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Discussions

Errors in climate model daily precipitation and temperature output: time invariance and implications for bias correction

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Abstract

When correcting for biases in general circulation model (GCM) output, for example when statistically downscaling for regional and local impacts studies, a common assumption is that the GCM biases can be characterized by comparing model simula-
tions and observations for a historical period. We demonstrate some complications in this assumption, with GCM biases varying between mean and extreme values and for different sets of historical years. Daily precipitation and maximum and minimum temperature from late 20th century simulations by four GCMs over the United States were compared to gridded observations. Using random years from the historical record we
select a "base" set and a 10-yr independent "projected" set. We compare differences in biases between these sets at median and extreme percentiles. On average a base set with as few as 4 randomly-selected years is often adequate to characterize the biases in daily GCM precipitation and temperature, at both median and extreme values; 12 yr provided higher confidence that bias correction would be successful. This suggests
that some of the GCM bias is time invariant. When characterizing bias with a set of consecutive years, the set must be long enough to accommodate regional low frequency variability, since the bias also exhibits this variability. Newer climate models included in the Intergovernmental Panel on Climate Change fifth assessment will allow extending this study for a longer observational period and to finer scales.

1 Introduction

The prospect of continued and intensifying climate change has motivated the assessment of impacts at the local to regional scale, which entails the prerequisite use of downscaling methods to translate large-scale general circulation model (GCM) output to a regionally relevant scale (Carter et al., 2007; Christensen et al., 2007). This down-
scaling is typically categorized into two types: dynamical, using a higher resolution climate model that better represents the finer-scale processes and terrain in the region of

interest; and statistical, where relationships are developed between large scale climate statistics and those at a fine scale (Fowler et al., 2007). While dynamical downscaling has the advantage of producing complete, physically consistent fields, its computational demands preclude its common use when using multiple GCMs in a climate change impact assessment. We thus focus our attention on statistical downscaling, and more specifically on the bias correction inherently included in it.

With the development of coordinated GCM output, with standardized experiments, formats, and archiving (Meehl et al., 2007), impact assessments can more readily use an ensemble of output from multiple GCMs. This allows the separation of various sources of uncertainties and the assessment to some degree of the uncertainty due to GCM representation of climate sensitivity (Hawkins and Sutton, 2009; Knutti et al., 2008; Wehner, 2010). In combining a selection of GCMs to form an ensemble, the inherent errors in each GCM must be accommodated. In the ideal case, if all GCM biases were stationary in time (and with projected trends in the future), removing the bias during an observed period and applying the same bias correction into the future should produce a projection into the future with lower bias as well. Ultimately this would place all GCM projections on a more or less equal footing.

Some past studies support the assumption of time-invariant GCM biases in bias correction schemes. For example, Macadam et al. (2010), who demonstrate that using GCM abilities to reproduce near-surface temperature anomalies (where biases in mean state are removed) was found to produce inconsistent rankings (from best to worst) of GCMs for different 20 yr periods in the 20th century. However, Macadam et al. (2010) found when actual temperatures were used to assess model performance, a more stable GCM ranking was produced. While studying regional climate model biases, Christensen et al. (2008) found systematic biases in precipitation and temperature related to observed mean values, although the biases between different subsets of years increased when they differed in temperature by 4–6 °C.

Biases in GCM output have been attributed to various climate model deficiencies such as the coarse representation of terrain (Masson and Knutti, 2011), cloud and

convective precipitation parameterization (Sun et al., 2006), surface albedo feedback (Randall et al., 2007), and representation of land-atmosphere interactions (Haerter et al., 2011) for example. Some of these deficiencies, as persistent model character-istics, would be expected to result in biases in the GCM output that are similar during different historical periods and into the future. For example, errors in GCM simulations of temperature occur in regions of sharp elevation changes that are not captured by the coarse GCM spatial scale (Randall et al., 2007); these errors would be expected to be evident to some degree in model simulations for any time period. However, as Haerter et al. (2011) state "bias correction cannot correct for incorrect representations of dynamical and/or physical processes", which points toward the issue of some GCM deficiencies producing different biases in land surface variables as the climate warms, generically referred to as time- and state-dependent biases (Buser et al., 2009; Ehret et al., 2012). For example, Hall et al. (2008) show that biases in the representation of Spring snow albedo feedback in a GCM can modify the summer temperature change sensitivity. This implies that as global temperatures climb in future decades, some bi-ases could be amplified by this feedback process. While we do not assess the sources of GCM biases explicitly, we aim to examine where different GCMs exhibit similar pre-cipitation and temperature biases between two sets of independent years, which may carry implications as to which sources of error are important in different regions.

Many of the prior assessments of GCM bias have been based on GCM simulations of monthly, seasonal, or annual mean quantities. Recognizing the important role of extreme events in the projected impacts of climate change (Christensen et al., 2007), statistical downscaling of daily GCM output can been used to provide information on the projected changes in regional extremes (e.g. Bürger et al., 2012; Fowler et al., 2007; Tryhorn and DeGaetano, 2011). While accounting for biases at longer time scales, such as monthly, can reduce the bias in daily GCM output, the daily variability of GCM output may have biases (such as excessive drizzle (e.g. Piani et al., 2010)) that cannot be addressed by a correction at longer time scales. By addressing biases at the daily

scale, we can assess the ability to correct for biases at a time scale appropriate for many extreme events (Frich et al., 2002).

Biases in daily GCM output can be removed in many ways. At its simplest, the perturbation, or "delta" method shifts the observed mean by the GCM simulated mean change, effectively accounting for GCM mean bias only (Hewitson, 2003), which is useful but has its limitations (Ballester et al., 2010). Separate perturbations can be applied to different magnitude events (e.g. Vicuna et al., 2010) to capture some of the potentially asymmetric biases in different portions of the observed probability distribution function. In its limit, perturbations can be applied along a continuous distribution, resulting in a quantile mapping technique (Maraun et al., 2010; Panofsky and Brier, 1968). This type of approach has been applied in a variety of formulations for bias correcting monthly and daily climate model output (e.g. Abatzoglou and Brown, 2011; Boé et al., 2007; Ines and Hansen, 2006; Li et al., 2010; Piani et al., 2010; Themeßl et al., 2012; Thrasher et al., 2012), and has been shown to compare favorably to other statistical bias correction methods (Lafon et al., 2012). Regardless of the approach, all of these methods of bias removal assume that biases relative to historic observations will be the same during the projections.

For this study, we examine the biases in daily GCM output over the conterminous United States. We address the following questions: (1) are the daily biases the same between median and extreme values? (2) Are biases the same over different randomly selected sets of years (i.e. time-invariant)? We address these using daily output from four GCMs for precipitation, and maximum and minimum daily temperature. We consider biases at both median and extreme values because, as attention focuses on extreme events such as heat waves, peak energy demand, and floods, the assumptions in bias correction of daily data at these extremes becomes at least as important as at mean conditions.

2 Methods and data

The domain used for this study is the conterminous United States, as represented by 20 individual 2° by 2° (latitude/longitude) grid boxes, shown in Fig. 1. For the period 1950–1999, daily precipitation, maximum and minimum temperature output were obtained from simulations of four GCMs listed in Table 1. These four GCM runs were those selected for a wider project aimed at comparing different statistical and dynamical downscaling techniques in California and the Western United States (Pierce et al., 2012). All GCMs were regridded onto a common 2-degree grid to allow direct comparisons of model output. While this coarse resolution inevitably results in a reduction of daily extremes that would be experienced at smaller scales due to effects of spatial averaging (Yevjevich, 1972), GCM-scale daily extremes are widely used to characterize projected future changes in important measures of impacts (Tebaldi et al., 2006).

As an observational baseline the 1/8 degree Maurer et al. (2002) data set for the 1950–1999 period was used, which was aggregated to the same 2-degree spatial resolution as the GCMs. This dataset consists of gridded daily cooperative observer station observations, with precipitation rescaled (using a multiplicative factor) to match the 1961–1990 monthly means of the widely-used PRISM dataset (Daly et al., 1994), which incorporates additional data sources for more complete coverage. This data set has been extensively validated, and has been shown to produce high quality streamflow simulations (Maurer et al., 2002). This data set was spatially averaged, by averaging all 1/8 degree grid cells within each of the 2-degree GCM-scale grid boxes, which represent approximately $40\,000\,\text{km}^2$. While GCM biases have been shown to have some sensitivity to the data set used as the observational benchmark (Masson and Knutti, 2011), the relatively high density station observations (averaging one station per 700–1000 km^2 (Maurer et al., 2002), much more than an order of magnitude smaller than the area of the 2-degree GCM cells) in the observational data set provides a reasonable baseline against which to assess GCM biases, especially when aggregated to the GCM scale.

To assess the variability of biases with time, the historical record was first divided into two pools: one of even years and the other of odd years. From each of these pools, years were randomly selected (without replacement) from the historical record: (1) a "base" set (between 2 and 20 yr in size) randomly selected from the even-year pool; (2) a "projected" set of 10 randomly-selected years drawn from the odd-year pool. As in Piani et al. (2010), a decade for the projected set size provides a compromise between the preference for as long a period as possible to characterize climate and the need for non-overlapping periods in a 50-yr observational record. In addition, the motivation for fixing a relatively short 10-yr set size derives from this study being connected to that of Pierce et al. (2012). In the Pierce et al. (2012) study the challenge was to bias correct climate model simulations consisting of a single decade in the 20th century and another decade of future projection, and the question arose as to whether the base period was of adequate size for bias correction. While longer climatological periods are favorable and more typical for characterizing climate model biases (e.g. Wood et al., 2004), recent research suggests that in some cases periods as short as a decade may suffice, adding only a minor source of additional uncertainty (Chen et al., 2011).

The same sets of years were used from both the GCM output and the observed data. There is no reason for year-to-year correspondence between the GCM output and the historical record as reflected in the observations, since GCM simulations are only one possible realization for the time period. However, the longer term climate represented by many years should be comparable, and it is the aggregate statistics of all years in the sample that are assessed. For each of these sets, cumulative distribution functions (CDFs) were prepared by taking all of the days in a season: summer, June–August (JJA) for maximum daily temperature (T_{max}); or winter, December–February (DJF) for precipitation (Pr) and minimum daily temperature (T_{min}). The use of a single season for each variable is for the purpose of capturing summer and winter extreme values for temperature, and cold season precipitation extremes, which are of particular importance in the Western United States where winter precipitation dominates the hydro-climatic characteristics (Pyke, 1972). We recognize the importance of other seasonal

variables for different regions of the domain, especially related to precipitation (e.g. Karl et al., 2009), but reserve a more comprehensive effort for future research. Within each season, two percentiles are selected for analysis: the median and the 95th percentile for Pr and T_{max}, and the median and 5th percentile for T_{min}.

A Monte Carlo experiment was performed by repeating 100 times the random selection of "base" sets and 10 yr "projected" sets. This number of simulations was chosen to provide adequate (so that repeated computations produced comparable results) sampling for all selections of sets of years without approaching the maximum number of combinations for the most limiting case, that is, 300 possible combinations of 2 yr selected from a pool of 25 yr. Also, a second set of 100 Monte Carlo simulations was performed, which produced indistinguishable results, showing this number of simulations is adequate for producing consistent results. For each of the base and projected sets, the constructed CDFs were used to determine the 50th and 95th (T_{max} and Pr) or 5th and 50th (T_{min}) percentiles for both observations and GCM output. The GCM biases relative to observations were calculated, composing two arrays of 100 values at each percentile. At each percentile and for each Monte Carlo simulation, the samples are compared using the following R index:

$$R = \frac{|B_P - B_B|}{(|B_P| + |B_B|)/2} \tag{1}$$

where B is the bias, the difference between the GCM value and the observed value, and the subscripts P and B indicate the projected and base sets, respectively; the vertical bars are the absolute value operator. What this index represents is the ratio of the difference in bias between the base and projected sets and the average bias of the base and projected sets. A value of R greater than one indicates a larger difference in bias between the two sets than the average bias of the GCM, meaning a higher likelihood that bias correction would degrade the GCM output rather than improve it. R has a range of $0 \leq R \leq 2$. This index is similar to that used by Maraun (2012) to characterize the effectiveness of bias correction of temperatures produced by regional

climate models. The principal difference in the R index to that of Maraun (2012) is that the R index is normalized by an estimate of the mean bias; since in this case both the base and projected sets are selected from the historical record, the mean of the two bias estimates (for the base and projected sets) is used to estimate the average bias.

5 The above procedure is repeated at each of the 20 selected grid cells and for the four GCMs included in this analysis.

As an alternative, the mean bias in the denominator could be estimated differently, such as using only the base period bias B_B. The advantage of using the R formulation above is that it is insensitive to which set is designated as "Projected" and which is

10 "Base". For example, $B_B = 4$, $B_P = 2$ and $B_B = 2$, $B_P = 4$ produce the same R value, but would not if only B_B or B_P were used in the denominator. This provides the additional advantage that, since both the base and projected sets are randomly drawn from the historical record and since the R index is insensitive to this designation, results for varying base set sizes with a fixed projected set size would be the same as those for

15 varying projected set sizes and a fixed base set size.

3   Results and discussion

Examples of CDFs for JJA T_{max} for a single grid cell for the NCAR CCSM3 GCM are illustrated in Fig. 2. For a random 20-yr base set (left panel) the GCM overestimates T_{max} (relative to observations) at all quantiles, and the bias appears similar for low and

20 high extreme values. For the 10-yr projected set (center panel), the bias appears similar to the base set, with the GCM overestimating T_{max} at all quantiles. However, the bias (right panel), calculated at 19 evenly spaced quantiles (0.05, 0.10, 0.95) shows asymmetry across the quantiles. Especially noticeable is that at low quantiles, representing extreme low T_{max} values, the bias for the base set is more than 1 °C greater than for

25 the projected set, while at median values the base and projected set biases are closer. While this represents just one random base and projected set, it illustrates some of the potential complications in assuming biases are systematic in GCM simulations.

For each of 100 Monte Carlo simulations, biases relative to observations for the base and projected sets are calculated, as is the difference between the bias for the base and projected sets, and finally the R index. The results across the domain for daily JJA T_{max} are illustrated in Figs. 3–5 for the GFDL model output.

Figure 3 shows that the mean (of the 100 Monte Carlo simulations) JJA T_{max} GFDL model biases (left panels) vary across the domain. These vary from large negative values (a cool bias) in the northern Rocky Mountain region and a warm bias throughout the central plains, especially at the high extreme (95 percentile), well known characteristics of this version of the model (Klein et al., 2006). The magnitude of the GCM bias at specific grid cells in Fig. 3 (left panels) shows consistency for any sample of years from the late 20th century, demonstrating that there is some spatial and temporal consistency in the GCM bias. This supports the concept of model deficiencies in representing detailed terrain and regional processes playing a role in creating the biases. Rather than the magnitude of the biases, the focus here is on determining whether at each point across the domain these biases are the same between two different randomly selected sets of years.

Figure 3 also shows that the mean differences between the two sets (base and projected) of biases in GCM T_{max} for both the 50th and 95th percentiles (center panels) are generally smaller than the GCM bias (left panels). This is reflected in most of the R values (right panels) having a mean below one, with the worst case being with the smallest base set sample (4 yr) for the extreme 95th percentile T_{max} statistic. Also of note in Fig. 3 is that there is a decline in the number of grid cells where R exceeds one between the 4 and 12 yr base set size, while little difference is evident between the 12 and 20 yr base set size. This suggests that, for daily simulations of JJA T_{max}, a 12-yr base set works nearly as well as a 20-yr base set for characterizing GCM biases, both for median and extreme values, and that there is a diminishing return for using larger base sets for characterizing bias. The potential for using base sets of different sizes is discussed in greater detail below.

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Figure 4 shows the bias and changes in bias for T_{min} for the GFDL model. Of note is that the locations of high and low biases in T_{min}, as with T_{max}, occur in the same regions for any base set size, again supporting the concept of a time-invariant, geographically based model deficiency underlying at least a portion of the bias. It is interesting to observe in Fig. 4 that the location of greatest bias, the grid cells with the greatest change in bias, and the points with R exceeding one, are all different from Fig. 3. This suggests that the factors driving biases in T_{min} are distinct from those affecting T_{max}, though it is beyond the scope of this effort to determine the sources of the biases in GCM output. In addition, the R index values in Fig. 4 are generally larger than in Fig. 3, with more grid cells exceeding a mean value of one for both the median and extreme at all base set sizes. This indicates that there are more grid cells in the domain where T_{min} biases are time-dependent than for T_{max} for this GCM.

Figure 5 shows the GFDL model bias for winter precipitation. The left column of the biases in median and extreme daily precipitation shows one distinct pattern not as evident as in the figures of T_{max} and T_{min}. In particular, the biases are substantially larger for the extremes, consistent with the broad interpretation of Randall et al. (2007) that temperature extremes are simulated with greater success by GCMs than precipitation extremes. As evident for T_{min} (Fig. 4) the number of occurrences of mean $R < 1$ in Fig. 5 (summarized in Table 2) is fairly consistent between all base set sizes. This indicates that, in the mean, a short base set of 4 randomly-selected years provides nearly as good a representation of the systematic GCM biases as a 20 yr set. The number of occurrences where the 95th percentile R (estimated as the 95th largest value of the 100 Monte Carlo samples) exceeds 1 drops sharply between a 4 and 12 yr base period. This indicates that, in the mean, a short base set of 4 yr provides nearly as good a representation of the systematic GCM biases as a 20 yr set. For a 95 % confidence threshold, however, a longer base set of 12 yr provides improvement in bias correction results.

Table 2 summarizes the right column of Figs. 3, 4, and 5 as well as the results for the other three GCMs included in this study, to assess whether some of the same patterns

observed for the GFDL model are shared across the four GCMs. Table 2 shows the pattern of larger base sets providing fewer occurrences of $R > 1$. This is more evident between 4-yr and 12-yr base sets; between 12 and 20-yr sets the results are broadly similar. However, in many cases both median and extreme values show comparable numbers of $R > 1$ occurrences at all base set sizes, with the exceptions in only a few cases (e.g. GFDL median T_{max} and T_{min}, and PCM and CCSM median Pr). This shows that for T_{max} and Pr, in the mean, bias correction would be successful in most cases using base set sizes of only 4 randomly selected years. The single case where bias correction for more than half of the cells would fail, ultimately worsening the bias, is CCSM extreme T_{min}, where 11 grid cells show $R > 1$ on average. For this case, even a 20 yr base set size does not alleviate the problem. This suggests that if the bias cannot be characterized with a few years of daily data, it may lack adequate time-invariance to be amenable to this form of bias correction with any number of years constituting a base set. It is interesting that this same model has the fewest number of occurrences of $R > 1$ for median daily T_{min}, and demonstrates successful bias correction even with a base set of 4 yr. Thus, different processes are likely responsible for the CCSM model biases in mean and extreme daily T_{min} values.

The above discussion focused on grid cells where the mean R index exceeded one, in which case on average the bias correction degrades the skill. To examine a more stringent standard, Table 2 also summarizes the number of grid cells in each case where the 95th percentile R values for each GCM, variable, and base set size, exceeds 1. This approximates the number of cells (outlined in Figs. 3–5) where a 95 % confidence that $R < 1$ cannot be claimed. Of the 20 grid cells analyzed in this study, as many as 18 show the $R < 1$ hypothesis being rejected (CCSM extreme T_{min} and GFDL median T_{min}) and in other cases as few as 3 occurrences (CNRM median T_{max}, CCSM extreme T_{max}). While bias correction has a positive effect in the mean, the value of R being below one with a high confidence (95 %) is not strongly supported, especially for T_{min} and Pr.

A final observation in Table 2 of the mean number of occurrences of $R > 1$ is that the GCM showing the fewest number of cases varies for different variables, base set sizes, and whether median or extreme statistics are considered. Since the relative rank among GCMs is not consistent across variables, it can be concluded that among the models used in this study no GCM can be broadly characterized as producing output that is more likely to benefit from statistical bias correction than any other GCM. However, in the case where a specific variable is of interest, some GCMs can clearly outperform others. For example, for maximum temperatures the CNRM model demonstrates more time-invariance in biases than the other GCMs. Thus, the apparent time-invariance of biases for a specific variable and spatial domain of interest may be considered as a criterion for GCM selection when constructing ensembles, though a more comprehensive evaluation of the effectiveness of this is reserved for future research.

To illustrate some of the results in Table 2, Fig. 6 shows the mean R values at all grid cells for a base set size of 12 yr and a projected set size of 10 yr. The most important feature to note is that in most cases the grid cells where average $R > 1$ are not the same for the different GCMs. The exceptions to this, where more than two of the four GCMs show $R > 1$, are the 5th percentile of minimum temperature (cells 3,12,15,17), the median precipitation (cells 1, 20) and the 95th percentile precipitation (cells 6, 15, and 14). Thus, different GCMs in general exhibit time-varying biases at different locations. This suggests that by relying on an ensemble of GCMs, a quantile mapping bias correction will be more likely on average to have a beneficial effect in removing biases.

While the above assesses the time-invariance of GCM biases for random sets of years, it is standard practice in statistical bias correction to use sets of *consecutive* years for both the base and projected sets. With long term persistence due to oceanic teleconnections producing decadal-scale variations in climate (e.g. Cayan et al., 1998), and GCMs showing improving capability to simulate similar variability (AchutaRao and Sperber, 2006), biases would be likely to show similar low frequency variability since there would not be temporal correspondence between observations and GCM

simulated low frequency variations. Figures 7 and 8 show two examples of this phenomenon using the GFDL model at two locations (other models show similar behavior). It should be emphasized that because of the lack of temporal correspondence, the biases in any one year cannot be used to evaluate the GCM performance; Figs. 7 and

5 8 are shown only to demonstrate the low-frequency variability evident in the biases. These two locations correspond to cells 2 and 17 (see Fig. 1), being roughly located over northern California and the Ohio River valley, respectively. While the smoothed lines in Figs. 7 and 8 are continuous through the record, only the seasonal statistics are presented, so for example, there is one value of JJA T_{max} for each year. While

10 the 50-yr period for which data were available for this study is inadequate for a robust statistical analysis of bias stability using samples of independent consecutive periods, these figures suggest that using a shorter period of 5 yr or fewer could produce GCM biases that are more time dependent. However, a series length of 11 yr appears to remove most of the effects of the low frequency oscillations, though some small effects

15 do remain for temperature for the West coast site. This could be due to the teleconnections between the Pacific Decadal Oscillation, which exhibits multidecadal persistence (Mantua and Hare, 2002), and western US climate (e.g. Hidalgo and Dracup, 2003). The presence of low frequency oscillations will vary for different locations and variables. While, as explained above, a time series analysis at each grid cell is not performed as

20 part of this study, the base set size used for statistical bias correction for any region should consider the presence and frequency of regionally-important oscillations.

    The variation in the base set size needed to characterize the systematic bias at different locations is further complicated by the variation in the ability of GCMs to simulate certain oscillations and their teleconnections to regional precipitation and temperature

25 anomalies. For the same two grid cells shown in Figs. 7 and 8, the variation in R index values for base set sizes from 2 to 20 yr is shown in Figs. 9 and 10. At both of these points bias in the median value for daily T_{max} can be removed effectively, with R index values reaching a low plateau with base set sizes with fewer than 10 yr of data. The variability among GCMs is much greater for T_{min}, with GFDL displaying the greatest R

values, which remain above 1.0 even with a 20 yr base set size for cell 2. By contrast, GFDL performs best of all the GCMs at cell 17, with low R index values achieved at 5–10 yr of base set size. Similarly, for precipitation there is a stark contrast between the GCM that shows the least ability to have its errors successfully removed by bias correction at the two locations. If the ability to apply bias correction successfully is to be considered as a criterion for GCM selection for a regional study, Figs. 9 and 10 demonstrate that the selection would be highly dependent on the variable and location of interest.

4   Summary and conclusions

We examined simulated daily precipitation and maximum and minimum temperatures from four GCMs over the conterminous United States, and compared the simulated values to daily observations aggregated to the GCM scale. Our motivation was to examine some of the basic assumptions involved in statistical bias correction techniques used to treat the GCM output in climate change impact studies. The techniques assume that the biases can be represented as the difference between observations and GCM simulated values, and that these biases will remain the same into the future.

We performed Monte Carlo simulations, randomly selecting years from the historic record to represent the base set, which varied in size, and a non-overlapping 10-yr projected set (drawn from a different set of years in the historical period). The biases for each Monte Carlo simulation were compiled for a median value of each variable, and one extreme value: the 95 % (non-exceedence) precipitation, 95 % T_{max}, and 5 % T_{min}. For each Monte Carlo simulation, an indicator, here termed the R index, was computed. The R index represents the change in bias between the base and projected sets, and normalizes this by the mean bias. The mean and approximate 95 % value of the R index were calculated to assess the likelihood that bias correction could be successfully applied at each grid cell for each variable.

Our principal findings are:

1. In most locations, on average the GCM bias is statistically the same between two different sets of years. This means a quantile-mapping bias correction on average can have a positive effect in removing a portion of the GCM bias.

2. For characterizing daily GCM output, our findings indicate variability in the number of years required to characterize bias for different GCMs and variables. On average a base set with as few as 4 randomly-selected years is often adequate to characterize the biases in daily GCM precipitation and temperature, at both median and extreme values. A base set of 12 yr provided improvement in the number of grid cells where high confidence in successful bias correction could be claimed.

3. For most variables and GCMs the characterization of the bias shows little improvement with base set sizes larger than about 10 yr. In a few cases the variability in bias between different sets of years is high enough that even a 20 yr base set size cannot provide the necessary time invariance between sets of years to allow successful bias correction with quantile mapping.

4. When considering consecutive rather than randomly selected years, the GCM biases exhibit low frequency variability similar to observations, and the selected base period must be long enough to remove their effect.

5. At any location, the biases in the base and projected sets of years for a particular variable were fairly consistent for any given GCM, regardless of base set size. This reflects that there are geographical manifestations to some of the GCM shortcomings that cause bias, such as the inadequate topography represented at coarse resolutions. There are differences between the magnitude of biases at the mean and extreme values (especially for precipitation), but the differences in the biases between the base and projected sets of years are comparable for both means and extreme values.

These findings can be interpreted as cautiously encouraging to those who use quantile mapping to bias correct GCM output to estimate climate change impacts. Our results

suggest that a statistical removal of the GCM bias, characterized by comparing GCM simulations for a historic period to observations, is on average justified and robust. There were rare cases where at one location (for a specific variable and statistic) an individual GCM might on average have biases that vary in time to the point where the
5   bias correction would actually increase bias. However, other GCMs did not generally exhibit this characteristic at the same point. This suggests that as long as an ensemble of many GCMs is used, on average the bias correction will be beneficial. Where only one or a few GCMs are used for a climate impact study, it may be advisable to investigate the time dependence of GCM biases before using the bias corrected output for
10   climate impacts analysis. In addition, the time invariance of biases for variables and locations of interest could potentially be used as a means to favor using certain GCMs for regional studies.

Since this study only examined the stationarity in time of daily GCM biases, those at longer time scales are not explicitly addressed. However, Maurer et al. (2010) show that
15   a quantile mapping bias correction of daily data can result in the removal of most biases in monthly GCM output. In another study, Coats et al. (2012), with details in Coats et al. (2010), found that quantile mapping of precipitation at the daily time scale resulted in monthly and annual distributions in remarkably good agreement with observations. This suggests that by bias correcting at a daily scale the biases at longer time scales
20   may also be accommodated.

Future work will extend this analysis for the new model formulations producing climate simulations for the IPCC Fifth Assessment for a larger ensemble and a longer observational period. This will allow the testing of model simulations for a longer observational period including the most recent decade, when large-scale warming has
25   accelerated, providing more extreme cases for the above tests. Biases and their time-invariance will also be investigated at scales finer than the 2° resolution used in this study, reflecting both the finer resolution of the new GCMs and the latest implementations of quantile mapping bias correction at finer scales. In addition, new daily observational data sets of close to 100 yr in length (e.g. Casola et al., 2009) will allow more

intensive investigation of GCM biases by facilitating compositing on different conditions such as regional climate or oscillation phase.

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Table 1. GCM names and runs used in this study.

Modeling Group	GCM Name	Model Runs	Primary Reference
Centre National de Recherches Meteorologiques, France	CNRM	CNRM CM3: 20c3m run 1	Salas-Mélia et al. (2005)
Geophysical Fluid Dynamics Laboratory, USA	GFDL	GFDL 2.1: 20c3m run 1	Delworth et al. (2006)
National Center for Atmospheric Research, USA	PCM	NCAR PCM1: 20c3m run 2	Washington et al. (2000)
National Center for Atmospheric Research, USA	CCSM	NCAR CCSM3: 20c3m run 5	Kiehl et al. (1998)

Table 2. Number of grid cells (out of the 20 in the domain) with mean (of 100 Monte Carlo simulations) $R > 1$ and, in paretheses, the number of occurences where 95-percentile of R exceeds 1, for three base sets sizes and two percentiles.

GCM	T_{max} Median	Extreme	T_{min} Median	Extreme	Pr Median	Extreme
CNRM	4 yr: 2(5) 12 yr: 1(3) 20 yr: 1(3)	4 yr: 2(5) 12 yr: 2(5) 20 yr: 2(5)	4 yr: 6(15) 12yr: 5(10) 20 yr: 5(8)	4 yr: 7(10) 12 yrs 7(10) 20 yr: 7(10)	4 yr: 7 (15) 12 yr: 6(11) 20 yr: 5(10)	4 yr: 8(13) 12 yr: 8(13) 20 yr: 8(13)
GFDL	4 yr: 6(14) 12 yr: 2(10) 20 yr: 2(8)	4 yr: 3(9) 12 yr: 3(9) 20 yr: 3(9)	4 yr: 9(18) 12 yr: 6(14) 20 yr: 5(12)	4 yr: 5(10) 12 yr: 5(10) 20 yr: 5(10)	4 yr: 3(14) 12 yr: 3(9) 20 yr: 3(7)	4 yr: 4(8) 12 yr: 4(8) 20 yr: 4(8)
PCM	4 yr: 4(8) 12 yr: 5(6) 20 yr: 5(6)	4 yr: 5(11) 12 yr: 4(9) 20 yr: 3(8)	4 yr: 6(16) 12 yr: 5(9) 20 yr: 4(9)	4 yr: 6(12) 12 yr: 3(7) 20 yr: 2(7)	4 yr: 6(11) 12 yr: 2(7) 20 yr: 2(7)	4 yr: 6(16) 12 yr: 5(10) 20 yr: 5(10)
CCSM	4 yr: 5(12) 12 yr: 4(8) 20 yr: 4(8)	4 yr: 2(3) 12 yr: 2(3) 20 yr: 2(3)	4 yr: 3(14) 12 yr: 3(6) 20 yr: 2(5)	4 yr: 11(18) 12 yr: 11(18) 20 yr: 11(18)	4 yr: 6(11) 12 yr: 4(10) 20 yr: 3(8)	4 yr: 3(9) 12 yr: 3(9) 20 yr: 3(9)

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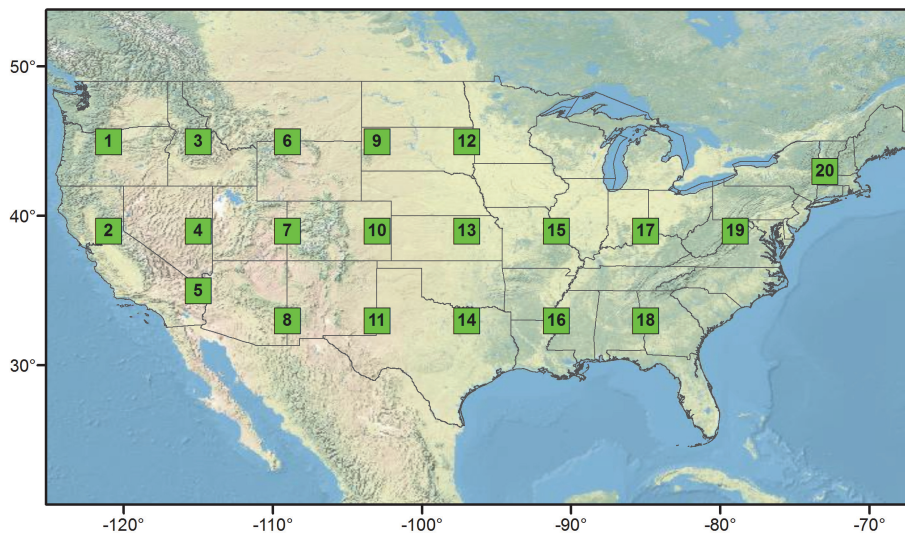
Fig. 1. Location of the 20 grid cells used in this analysis.
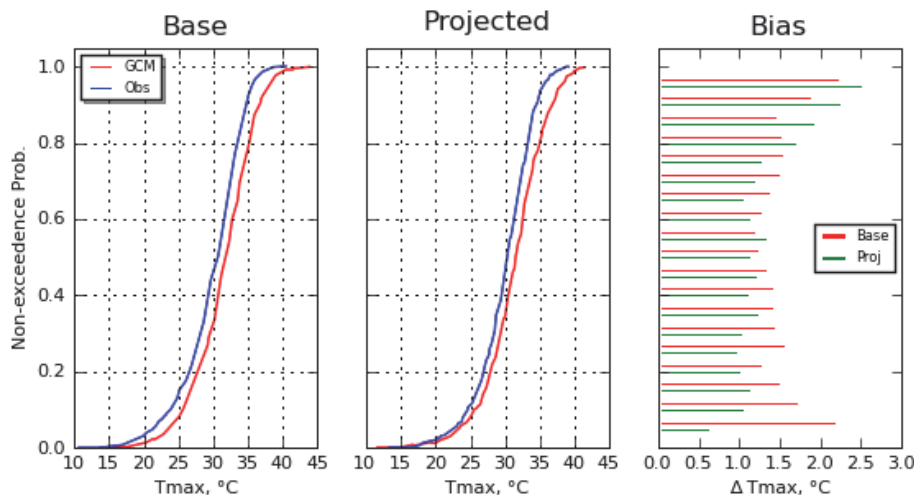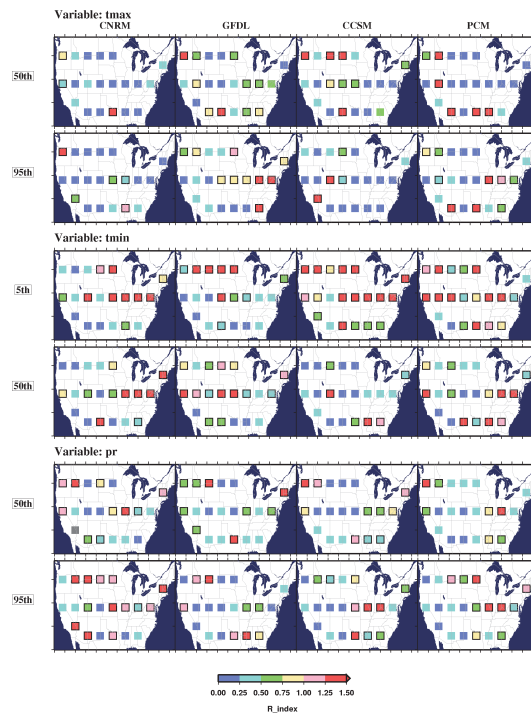
Fig. 2. Comparison of cumulative distribution functions of daily summer (JJA) maximum temperature between a GCM (NCAR CCSM3 in this case) and observations for a single grid point at 39° N 121° W (cell 2 in Fig. 1). Base set is a 20-yr random sample from 1950–1999 (left panel); Projected is a different 10-yr random sample from the same period (center panel), and bias (right panel) is calculated at 19 evenly spaced quantiles (0.05, 0.10,…,0.95).
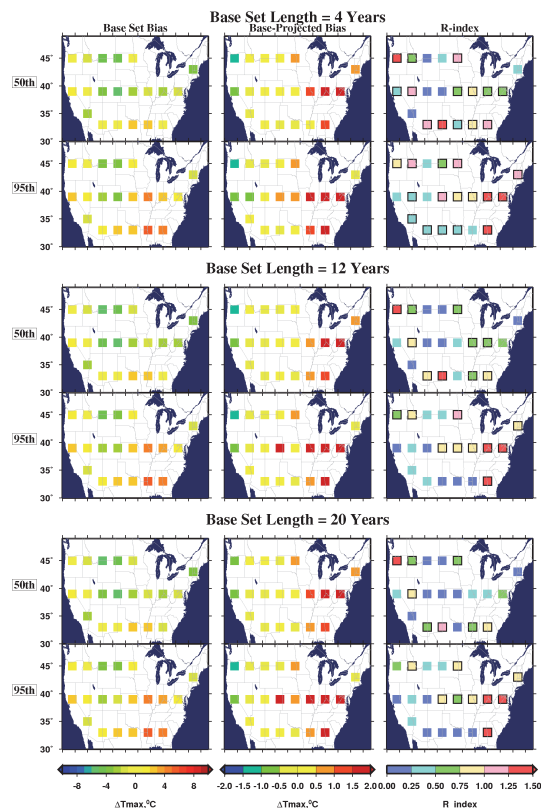
Fig. 3. Mean bias (of 100 Monte Carlo simulations) in daily JJA T_{max} for the GFDL model output for three different base set sizes (left panels), the mean difference in bias between the base and projected sets (center panels), and the mean R index value (right panels). Grid cells with dark outlines indicate where R values are not consistently less than 1 at 95 % confidence. Projected set size is 10 yr.
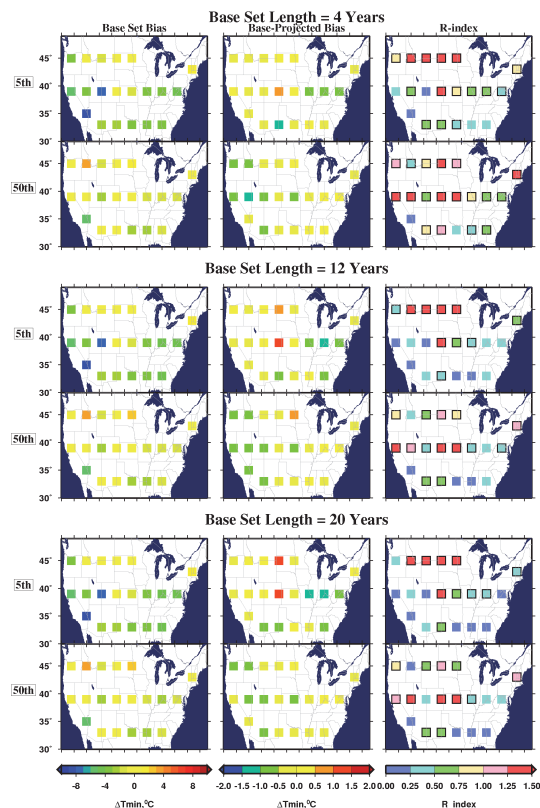
Fig. 4. Same as Fig. 3 but for DJF minimum daily temperature.
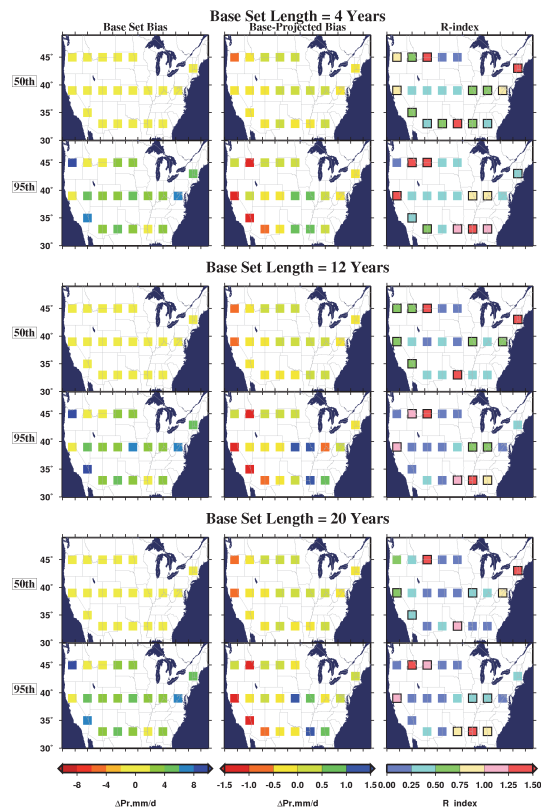
Fig. 5. Same as Fig. 3, for DJF precipitation.

Fig. 6. R values for a 12 yr Base set and a 10 yr Projected set for T_{max}, T_{min}, and Pr for the 4 GCMs included in this study. As with Figs. 3–5, grid cells with dark outlines indicate where R values are not consistently less than 1 at 95 % confidence.
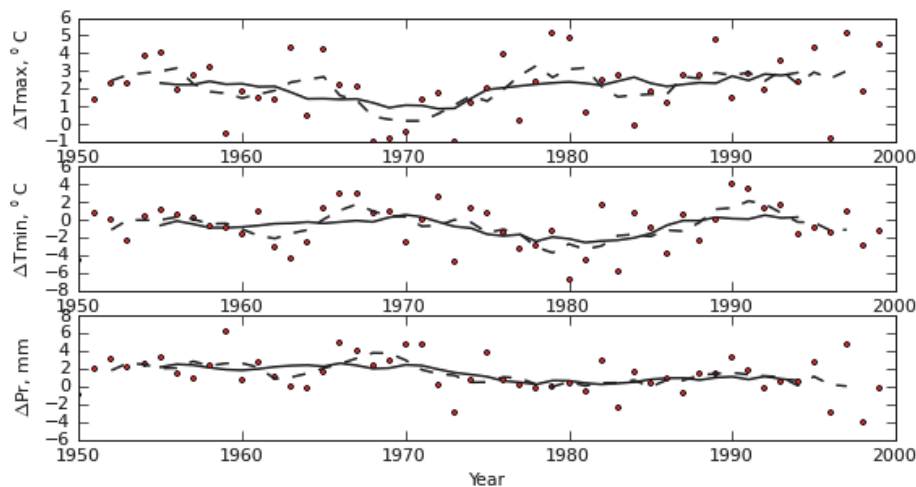
Fig. 7. Biases in seasonal statistics of daily T_{max}, T_{min}, and Pr based on the GFDL model from 1950–1999 at grid cell 2 (see Fig. 1). Points are biases in the median for the seasonal statistic for each year, dashed line is a 5-yr running mean, and the solid line is an 11-yr mean.
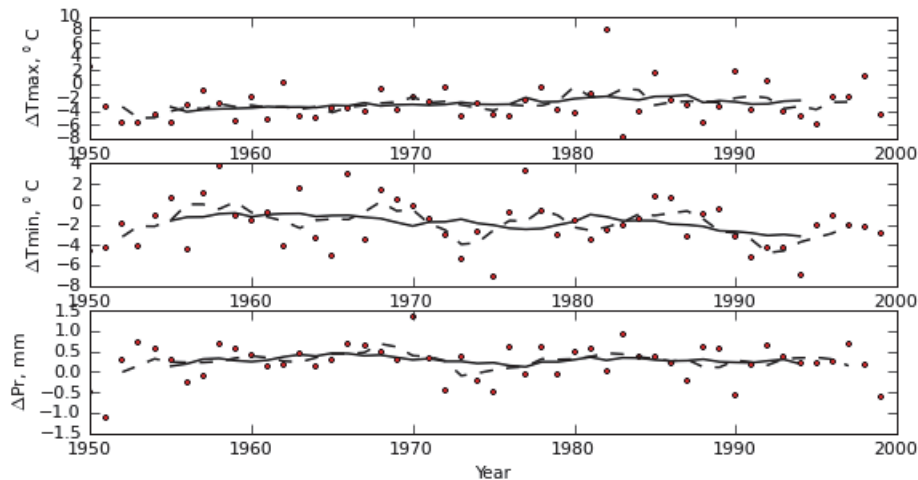
Fig. 8. Same as Fig. 7, for cell 17 (see Fig. 1).

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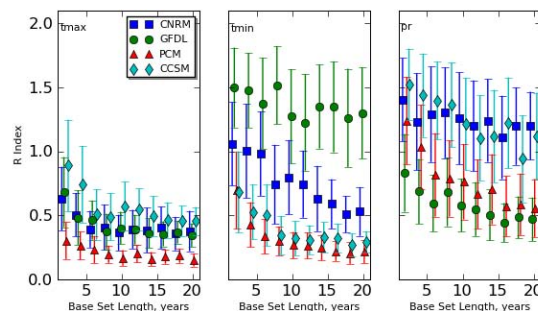
Fig. 9. For Cell number 2 (see Fig. 1), R index values for base set sizes from 2 to 20 yr. Points are for the mean R value for the median values of the variables; the bar indicates one standard deviation centered around the point.
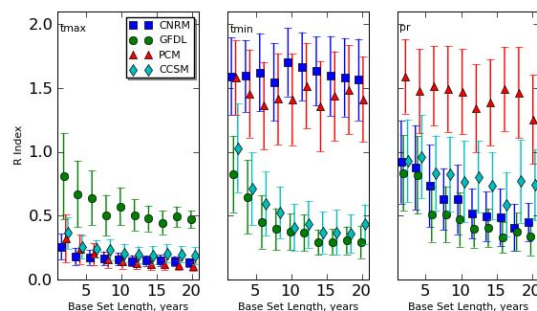
Fig. 10. Same as Fig. 9, but for cell 17.