Evaluating IPCC AR4 cool-season precipitation simulations and projections for impacts assessment over North America

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Abstract General circulation models (GCMs) have demonstrated success in simulating global climate, and they are critical tools for producing regional climate projections consistent with global changes in radiative forcing. GCM output is currently being used in a variety of ways for regional impacts projection. However, more work is required to assess model bias and evaluate whether assumptions about the independence of model projections and error are valid. This is particularly important where models do not display offsetting errors. Comparing simulated 300-hPa zonal winds and precipitation for the late 20th century with reanalysis and gridded precipitation data shows statistically significant and physically plausible associations between positive precipitation biases across all models and a marked increase in zonal wind speed around 30°N, as well as distortions in rain shadow patterns. Over the western United States, GCMs project drier conditions to the south and increasing precipitation to the north. There is a high degree of agreement between models, and many studies have made strong statements about implications for water resources and about ecosystem change on that basis. However, since one of the mechanisms driving changes in winter precipitation patterns appears to be associated with a source of error in simulating mean precipitation in the present, it suggests that greater caution should be used in interpreting impacts related to precipitation projections in

this region and that standard assumptions underlying bias correction methods should be scrutinized.

Keywords Precipitation · General circulation model (GCM) · Bias · Storm track

1 Introduction

During the last 5 years, a number of studies have highlighted projected drying in southwestern North America (Diffenbaugh et al. 2008; Hoerling and Eischeid 2007; Meehl et al. 2005; Seager and Vecchi 2010; Seager et al. 2007). These studies, however, have generally not assessed potential changes in precipitation in the context of the current portfolio of GCMs' realism in simulating climatological precipitation over western North America, with regard to the dynamics driving winter precipitation in the region, or relative to observed trends. Although models generally simulate global precipitation well (Dai 2006; Randall et al. 2007), small errors are not usually addressed. Common error metrics, such as the root-mean-square (RMS) error, are biased toward identifying large absolute errors. In arid regions such as western North America, however, relatively small absolute errors in precipitation could be significant in terms of percent of observed precipitation and in the conclusions drawn from impacts models, such as those designed to simulate future hydrological or ecological conditions.

Western North America typically receives winter precipitation from large frontal storms developed over the Pacific Ocean (Barry and Chorley 2003). High baroclinicity in mid-latitude storm tracks (Hoskins and Valdes 1990) tends to generate these storms (Chang et al. 2002). The strength and position of the storm track are strongly related

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to those of the jet stream (Christoph et al. 1997), where baroclinicity peaks, though latent heating also contributes to sustaining the storm track (Chang et al. 2002). Thus, winter precipitation over western portions of North America should be associated with the speed and/or position of the westerly jet.

Analysis by Garreaud (2007) confirms the relationship between zonal wind and precipitation for the west coast of North America. In addition, the Pacific/North American pattern (PNA), which describes the relative zonality of flow across the United States, is well correlated with precipitation. Strongly zonal flow is associated with wetter conditions over much of the West, although the spatial details of the relationship vary by month (Leathers et al. 1991).

Numerous studies note poleward shifts in the position of the jets and storm tracks in both hemispheres with warming (Kidston and Gerber 2010; Lorenz and DeWeaver 2007; Seidel et al. 2008; Yin 2005), and a slight northward shift in the latitude of the Northern Hemisphere mid-winter jet stream during the late 20th century was identified by Archer and Caldeira (2008). There is still debate as to whether this shift is caused by the expansion of the Hadley cell (e.g., Seidel et al. 2008), changes in the altitude of the tropopause (Lorenz and DeWeaver 2007; Lu et al. 2007), or increasingly positive annular mode indices (Previdi and Liepert 2007).

A northward shift in the position of the jet, whether driven from the tropics or from the pole, should manifest in reduced precipitation over the southwestern portion of North America during the winter and increased precipitation to the north and east. This is the pattern projected for the 21st century by the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4, Christensen et al. 2007) and described by numerous other studies (Held and Soden 2006; Meehl et al. 2005; Previdi and Liepert 2007; Seager et al. 2007). Recent work by Seager et al. (2010) and Seager and Vecchi (2010) confirms that changes in the storm track contribute to decreasing subtropical precipitation and increasing high-latitude precipitation.

Recent studies by Santer et al. (2009) and Pierce et al. (2009) have addressed whether it is desirable or even appropriate to screen models for skill before using them in investigating the cause of climate trends or in making projections of regional climate change. They found little relationship between projected changes in climate and the realism of model simulated modern climate (Pierce et al. 2009). This confirmed other studies addressing temperature (e.g., Brekke et al. 2008), and it appears to be due in large part to offsetting or conflicting errors between models (Pierce et al. 2009). Liang et al. (2008), however, found that model bias in temperature and precipitation may impact projections over the United States and that bias may not always be amenable to simple linear bias-correction techniques.

It seems the question of how, where, and to what extent model bias impacts projections is still open, particularly at regional scales. Thus we suggest that, before undertaking regional projection studies, it is important to investigate the presence or absence of bias in target variables, as well as its association with relevant climate processes, and to assess the relationship between error and projected changes. This can inform appropriate use of the data, as well as highlighting potential uncertainties. Such a priori investigation may be particularly important where there is systematic or non-offsetting bias within the set of models chosen for study, as is the case with cool-season precipitation in western North America.

We address four questions about simulation of cool-season precipitation and projections of precipitation change for North America. First, we ask how realistic are simulations of climatological cool-season precipitation over North America, with a particular focus on the arid regions of western North America. We investigate simulations of two aspects of the cool-season precipitation delivery system—the mid-latitude jet and storm track. Finally we ask whether there is a relationship between model biases and the magnitude or direction of precipitation changes under the A1B scenario and whether, given the presence of model error, there is reason to preferentially use a subset of models for precipitation projections.

Here we find that the models used in IPCC AR4 have a systematic bias toward overestimating cool-season (November–April) precipitation. They tend to overestimate the speed of upper-level westerly winds near 30°N and generally have a southward bias in storm activity, both of which may be influenced by the smoothed representation of topography in the models. Over the southwestern portion of the continent, there is a correlation between model error and projected changes in precipitation, with the wettest models producing somewhat greater drying than those that more accurately simulate mean precipitation. The relationship is weak, and additional analysis suggests that it may not provide significance guidance in choosing a subset of models for regional climate change impacts studies. However, this analysis as a whole suggests that bias in the simulation of zonal winds may influence projected changes in precipitation, increasing the uncertainty associated with those projections.

2 Materials and methods

2.1 Data and models

We evaluated the ability of 18 of the IPCC AR4 coupled GCMs to simulate cool-season (November–April) precipitation over North America and its delivery by the storm

Table 1 Coupled general circulation models and runs used

Model	Group	20C3M	A1B
*BCCR-BCM2.0	Bjerknes Centre for Climate Research	Run 1 of 1	Run 1 of 1
*CCCMA-CGCM3.1(t47)	Canadian Centre for Climate Modeling & Analysis	Run 1 of 5	Run 1 of 5
*CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques	Run 1 of 1	Run 1 of 1
*CSIRO-Mk3.0	CSIRO Atmospheric Research	Run 1 of 3	Run 1 of 1
*GFDL-CM2.0	NOAA/Geophysical Fluid Dynamics Laboratory	Run 1 of 3	Run 1 of 1
*GFDL-CM2.1	NOAA/Geophysical Fluid Dynamics Laboratory	Run 2 of 5	Run 1 of 1
*GISS-AOM	NASA/Goddard Institute for Space Studies	Run 1 of 2	Run 1 of 2
*GISS-ER	NASA/Goddard Institute for Space Studies	Revised, from NASA website	Run 2 of 5 (precip); 1 of 5 (u-wind)
*IAP-FGOALS1.0	LASG/Institute of Atmospheric Physics	Run 1 of 3	Run 2 of 3
*INM-CM3.0	Institute for Numerical Mathematics	Run 1 of 1	Run 1 of 1
IPSL-CM4	Institute Pierre Simon Laplace	Run 1 of 2	Run 1 of 1
MIROC3.2 (hires)	Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change	Run 1 of 1	Run 1 of 1
MIROC3.2 (medres)	Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change	Run 1 of 3	Run 1 of 3
*MRI-CGCM2.3.2	Meteorological Research Institute	Run 1 of 5	Run 1 of 5
NCAR-CCSM3.0	National Center for Atmospheric Research	Run 6 of 10	Run 1 of 9
NCAR-PCM1.0	National Center for Atmospheric Research	Run 1 of 4	Run 1 of 5
UKMO-HadCM3	Hadley Center for Climate Prediction and Research, Met Office	Run 1 of 2	Run 1 of 1
UKMO-HadGEM1	Hadley Center for Climate Prediction and Research, Met Office	Run 1 of 2	Run 1 of 1
NCAR-CCSM3.0 ensemble	National Center for Atmospheric Research	Runs 1–7 and 9 of 10	Run 1

Further information about the models can be found at <http://www-pcmdi.llnl.gov/>

* Models for which storm track analyses were performed

track over the last two decades of the 20th century. The winters of 1979/80–98/99 were chosen because the National Centers for Environmental Prediction—Department of Energy—Atmospheric Model Inter Comparison Project (NCEP-DOE-AMIP-II) reanalysis (hereafter NCEP2, Kanamitsu et al. 2002), the Global Precipitation Climatology Project (GPCP, Yin et al. 2004), the Global Precipitation Climatology Centre (GPCC, Rudolf et al. 1994), the University of Delaware gridded precipitation (Legates and Willmott 1990; Willmott and Matsuura 1995), PRISM (Daly et al. 1994), and the Climate of the 20th Century simulations evaluated all had monthly data coverage throughout the period. Climate model output from the A1B scenario was used to investigate relationships between model bias and projected changes in cool-season precipitation. Projections were evaluated for the late 21st century (2079/80–98/99). For statistical analyses, a single run was used from each of the models' simulations. We also constructed an eight-member ensemble of the NCAR-CCSM3.0 model for the late 20th century and 18-member multi-model ensembles consisting of one run

from each model for both time periods. Table 1 describes models and runs used. Model output was downloaded from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at <http://www-pcmdi.llnl.gov/>.

Model simulations of seasonal precipitation were compared to precipitation from five commonly used gridded datasets to account for differences in precipitation estimates between the observation-based products. The monthly $2.5^\circ \times 2.5^\circ$ GPCP data set is compiled from rain gauge data at 6,500–7,000 locations and from satellite estimates of precipitation (Adler et al. 2003) and was downloaded from the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (NOAA ESRL) at <http://www.esrl.noaa.gov/psd/data/gridded/>. On land, GPCP data are comparable to the Climate Prediction Center Merged Analysis of Precipitation (Yin et al. 2004). GPCC data at $1.0^\circ \times 1.0^\circ$ and $2.5^\circ \times 2.5^\circ$ resolution are derived solely from gauge data at several thousand meteorological stations (Rudolf et al. 1994) and were retrieved from the KNMI Climate Explorer at <http://climexp.knmi.nl/>. University of Delaware estimates of precipitation were also

derived from gauge data and interpolated at $0.5^\circ \times 0.5^\circ$ (Legates and Willmott 1990; Willmott and Matsuura 1995); they are available from the University of Washington's Joint Institute for the Study of the Atmosphere at <http://jisao.washington.edu/data/>. Given the strong elevational gradients in precipitation in mountainous regions (see Fig. 1f—PRISM precipitation at 4 km resolution), we also compared modeled precipitation with high-resolution PRISM estimates (Daly et al. 1994; available on-line at <http://www.prism.oregonstate.edu/>) composited into 52×52 km grid cells. Figure 1 shows the average cool-season (November–April) precipitation over the study period for each of the five data sets, as well as the very high resolution PRISM data.

Simulations of zonal wind and of the storm track at 300 hPa were compared with the $\sim 1.9^\circ \times 1.875^\circ$ NCEP2 reanalysis (Kanamitsu et al. 2002), also available from the NOAA ESRL website.

2.2 Data preparation

For each model and for the NCEP2 reanalysis, the monthly average zonal wind at 300 hPa was calculated at each grid point. Cool-season (November–April) averages were calculated for each year for the complete grid, as well as for global latitudinal bands and for zonal bands over the eastern Pacific/western North America (EPWNA) region

Fig. 1 Average cool-season (November–April) precipitation, 1979/80–98/99 (mm), in five gridded precipitation datasets. **a** Global Precipitation Climatology Project, **b** Global Precipitation Climatology Centre, 2.5° resolution, **c** Global Precipitation Climatology Centre, 1.0° resolution, **d** University of Delaware, **e** PRISM, smoothed to 52 km, **f** PRISM at 4 km resolution; percent difference between the GPCP and **g** Global Precipitation Climatology Centre, 2.5° resolution, **h** Global Precipitation Climatology Centre, 1.0° resolution, **i** University of Delaware, **j** PRISM, smoothed to 52 km

($\sim 220^\circ$ to $\sim 260^\circ$). In order to make more straightforward comparisons between models, zonal winds and storm tracks were regridded to match the NCEP2 grid using one- and two-dimensional linear interpolation (Matlab R2008b). Changes introduced by regridding were few and small.

Cool-season average values of 300-hPa zonal wind from the reanalysis were tested for normality using the Lilliefors test (Lilliefors 1967). At $\alpha = 0.05$, fewer than 10% of individual grid cells or latitudinal bands displayed non-normal distributions, and there did not seem to be a spatial pattern in the location of non-normality. Because the zonal wind data were, by and large, normally distributed, we calculated 95% confidence intervals around the zonal averages via $X \pm t_{0.05, 2\text{-tailed}, v} * s$, where s is the standard deviation and v is the degrees of freedom equal to $n - 1$ (Zar 1999).

To evaluate the quality of precipitation simulations, simulated precipitation was regridded to match the grids of the observed datasets using a two-dimensional linear interpolation (Matlab R2008b). Other gridding schemes ($1^\circ \times 1^\circ$ and $5^\circ \times 5^\circ$) were explored to determine if they changed the results of the error analysis; differences between gridding schemes were minimal. Absolute and percent differences from observed precipitation were calculated from the average cool-season value for each grid cell.

Projections from the A1B scenario were processed to calculate average November to April precipitation over the period 2079/80–98/99 in the same way that simulations of the 20th century were treated. Those averages were also regridded to match the gridding of the observational dataset so that equivalent areas could be compared. Model runs used for this analysis are listed in Table 1.

2.3 Zonal circulation

We calculated monthly Northern Hemisphere storm tracks as the daily variance of first-differenced 300-hPa meridional wind, as described in Quadrelli and Wallace (2002). Cool-season (November–April) storm track activity is a simple average of the monthly values. The storm track metric calculated from variance in meridional wind does lack detail about individual storms (e.g., frequency, intensity, duration, and path) and their relationship to precipitation. Nevertheless, the method is computationally efficient and does not require sub-daily data, which makes it an attractive method for comparing multiple models.

The daily data required for this calculation were available for only 11 of the models in this study, and we had hoped to use a larger pool of models. To test the assumption that 300-hPa zonal winds are a reasonable proxy for storm track, we correlated globally averaged simulated 300-hPa zonal wind speeds from 23.75° and 41.25°N (grid-

cell centers 25° – 40°N) and simulated storm tracks. This analysis shows that increased wind speeds are associated with enhanced cool-season storm track activity south of about 40°N and reduced storminess to the north (Fig. 2). This is as expected based on the results of Chang et al. (2002) and Christoph et al. (1997). As a result, we use 300-hPa zonal wind-speed around 30°N in addition to storm track to expand the number of models that can be evaluated in this study. Throughout the paper, the phrase storm track refers specifically to the metric calculated from variance in meridional wind. Zonal wind is described as zonal wind or as the jet.

2.4 Statistical analysis

Since the relationships between climate variables are not necessarily linear, we use the non-parametric Spearman correlation throughout the paper. The Spearman correlation is also robust to non-normality (Zar 1999), which may exist within the large data fields. This is of particular concern for precipitation. Similarly, relationships expressed in our data might not always fit the assumptions of least-squares regression. As a result, a robust biweight regression method that reduces the influence of outliers was used (Matlab R2008b). Comparison of the two regression methods showed the results to be largely similar (not shown).

Limiting the analysis to one realization per model is necessary for statistical analysis, but there is some question about whether the 18 model runs are strictly independent, particularly as there are three related pairs of models: GFDL-CM2.0 and CM2.1, GISS-AOM and GISS-ER, and MIROC3.2 (hires) and (medres). The two GFDL models are built on the same grid but have different orographies, use different dynamical cores and differ in their simulation of mid-latitude winds (Delworth et al. 2006). As our analysis is centered on the relationship between precipitation and mid-latitude winds, we feel that we can consider the two GFDL models to be sufficiently independent.

Fig. 2 Spearman correlation between globally averaged cool-season (November–April) 300-hPa zonal wind from 23.75° to 41.25°N and cool-season storm track activity over the Pacific Ocean and North America. Solid contours indicated positive correlations; dashed contours negative, and the zero contour is omitted. Dark, moderate, light and very slight shading indicate statistical significance exceeding 99, 95, 90, and 80%

Although NASA produced and runs both GISS-ER and GISS-AOM, they are substantially different models (Schmidt et al. 2006). MIROC3.2 (hires) and (medres) are the same model run at different resolutions, increasing the potential that the results of these two models are not independent. Practically, however, they differ in their representation of orography, in zonal wind profiles with latitude over the EPWNA region, and in their spatial precipitation patterns. As a result we are not overly concerned about the independence of these two models in this situation.

3 Results

3.1 Zonal circulation

Simulations typically overestimate global and EPWNA cool-season wind speeds at 300 hPa between 20° and 40° N, while slightly underestimating wind speeds around 50°N (Fig. 3a, b). Between 20° and 30°N, all of the individual model runs and both ensembles simulate wind speeds above the average value from NCEP2 over the EPWNA region. Indeed, four of the models (GISS-AOM, IAP-FGOALS1.0, NCAR-PCM1, and UKMO-HadCM3)

Fig. 3 Average cool-season (November–April, 1979/80–98/99) 300 hPa-zonal wind speeds over **a** the eastern Pacific Ocean and western North America (220° to 260°) and **b** globally. Individual models are shown by fine colored lines, the NCAR-CCSM3.0 ensemble with a heavy purple line, the multi-model ensemble with a heavy black dashed line, and the NCEP2 average with a heavy black line. The 95% confidence interval around the NCEP2 mean is shown by the gray shading

simulate wind speeds outside the 95% confidence interval over the EPWNA (Fig. 3a). Globally, only two models simulate zonal wind speeds ca. 30°N less than those in NCEP2 (BCCR-BCM2.0 and GISS-ER). Ten simulate wind speeds outside the 95% confidence interval (CCCMA3.1 (t47), CSIRO-Mk3.0 GFDL-CM2.1, GISS-AOM, IAP-FGOALS, 1.0, IPSL-CM4, MIROC3.2 (hires), MRI-CGCM2.3.2, NCAR-PCM, and UKMO-HadCM3), and the multi-model ensemble falls near the top of the 95% confidence interval (Fig. 3b).

The opposite is true at approximately 60°N. Over the EPWNA, only two models (NCAR-PCM and NCAR-CCSM3.0) simulate wind speeds faster than those in NCEP2, while one model simulates winds slow enough to fall below the 95% confidence interval (INM-CM3.0). In the global analysis, two models simulate wind speeds above the average from NCEP2 (NCAR-PCM and GISS-ER, in which wind speeds exceed the NCEP2 95% confidence interval). Six models simulate winds that fall below the NCEP2 95% confidence interval (CSIRO-Mk3.0, GFDL-CM2.0, INM-CM3.0 IPSL-CM4, and MIROC3.2 (hires), MIROC3.2 (medres)).

Consistent with the zonal wind evaluation, most of the 11 models with daily meridional wind data show slightly decreased storm track activity to the north and statistically significant increases in storm track activity to the south. Because the models generally have much lower overall meridional wind variance than the reanalysis, Fig. 4 shows the simulated storm track normalized to each model's Northern Hemisphere average storm track activity minus the normalized storm track calculated from the reanalysis. One notable exception is CCCMA3.1 (t47), which shows generally increased storm track activity across the Pacific Ocean in comparison to NCEP2. It is also the only model to have average Northern Hemisphere meridional wind variance similar in magnitude to NCEP2 ($\text{CCCMA3.1 (t47)} = 122.2 \text{ m}^2 \text{ s}^{-2}$, $\text{NCEP2} = 118.5 \text{ m}^2 \text{ s}^{-2}$, model ensemble (11) = $99.7 \text{ m}^2 \text{ s}^{-2}$).

3.2 Precipitation bias

During the cool season, observations show that the eastern third of the continent is wetter than most of the western two-thirds of the continent, although coastal regions of the western United States and Canada between approximately 40°N and 55°N are quite wet, as are high elevation regions (Fig. 1a–f). The driest portions of the continent include Mexico and the southwestern United States. All of the models evaluated here simulate wetter winters on the eastern portion of the continent than the west (not shown). In addition, models simulate wetter conditions in the northwestern portion of the continent than in the southwestern region. All of the models are successful in

Fig. 4 Difference between average cool-season (November–April) storm track activity simulated by IPCC AR4 models and the NCEP2 reanalysis. All grid-cell values were normalized to the hemispheric average storm track activity before comparison to accommodate substantial differences in overall storm activity

simulating high precipitation over the North Atlantic off of the New England coast (Fig. 5).

Over the northern Midwest, the northeastern United States and southeastern Canada, model errors are typically within 25% of observed values, although some models have wet biases of 25–50% of observed precipitation in southeastern Canada (Fig. 5). The GISS-ER and BCCR-BCM2.0 models simulate drier than observed conditions over the northern Midwest and portions of southeastern Canada. Most models simulated drier than observed conditions near the Gulf Coast, with some models simulating only 25% of observed precipitation.

The most notable characteristic of the simulations is that all of the models overestimate precipitation over much of western North America and Mexico by at least 25%, with

errors approaching 300%. The largest percent errors typically occur over the arid portions of the southwestern United States and Mexico, but positive biases are also common over the northern Rocky Mountains. The Hadley models (UKMO-HadCM3 and UKMO-HadGEM1) have the smallest cool-season precipitation errors over western North America as a whole. Although a small number of models display dry errors along the coast of southern California and Mexico, UKMO-HadGEM1 is unusual in that it underestimates winter precipitation in the southern Great Basin, as well. UKMO-HadGEM1's largest errors occur over the Montana Rocky Mountains and south central Mexico, where they approach 200%. In contrast to the dry bias over the Southwest in UKMO-HadGEM, UKMO-HadCM3 has errors of 50–100% over most of the western

Fig. 5 Percent difference between model simulations of November to April precipitation and precipitation from Global Precipitation Climatology Project (GPCP) over the years 1979/80–98/99 (a–t). Also shown are percent differences between the multi-model

ensemble and the **u** Global Precipitation Climatology Centre, 1.0° resolution, **v** Global Precipitation Climatology Centre, 2.5° resolution, **w** University of Delaware, **x** PRISM, smoothed to 52 km, precipitation datasets

United States and the southern Canadian prairies with errors near 200% over central Mexico.

All of the other models evaluated here have errors of up to 300% over at least part of western North America. BCCR-BCM2.0 simulates relatively small areas of error over much of the United States, but errors of nearly 300% over much of northern Mexico and parts of Texas. CCCMA-CGCM3.1(t47) and MRI-CGCM2.3.2 simulate

relatively small errors, typically less than 100%, over much of the western United States and Canada but produce larger errors over central Mexico. The simulation by MIROC3.2 (medres) is similar but has slightly larger errors over the inland Pacific Northwest. All of the remaining models have errors of over 100% across much of western North America. Many models, however, are more successful over the eastern Pacific Ocean and along the California coast,

where errors tend to be small. In addition, both positive and negative errors are common over coastal portions of the Pacific Northwest and western British Columbia. Neither the 8-run NCAR-CCSM3.0 ensemble nor the multi-model ensemble produced substantially lower errors than the individual runs.

Sensitivity of this analysis to the observational dataset used is low. As shown in Fig. 1g–j, there are differences between the precipitation data sets evaluated here, particularly over western North America. However, these differences are relatively small in comparison to the precipitation biases found in AR4 models. The other precipitation datasets are somewhat wetter than GPCP over the Arizona–New Mexico border, in central Texas, and in the coastal northwest (0–75%); they are somewhat drier over the Great Basin and plains (0–75%). However, these uncertainties are relatively small in relation to model biases which, on average, exceed +75% over much of the western United States and approach +300% over central Mexico (Fig. 5).

Higher resolution observed precipitation datasets are better at capturing orographically driven precipitation patterns over western North America. When model output is interpolated to match higher resolution observational datasets, the models' inability to produce detailed rainfall patterns associated with orography is more apparent than when simulations are compared to observational data at coarser resolution (cf. Fig. 5t–x). This accounts for some of the discrepancies in the patterns generated by comparing simulated precipitation to different observational precipitation datasets.

Percent errors in precipitation over drier portions of North America are quite large, in part because of generally low precipitation. However, as can be seen in Fig. 6a, seasonal precipitation errors in the multi-model ensemble are often in excess of +50 mm and approach +400 mm in portions of the inland northwest. The absolute error map also emphasizes dry errors along the typically rainy west coast that might be obscured in the percent error map.

3.3 Association of precipitation and zonal wind

To test the assumption that precipitation is related to zonal wind, several characteristics of upper-level zonal wind over the EPWNA were correlated with precipitation amount. Figure 6a shows the absolute bias in precipitation for the multi-model ensemble. Figure 6b–d show the correlation between each model's average cool-season precipitation and its (b) maximum 300 hPa zonal wind speed, (c) latitude of maximum zonal winds, and (d) average zonal wind speed over the region of enhanced mid-latitude winds (23.75°–42.25°N). Models with increased wind speeds

have greater precipitation over much of the southwestern United States and drier conditions to the north (Fig. 6b, d). Positive correlations over the western states reach 95% significance. There is a strong negative response over the Pacific Northwest and coastal British Columbia. Models with peak zonal wind speeds further north show reduced precipitation over the Southwest, though with little response in the northwest (Fig. 6c).

Fig. 6 Cool-season (November–April) precipitation error (mm) for the multi-model ensemble versus the Global Precipitation Climatology Project (GPCP) observational dataset, 1979–1999 (a). Spearman correlation of each model's average cool-season precipitation with its average maximum 300-hPa zonal wind speed (b), with its latitude of maximum zonal wind (c) and with average 300-hPa zonal wind speed over the eastern Pacific Ocean and western North America between 23.75° and 41.25°N (d). Absolute precipitation error predicted by regressing precipitation error against average 300-hPa zonal wind speed over the eastern Pacific Ocean and western North America between 23.75° and 41.25°N (e). Boxes in the figures outline regions over which wind speeds were averaged. Solid and dashed lines show areas of 95 and 99% statistical significance on the correlation maps

All of the models simulated 300-hPa wind speeds stronger than those seen in the NCEP2 reanalysis, and most models had some degree of wet error over the western United States. Interestingly, UKMO-HadGEM1, the only model to display widespread negative errors over the Southwest, and one of the few to have positive errors over the coastal Northwest, had peak zonal winds around 47°N, far north of their position in the NCEP2 reanalysis (27.5°N).

To investigate the magnitude of error in precipitation that could be caused by error in simulated zonal wind, we performed a robust regression of absolute errors in precipitation on errors in zonal wind between 23.75° and 41.25°N (grid-cell centers 25°–40°N). Figure 6a shows the absolute precipitation error for the multi-model ensemble, while Fig. 6e shows the precipitation error predicted by a regression on wind speed error. The sign of the error calculated using the regression is the same as that of the absolute difference from observed precipitation over much of Mexico, the Southwest and the central Great Plains. There is also a fair amount of agreement over the British Columbia coast. Over the Gulf Coast, fairly large negative errors are not captured by the regression model, despite the fact that most of the models underestimate precipitation in the lower Mississippi Valley. In the Pacific Northwest there are large changes in the sign of the error from the west (generally negative) to the east (positive). The negative impact on precipitation suggested by the regression model does appear to be expressed west of the coastal mountains (Cascade Range in Washington and Oregon and the Coast Mountains of British Columbia). East of the Cascades, the regression-based and calculated errors disagree. Despite some minor areas of disagreement, these analyses confirm that increased average zonal wind speed in a model is associated with elevated climatological precipitation over the western United States. These findings are in line with the Garreaud (2007) analysis and with the fact that on synoptic time scales, zonal flow is often associated with wetter conditions over western North America (Byrne et al. 1999; Leathers et al. 1991).

There is some indication that the representation of topography in the models may contribute to the zonal wind bias and thus to precipitation errors over the Southwest and Mexico. Models with greater land volume in the Rocky Mountain region (30°–55°N/245°–260°) tend to have reduced wind speeds around 30°N (Fig. 7a) and increased precipitation over the Pacific Northwest (Fig. 7b). Relationships between topography and Northern Hemisphere zonal flow have been discussed for decades (e.g., Bolin 1950; Chang 2009), and it has been demonstrated that models with more realistic topography produce more realistic precipitation patterns regionally (Bala et al. 2008). As can be seen in Fig. 8, none of the models display

Fig. 7 Correlation of mountain volume in the Rocky Mountain region (30° to 55°N and 245° to 260°, outlined by the black box) with **a** 300-hPa zonal wind and **b** precipitation amount. Solid contours indicated positive correlations; dashed contours negative, and the zero contour is omitted. Dark, moderate, light and very slight shading indicate statistical significance exceeding 99, 95, 90, and 80%

especially realistic topography, particularly with regard to coastal mountain ranges. However, it is beyond the goals of the current study to detail the physical mechanisms by which differences in orography may contribute to differences in zonal flow and precipitation patterns.

3.4 Projected changes in precipitation

There appear to be links between errors in simulated cool-season precipitation over western North America and simulation of the region's precipitation delivery system, namely with upper-level zonal winds and the storm track. Since projected changes in mean cool-season precipitation are posited based in part on changes in the storm track (Seager and Vecchi 2010), which may be related to changes in the mean position of the zonal winds (e.g., Meehl et al. 2005; Yin 2005), it is important to examine whether projected changes in precipitation are related to errors present in late 20th century simulations.

Figure 9a shows a slight northward shift in the location of and a statistically significant increase in the speed of maximum zonal winds over the EPWNA (average = +1.16 m s⁻¹, $p = 0.0031$ by a two-sided paired t test). As can be seen in Fig. 9b, most models show an increase in maximum zonal wind speeds. Although the overall northward shift in the latitudinal position of peak zonal winds in this region is not statistically significant ($p > 0.4$), a closer examination suggests that the lack of significance is driven by the three models (IAP-FGOALS1.0, MIROC3.2(medres) and UKMO-HadGEM1)

Fig. 8 Western North American orography in each of the models used here (a–r). Mean orography, regridded to match the Global Precipitation Climatology Project (s). Observed topography at 2' resolution from ETOPO2v2 (t)

Fig. 9 Multi-model ensemble simulations of 300-hPa zonal winds over the eastern Pacific/western North American region (220°–260°) for the late 20th (*dotted*) and late 21st centuries (*dashed*) against the NCEP2 reanalysis, as shown in Fig. 3a (a). Change in the speed (b) and location (c) of maximum 300-hPa zonal winds in each model between the late 20th and 21st centuries. Models are shown in the order (1) BCCR-BCM2.0, (2) CCCMA-CGCM3.1(t47), (3) CNRM-CM3, (4) CSIRO-Mk3.0, (5) GFDL-CM2.0, (6) GFDL-CM2.1, (7) GISS-AOM, (8) GISS-ER, (9) IAP-FGOALS1.0, (10) INM-CM3.0, (11) IPSL-CM4, (12) MIROC3.2(hires), (13) MIROC3.2(medres), (14) MRI-CGCM2.3.2, (15) NCAR-CCSM3, (16) NCAR-PCM1, (17) UKMO-HadCM3, (18) UKMO-HadGEM1, (19) CCSM ensemble, (20) Multi-model ensemble

which simulate 20th century peak 300-hPa zonal winds north of 40°N (Fig. 3a). Because these models initially exhibit two peaks in wind speed (one just south of 30°N, and another near 45°N), slight changes in wind speed at either of these latitudes can cause a large apparent change in latitude of maximum winds. That is indeed what happens in two of these models (IAP-FGOALS1.0 and UKMO-HadGEM1), which show southward shifts in the position of maximum 300-hPa zonal winds in excess of 20° (Fig. 9c) associated with decreases in wind speed between 45° and 50°N and increases around 30°N (not shown). If the three models that initially exhibit peak 300 hPa wind speeds north of 40°N are dropped from the analysis, the northward shift in the position of peak zonal winds

becomes statistically significant ($p < 0.01$, paired t test). Unlike in the Southern Hemisphere analysis of Kidston and Gerber (2010), changes in the location and speed of maximum winds over the EPWNA are not correlated with bias in their simulation during the late 20th century.

Although there is a statistically significant correlation with peak 300-hPa zonal wind speeds over the EPWNA that explains nearly 30% of the variance in percent precipitation error over the Southwest (25°–35°N/235°–260°, Fig. 10a) and a weaker relationship between the latitude of maximum zonal winds and precipitation (Fig. 10b), it initially appears that changes in the speed and location of 300-hPa zonal winds are not strongly associated with changes in precipitation over the region (Fig. 10c, d). However, when the three models that initially simulate maximum winds north of 40°N are removed, a stronger relationship between changes in zonal wind and changes in precipitation becomes apparent. The correlation is not significant due to a decrease in precipitation accompanying a decrease in peak 300 hPa zonal winds in NCAR-CCSM3.0. Among the other models, it appears that larger increases in wind speed are associated with more substantial changes in precipitation (Fig. 10e). Changes in the position of the jet appear important, too. Models that simulate northward shifts in peak winds only simulate decreases in precipitation; models where the location of peak zonal flow does not change sufficiently to be resolved by the gridding scheme can experience both increases and decreases in precipitation (Fig. 10f).

These changes do not translate to region-wide statistically significant correlations between error and projected change in precipitation (Fig. 10g, h). Over the Southwest those models that most closely simulate late 20th century precipitation disagree about the sign of precipitation change over the next century (Fig. 10g, h). UKMO-HadCM3 projects a slight increase in precipitation (6.5 mm or 7.1%), UKMO-HadGEM and MRI-CGCM2.3.2 project small decreases in precipitation of –8.1 mm (–5.9%) and –15.5 mm (–11.3%), respectively, while MIROC3.2 (medres) projects a fairly substantial decrease (–40.5 mm or –30.6%). It is noteworthy that two of the four models with the smallest precipitation biases over this region also simulate peak zonal winds north of 40°N.

Although region-wide relationships between bias and projected change in precipitation are not statistically significant, there are potentially important correlations between projected changes in precipitation for the late 21st century and simulated precipitation errors for the late 20th century in regions where the models are most consistently incorrect (the southwestern United States and Mexico, Fig. 11a). Using percent change, rather than absolute change weakens the relationship between late 20th century simulations and the future, but the relationship is still

Fig. 10 For the Southwest (25°–35°N/235°–260°), late 20th century percent error in precipitation versus **a** speed and **b** latitude of maximum 300-hPa zonal winds over the eastern Pacific/western North American region (220°–260°). Percent change in precipitation versus projected change in **c** speed and **d** latitude of maximum 300-hPa zonal wind speeds over the EPWNA. **e** and **f** are the same as (c) and (d), without the three models that simulate late 20th century maximum zonal winds near 45°N. Projected absolute changes in precipitation (**g**) and percent changes in precipitation (**h**) projected for 2079/80–98/99 for each model in relation to its average percent error over the Southwest. Changes are relative to each model's 1979/80–98/99 mean

Fig. 11 Spearman correlation between November to April precipitation simulated for 1979/80–98/99 and the **a** change in precipitation or **b** percent change in precipitation projected for 2079/80–98/99. Solid contours indicated positive correlations; dashed contours negative, and the zero contour is omitted. Dark, moderate, light and very slight shading indicate statistical significance exceeding 99, 95, 90, and 80%

statistically significant at 90–95% over portions of southern California and central Arizona, including the Los Angeles and Phoenix metro areas (Fig. 11b). These regions also show statistically significant relationships between simulated modern precipitation amount and characteristics of the zonal flow (see Fig. 6), suggesting that projected changes in precipitation may not be mechanistically independent of error in modern precipitation simulations generated by bias in the representation of the zonal flow. It can also be argued that even weak relationships between error and projected change may be a problem for bias correction methods that assume strict independence between change and error.

4 Discussion

Over much of the West, only part of the precipitation error can be ascribed to errors in zonal wind speed (Fig. 6). This suggests that other factors may contribute, as well. For example, the disagreement between actual errors and those produced by regression on zonal wind-speed errors may be because positive precipitation errors in this region are related more to the absence of significant rain shadows in the models, as the Cascades, Sierra Nevada, Coast Ranges, and the northern Rocky Mountains are not well resolved (Fig. 8). As all of the models have subdued orography and all demonstrate wet biases on the lee side of mountains, rain shadow effects probably contribute to precipitation errors in the northwest, an argument that is well supported in the literature (Bala et al. 2008; Pierce et al. 2009).

Warmer than observed sea surface temperatures (SSTs) could presumably feed larger or wetter storms, much the way that warm SSTs off the southwestern coast of the United States are associated with greater precipitation during warm phases of the Pacific Decadal Oscillation (Mantua et al. 1997). Many, but not all of the models have warm SST biases along the southwest coast of North America; however, the patterns are not as consistent between models (Randall et al. 2007, Fig. S8.1) as are the errors in precipitation (Fig. 5). Kumar et al. (2008) compared a coupled run from the NCEP Climate Forecast System model, with a warm SST bias to output from the atmospheric component of the model forced with realistic SSTs. There were no differences in precipitation over western North America, suggesting that the warm SST biases in that model had little impact on precipitation in the region. It is also possible that wet biases in precipitation are the result of excess moisture in the atmosphere. However, on an annual basis, zonally averaged specific humidity biases are not consistent between models. Some models simulate a wetter atmosphere than the ERA-40 reanalysis, while others a drier atmosphere (Randall et al. 2007 Fig. S8.X).

The models used in this study also differ in their ability to simulate ENSO (ArchutaRao and Sperber 2006) and the extra-tropical teleconnections to ENSO (Dai 2006). Differences in tropical convection could tend to shift the climatological position of the storm track, much as occurs interannually with ENSO variability (Seager et al. 2009). Between-model differences in the variability of ENSO—in those models with generally realistic teleconnections—could also impact the variability of precipitation over parts of North America. Over the relatively short climatology used here (two decades), it is also possible that between-model variability in ENSO event magnitude or frequency could impact mean precipitation.

Although correlations between error and projected changes in precipitation only reach 99 or 95% significance in fairly limited locations (Fig. 11a), even a 20% chance that the projections are not independent from error may be cause for concern. It implies that simple bias-correction techniques, such as the commonly employed delta method (i.e., applying change or percent change to observations) may not be completely adequate. Conversely, results shown in Fig. 10g and h, where models with the smallest percent errors disagree about even the direction of precipitation change, suggest that screening models for the ability to simulate modern precipitation may not decrease projection uncertainty or quality, as established by Pierce et al. (2009). Determining why the four models with the most realistic climatological precipitation for this season and region disagree may be key in better understanding the magnitude and pace precipitation change. Recent work by

Seager and Vecchi (2010) suggest that the magnitude of precipitation changes are a model projects for the Southwest related to the changes it simulates in ENSO, perhaps explaining the divergence between this subset of four models.

A better understanding of how zonal winds and precipitation are related in the model may also provide insight to disagreements in the sign of projected changes in precipitation over portions of the western United States. Around 35°N, about half of the models suggest increasing precipitation and half decreasing (Christensen et al. 2007). In a water-limited region with a growing population, like the American West, better understanding potential changes in water availability will be crucial.

It appears that bias in the simulation of the mid-latitude circulation influences the simulation of modern precipitation. Many aspects of the mid-latitude circulation are implicated in changing precipitation patterns over the West. Although this does not invalidate apparently robust projection for drying, it does increase uncertainty about the magnitude and pace of future precipitation changes and suggests that we may need to evaluate a wider range of precipitation scenarios than suggested by a given suite of GCMs.

5 Conclusions

All of the 18 models investigated in this study had substantial wet biases over at least part of western North America during the cool season (November–April), when compared to 1979/80–98/99 data from the Global Precipitation Climatology Project (GPCP) and four other commonly used data sets. Precipitation was generally well simulated over the eastern United States and southeastern Canada. The largest percent errors were observed over the southwestern United States and Mexico, with somewhat smaller but consistent errors over the Rocky Mountain region. Precipitation errors in the model over the southwestern United States and northern Mexico appear to be related to biases in the speed and/or latitude of peak zonal winds aloft, while those in the Pacific Northwest appear to be related to difficulties in simulating the precipitation patterns generated by the Cascades, the Sierra Nevada, and the northern Rocky Mountains.

The fact that the bias in precipitation appears to be related to the mechanisms implicated in projected changes in precipitation means that it could impact our estimates of uncertainty in precipitation projections. Although there is still debate over why the storm track is projected to move northward, the projection is considered robust (Yin 2005). The fact that this will occur in models against a mean state that is different than observed could influence the

magnitude and/or timing of precipitation changes. Detailed study of the response of zonal mean flow and storm track characteristics in individual models to greenhouse gas forcing in the context of their current biases will allow us to better understand changing precipitation patterns over western North America. Such study could also reduce uncertainty in precipitation projections.

The plausible physical relationship between a cause of precipitation error and a mechanism driving changes in precipitation, combined with statistically significant relationships between error and projected changes in precipitation over some parts of western North America suggest that many commonly use bias-correction techniques may not always be appropriate, as noted by Liang et al. (2008). However, the large errors require that some sort of bias-correction be applied if projections are used to evaluate potential impacts on ecosystems or water resources. The potential for dependence between bias and projection, combined with the relatively large uncertainties in the trajectory of precipitation change underscore the need to evaluate multiple precipitation scenarios under warming conditions.

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