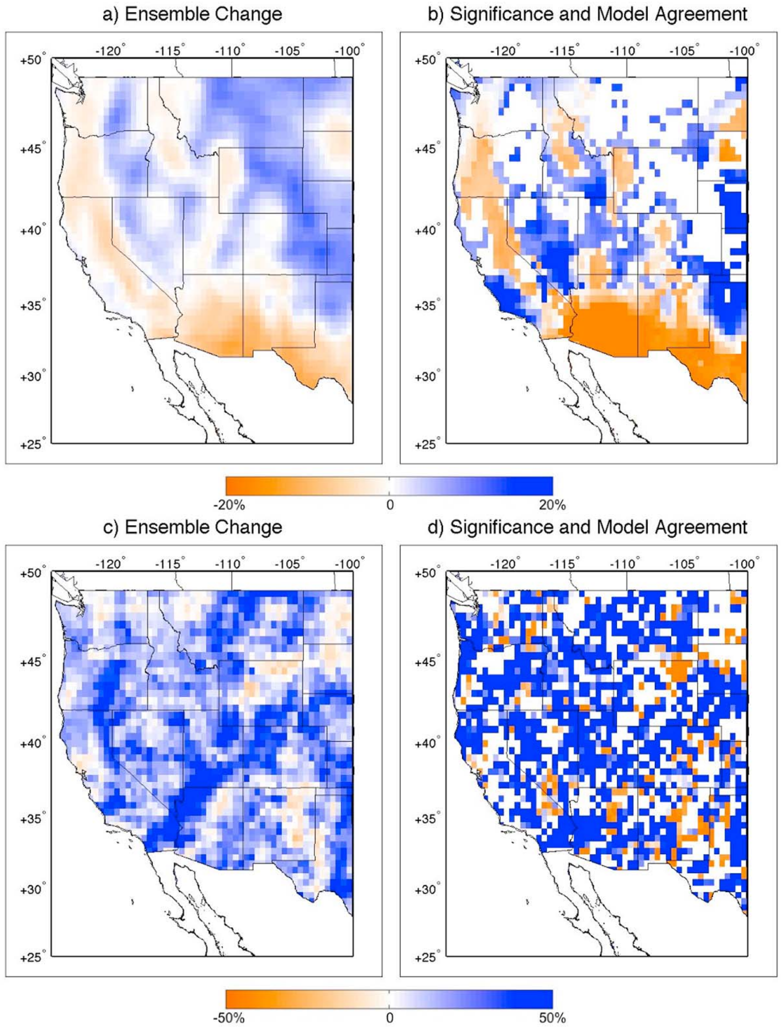

Figure 3. (a) Ensemble average percent change in mean winter precipitation between the historical (1968–1999) and future (2038–2070) periods for all simulations. (b) Ensemble average percent change in mean winter precipitation for *only* those models with statistically significant changes and *only* where more than 4 models agree on the sign of the change. (c) Ensemble average percent change in 50-year return period winter precipitation between the historical (1968–1999) and future (2038–2070) periods for all simulations. (d) Ensemble average percent change in 50-year return period winter precipitation for *only* those models with statistically significant changes and *only* where more than 4 models agree on the sign of the change.

Text S1. We used the Climate Prediction Center (CPC) US Unified Precipitation [*Higgins et al.*, 1996], at a 0.25° resolution, as the observational dataset to compare to the model simulations. We also used the North American Regional Reanalysis (NARR) [*Mesinger et al.*, 2006] as the 32 km resolution assimilated product, more similar to model simulations than the observations, but which also assimilates observed precipitation. The eight downscaled simulations, CPC data and NARR data overlap for the period 1979–1999, so our comparisons with observations are for this period.

2.2. Statistics of Extremes

[6] Statistical analysis of precipitation extremes in a changing climate has traditionally been done using the upper quantiles of the distributions [*Gutowski et al.*, 2010] or using generalized extreme value (GEV) theory [*Kharin and Zwiers*, 2005; *Fowler et al.*, 2007]. In this work we use a "peaks over a threshold" (POT) approach [*Katz*, 2010] that fits a theoretical distribution to the data above a certain threshold on the upper tail of the distribution [*Katz et al.*, 2002; *Katz*, 2010]. This methodology is particularly useful when analyzing RCM simulations where only time-slice experiments of a limited number of years are available as it allows for a larger sample size than the GEV approach. Throughout our work we use daily data to calculate the 20-year and 50-year return levels, on a cell-by-cell basis, for both the historical and future periods. Details of the statistical approach and calculation of statistical significance are provided in sections S2 and S3 of Text S1.

3. Results

3.1. Climatology in the Historical Period

[7] Winter precipitation climatology in the Western US is characterized by high precipitation over the western coast of Washington, Oregon and California with the clear topographic

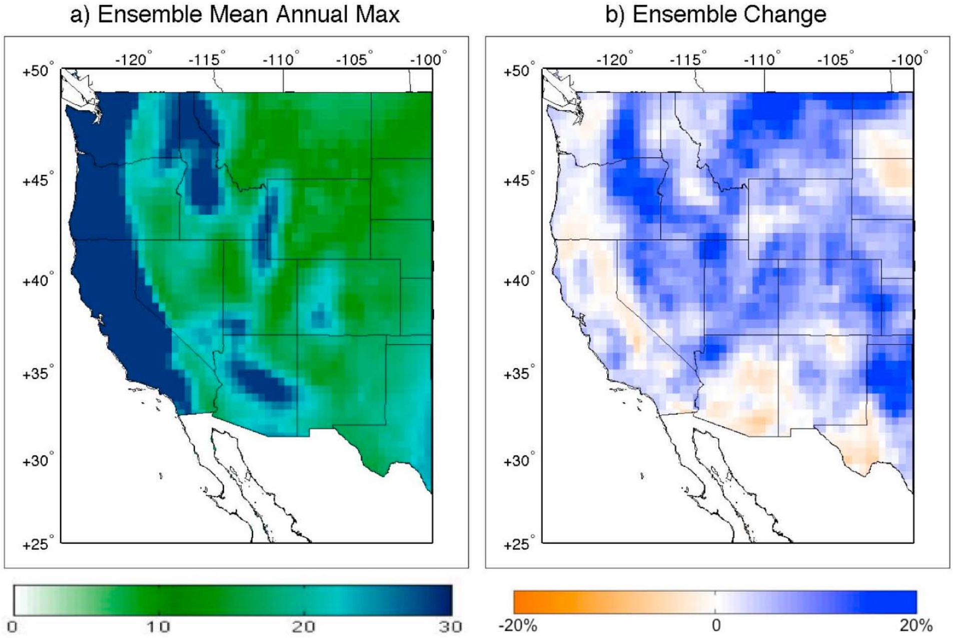

Figure 4. Winter 1968–1999 average annual maximum winter precipitation for (a) multi-model ensemble of the eight downscaled simulations. (b) Ensemble average percent change between the historical (1968–1999) and future (2038–2070) periods.

influence of the major mountain ranges which include the Cascade Range, the Bitterroot Range, the Wasatch Range, the Sierra Nevadas, the Coastal Range and the Front and Park Ranges (Figures 1a and 1b). The winter precipitation climatology of the ensemble average of the eight downscaled simulations show realistic spatial patterns, when compared to the CPC observed and NARR- derived winter precipitation (Figure 1c) despite a generalized positive bias in the downscaled simulations and loss of spatial detail particularly in the Coast Range of California, where the precipitation peak is not seen in the model ensemble (individual model results are shown in Figure S2). We subdivide the Western US into four sub regions: northwest (NW), northeast (NE), southwest (SW) and southeast (SE) (Figure S1a) to more easily visualize individual model estimates (Figure 2a). The northwestern US has the highest winter precipitation (reaching 4.5 mm/day in the coast), whereas the interior west receives only about 1 mm/day during the winter season. The SE region includes the North American Monsoon region, which has peak precipitation in the summer and receives only about 0.8 mm/day during the winter. All eight simulations overestimate mean winter precipitation, but some models are consistently higher by about 1 to 1.5 mm/day (Figure 2a). Averaged over the entire domain, the *rcm*3*_gfdl* has the largest positive bias, and *crcm_cgcm*3 and *wrf_hadcm*3 have the smallest.

3.2. Extreme Events in the Historical Period

[8] Using the POT statistical approach, we calculate the 20-year and 50-year return period daily maximum winter historical (1968–1999) precipitation for all grid cells in each of the eight dynamically downscaled simulations and for the CPC and NARR output. The patterns of the 20-year, and 50-year return period winter daily maximum precipitation for the Western US show very similar spatial patterns to the climatological mean winter precipitation (Figures 1d–1f show the 50-year events). The spatial patterns of the 20-year return period events are quite similar, albeit with smaller intensity (not shown). In comparison to the climatology, certain regions (e.g., the Mogollon Rim in central Arizona, the region of central Texas and the Southern Coastal Range) stand out because of their intense extreme precipitation events despite modest climatological means. This is due to a few large and intense winter storms with otherwise low precipitation in these regions. Compared to CPC and NARR, 50-year precipitation, the ensemble average shows reasonable spatial distribution with a positive bias throughout the region (Figure 1f). It is important to note, however, that NARR seems to underestimate 50-yr precipitation when compared to CPC over the Mogollon Rim, Texas and the Coastal Range, indicating that the multi-model ensemble resembles CPC rather than NARR in these regions (Figures 1d and 1e). The multi-model ensemble simulations show large positive biases over the western coastal mountains and the southern part of the domain (see regions NW, SE and SW in Figure 2c), largely due to overestimations in the *mm*5*_ccsm*, *rcm*3*_gfdl* and *wrf_ccsm* models (Figure S4). Over the entire domain, *wrf_ccsm* shows the largest positive bias for the 20-year and 50-year magnitudes, in some cases more than 100% overestimation, while the *crcm_cgcm*3 shows the smallest bias.

3.3. Changes in Future Climatology

[9] Percent changes in future winter precipitation are calculated on a cell-by-cell basis. The ensemble average spatial pattern shows future increases in mean winter precipitation over the interior west and decreases in the southern and western parts of the region (Figure 3a). The regions where four or more models agree in the sign, and the changes are statistically significant, are shown in Figure 3b. The southwestern US, northern California and western Oregon show a statistically significant decrease in mean precipitation with general model agreement (Figure 3b). The interior west shows generalized increases in future mean precipitation,

although the changes are not as robust and there is significant spatial heterogeneity. The area-averaged analysis over the sub regions shows a 7.5% decrease in the SE region (southwestern US) with strong model agreement (Figure 2d). In general, the changes in mean winter precipitation show statistically significant decreased mean precipitation in the southwest and the western coast, and (less statistically robust) increases in mean precipitation in the interior west.

3.4. Changes in Future Extreme Events

[10] We estimated changes in the intensity of future precipitation extremes on a cell-by-cell basis, as percent changes in the intensity for a particular return period N = 20 and 50-years ((Fut x_{Nyr} − Hist x_{Nyr}) x100/Hist x_{Nyr}). The spatial pattern of the changes in 50-year return period precipitation is heterogeneous and varies considerably among models (Figure S5). However, the ensemble average shows generalized increases throughout the region (Figure 3c), the changes are statistically significant and the models generally agree on the sign of the changes throughout the domain (Figure 3d). The changes in the intensity of extremes, averaged over the entire domain, is positive for all eight simulations ranging from about 5% to 25% increase in extremes (Figures 2e and 2f). For specific regions only a few models show decreases in the intensity of extreme events. The *wrf_hadcm*3 shows the largest increases for the domain as a whole, while the *crcm_ccsm* shows the smallest increases. Averaged over the entire domain, the multi-model area-averaged mean shows a 12.6% increase in 20-year precipitation and 14.4% increase in 50-year precipitation. Notably, all eight models show increases in 50-yr and 20-yr return period winter precipitation.

4. Discussion and Conclusions

[11] We have analyzed future changes in extreme precipitation events as simulated by dynamically downscaled GCM projections with the goal of providing useful estimates for engineering design of water management structures. We were motivated to use dynamically-downscaled simulations because RCMs are better able to capture the mean and extreme precipitation at the local scale than their driving GCMs [*Leung and Qian*, 2009]. We find that the RCMs reasonably reproduce the climatological spatial variability of both mean and extreme precipitation, however, all simulations have a positive bias in precipitation intensity over the Western US, which seems to be a consistent problem with downscaled simulations for the region [*Wang et al.*, 2009].

[12] Projected future changes in mean winter precipitation show a clear geographical pattern, with increases in the interior west and decreases in the southwest and the coastal regions. This is consistent with GCM projections, as shown by the *IPCC* [2007]. However, these changes are generally small, statistically significant in the southwest but not in the rest of the domain. On the other hand, we find pervasive and statistically significant increases in extreme winter precipitation throughout the domain. All eight simulations analyzed in this work consistently show an increase in the intensity of area-averaged extreme winter precipitation with the multi-model mean projecting a 12.6% increase in 20-year 24-hour precipitation and a 14.4% increase in 50-year 24-hour precipitation for the period 2038–2070 as compared with the 1968–1999 historical period. However, there are large differences, and generally a lack of consistency among models in the spatial variations of model-projected changes in extremes, notwithstanding that almost all models agree on area-averaged increases. The spatial heterogeneity could in part be due to the small statistical sample size when looking at very low probability events. Using a different metric, the mean annual maximum (MAM) daily precipitation, we find consistent results. The MAM approach shows generalized increase intensity in the future, but the spatial pattern is more spatially homogeneous (Figure 4).

[13] While our analysis has focused on daily precipitation statistics, engineering design of water infrastructure requires information at the event timescale (sub-daily or even sub-hourly) where the changes might not be the same as those seen in the daily data. As we move forward providing information that is relevant for urban regions, it is important that we focus on higher temporal and spatial resolutions where the convective dynamics are explicitly resolved. It is also important to note that intensification of extreme events will affect many other aspects of society and the natural environment. These include agriculture, plant and animal species, ecosystems structure and habitat [*Diffenbaugh et al.*, 2005; *Easterling et al.*, 2000]. It is therefore increasingly evident that, following the current warming trend, different socioeconomic and natural sectors of the western US will likely be affected by more intense precipitation extremes.

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References

Allen, M., and W. Ingram (2002), Constraints on future changes in climate and the hydrologic cycle, *Nature*, *419*, 224–232, doi:10.1038/nature01092.

Archer, C. L., and K. Caldeira (2008), Historical trends in the jet streams, *Geophys. Res. Lett.*, *35*, L08803, doi:10.1029/2008GL033614.

Christensen, J. H., T. R. Carter, M. Rummukainen, and G. Amanatidis (2007), Evaluating the performance and utility of regional climate models: The PRUDENCE project, *Clim. Change*, *81*, 1–6, doi:10.1007/s10584-006-9211-6.

Diffenbaugh, N. S., J. S. Pal, R. J. Trapp, and F. Giorgi (2005), Fine-scale processes regulate the response of extreme events to global climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *102*(44), 15,774–15,778, doi:10.1073/pnas.0506042102.

Easterling, D., G. Meehl, C. Parmesan, S. Changnon, T. Karl, and L. Mearns (2000), Climate extremes: Observations, modeling, and impacts, *Science*, *289*, 2068–2074, doi:10.1126/science.289.5487.2068.

Emori, S., and S. Brown (2005), Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate, *Geophys. Res. Lett.*, *32*, L17706, doi:10.1029/2005GL023272.

Fowler, H. J., and M. Ekstroem (2009), Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes, *Int. J. Climatol.*, *29*(3), 385–416, doi:10.1002/joc.1827.

Fowler, H. J., M. Ekstrom, S. Blenkinsop, and A. P. Smith (2007), Estimating change in extreme European precipitation using a multimodel ensemble, *J. Geophys. Res.*, *112*, D18104, doi:10.1029/2007JD008619.

Groisman, P., R. Knight, and T. Karl (2001), Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century, *Bull. Am. Meteorol. Soc.*, *82*(2), 219–246, doi:10.1175/1520-0477(2001)082<0219:HPAHSI>2.3.CO;2.

Groisman, P., R. Knight, D. Easterling, T. Karl, G. Hegerl, and V. Razuvaev (2005), Trends in intense precipitation in the climate record, *J. Clim.*, *18*(9), 1326–1350, doi:10.1175/JCLI3339.1.

Gutowski, W. J., et al. (2010), Regional extreme monthly precipitation simulated by NARCCAP RCMs, *J. Hydrometeorol.*, *11*(6), 1373–1379, doi:10.1175/2010JHM1297.1.

Hardwick Jones, R., S. Westra Seth, and A. Sharma (2010), Observed relationships between extreme sub-daily precipitation, surface temperature, and relative humidity, *Geophys. Res. Lett.*, *37*, L22805, doi:10.1029/2010GL045081.

Hegerl, G., F. Zwiers, P. Stott, and V. Kharin (2004), Detectability of anthropogenic changes in annual temperature and precipitation extremes, *J. Clim.*, *17*(19), 3683–3700, doi:10.1175/1520-0442(2004)017<3683:DOACIA>2.0.CO;2.

Higgins, R. W., J. E. Janowiak, and Y.-P. Yao (1996), A gridded hourly precipitation data base for the United States (1963–1993), *Atlas 1*, 46 pp., Clim. Predict. Cent., NCEP, Camp Springs, Md.

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Kanamitsu, M., et al. (2002), NCEP-DOE AMIP-II reanalysis (R-2), *Bull. Am. Meteorol. Soc.*, *83*(11), 1631–1643, doi:10.1175/BAMS-83-11-1631.

Katz, R. W. (2010), Statistics of extremes in climate change, *Clim. Change*, *100*, 71–76, doi:10.1007/s10584-010-9834-5.

Katz, R., M. Parlange, and P. Naveau (2002), Statistics of extremes in hydrology, *Adv. Water Resour.*, *25*, 1287–1304, doi:10.1016/S0309-1708(02)00056-8.

Kharin, V., and F. Zwiers (2000), Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM, *J. Clim.*, *13*(21), 3760–3788, doi:10.1175/1520-0442(2000)013<3760:CITEIA>2.0.CO;2.

Kharin, V., and F. Zwiers (2005), Estimating extremes in transient climate change simulations, *J. Clim.*, *18*(8), 1156–1173, doi:10.1175/JCLI3320.1.

Kharin, V. V., F. W. Zwiers, X. Zhang, and G. C. Hegerl (2007), Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations, *J. Clim.*, *20*(8), 1419–1444, doi:10.1175/JCLI4066.1.

Lenderink, G., and E. Van Meijgaard (2008), Increase in hourly precipitation extremes beyond expectations from temperature changes, *Nat. Geosci.*, *1*, 511–514, doi:10.1038/ngeo262.

Leung, L. R., and Y. Qian (2009), Atmospheric rivers induced heavy precipitation and flooding in the western US simulated by the WRF regional climate model, *Geophys. Res. Lett.*, *36*, L03820, doi:10.1029/2008GL036445.

Mearns, L., W. Gutowski, R. Jones, L. Leung, S. McGinnis, A. Nunes, and Y. Qian (2009), A regional climate change assessment program for North America, *Eos Trans. AGU*, *90*, 311–312, doi:10.1029/2009EO360002.

Meehl, G. A., C. Tebaldi, H. Teng, and T. C. Peterson (2007), Current and future US weather extremes and el Niño, *Geophys. Res. Lett.*, *34*, L20704, doi:10.1029/2007GL031027.

Mesinger, F., et al. (2006), North American regional reanalysis, *Bull. Am. Meteorol. Soc.*, *87*, 343–360, doi:10.1175/BAMS-87-3-343.

Milly, P. C. D., et al. (2008), Stationarity is dead: Whither water management?, *Science*, *319*(5863), 573–574, doi:10.1126/science.1151915.

Min, S.-K., X. Zhang, F. W. Zwiers, and G. C. Hegerl (2011), Human contribution to more-intense precipitation extremes, *Nature*, *470*(7334), 378–381, doi:10.1038/nature09763.

O'Gorman, P. A., and T. Schneider (2009), The physical basis for increases in precipitation extremes in simulations of 21st-century climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(35), 14,773–14,777, doi:10.1073/pnas.0907610106.

Schliep, E. M., D. Cooley, S. R. Sain, and J. A. Hoeting (2010), A comparison study of extreme precipitation from six different regional climate models via spatial hierarchical modeling, *Extremes*, *13*(2), 219–239, doi:10.1007/s10687-009-0098-2.

Seidel, D. J., Q. Fu, W. J. Randel, and R. J. Reichler (2008), Widening of the tropical belt in a changing climate, *Nat. Geosci.*, *1*, 21–24, doi:10.1038/ngeo.2007.38.

Sugiyama, M., H. Shiogama, and S. Emori (2010), Precipitation extreme changes exceeding moisture content increases in MIROC and IPCC climate models, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(2), 571–575, doi:10.1073/pnas.0903186107.

Sun, Y., S. Solomon, A. Dai, and R. W. Portmann (2007), How often will it rain?, *J. Clim.*, *20*(19), 4801–4818, doi:10.1175/JCLI4263.1.

Tebaldi, C., K. Hayhoe, J. M. Arblaster, and G. A. Meehl (2006), Going to the extremes, *Clim. Change*, *79*(3–4), 185–211, doi:10.1007/s10584-006-9051-4.

Trenberth, K. E. (1999), Conceptual framework for changes of extremes of the hydrological cycle with climate change, *Clim. Change*, *42*(1), 327–339, doi:10.1023/A:1005488920935.

Trenberth, K., A. Dai, R. Rasmussen, and D. Parsons (2003), The changing character of precipitation, *Bull. Am. Meteorol. Soc.*, *84*(9), 1205–1217, doi:10.1175/BAMS-84-9-1205.

Wang, S., R. R. Gillies, E. S. Takle, and W. J. Gutowski Jr. (2009), Evaluation of precipitation in the Intermountain Region as simulated by the NARCCAP regional climate models, *Geophys. Res. Lett.*, *36*, L11704, doi:10.1029/2009GL037930.

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott, and T. Nozawa (2007), Detection of human influence on twentieth-century precipitation trends, *Nature*, *448*(7152), 461–465, doi:10.1038/nature06025.

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