IPCC’s 20th Century Climate Simulations:
Varied Representations of North American Hydroclimate Variability

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Abstract

Past climate change projections are not indicative of a global homogeneous change but changes at regional scales. Thus, it is important to have a better understanding of the current climate at those scales. Society’s dependence on water resources increases interest in hydroclimate. A region of great hydroclimate interest is North America, where water resources are recharged during winter, and expended during summer.

The annual cycle of precipitation, as well as interannual variability of North American hydroclimate during summer months are analyzed in coupled simulations of the 20th century climate. The state-of-the-art general circulation models, participating in the 4th Assessment Report for the IPCC, included in the present study are the American’s CCSM3, PCM, GISS-EH, and GFDL-CM2.1; the British UMKO-HadCM3, and the Japanese MIROC3.2(hires). Data sets with proven high quality such as NCEP’s North American Regional Reanalysis, and CPC’s US-Mexico precipitation analysis are used as targets for simulations.

Climatological precipitation is not easily simulated. While models capture winter precipitation very well over the US northwest, they encounter failure over the US southeast in the same season. Summer precipitation over central US and Mexico is also a great challenge for models, particularly the timing. In general UKMO-HadCM3 is the closer to observations.

Models’ potential in simulating interannual hydroclimate variability over North America during the warm-season is varied and limited to the central US. Models like PCM, and in particular UKMO-HadCM3, exhibit reasonably well the observed distribution and relative importance of remote and local contributions to precipitation variability over the region — convergence of remote moisture fluxes dominate over local evaporation. However, models like CCSM3 and GFDL-CM2.1 exhibit intense local recycling of precipitation and weak convergent moisture fluxes, in contrast with warm-season observations. In the other extreme are models like GISS-EH and MIROC3.2(hires) that prioritize the remote influence of moisture fluxes and neglect the local influence of evaporation to the regional precipitation variability.
Introduction

Extreme weather and climate events have profound impact on the societies and environment of the region affected. Events like Europe’s major heat-wave during the summer of 2003, the above average Atlantic hurricane activity in both 2003 and 2004, the first hurricane ever in the South Atlantic in 2004, the above normal rain and crops in the Sahel region during the 2003-2004 cycle, and the persistent drought condition over western United states, just for mentioning some (e.g., see the Extreme Weather and Climate Events web-page from the National Climate Data Center at: http://lwf.ncdc.noaa.gov/oa/climate/severewhether/extremes.html), have been deemed without questioning as evidence of the presence of global warming.

Attending to the heterogeneity of the distribution of the climate controls over the planet there is no basis to expect that, under the scenario of a global climate change, extreme events will be of the same type everywhere in the world. Thus, the importance of understanding regional climates before ascertains the effects of a global climate change over it. A clear understanding of the current and future climate can only be achieved by analyzing observed data and conducting modeling studies.

Interest in regional climate change, specially hydroclimate, is intense due to the increasing societal needs for sustainable water supply, management of water resources, and mitigation/prevention of hazardous hydroclimate episodes. Hence, the economic and social value of regional hydroclimate predictions is unquestionable. The scientific value is also enormous, especially if the region is densely observed, for it can then provide an opportunity for model validation. A region of great hydroclimate interest is North America, where water resources are recharged during winter and early spring months, and largely depleted during summer months.

The authors have recently concluded an analysis of Great Plains hydroclimate variability focusing on the anomalous atmospheric water-balance in the warm-season months in nature and state-of-the-art atmospheric simulations (Ruiz-Barradas and Nigam 2005a, 2005b). The structure of precipitation and the role of local and remote water sources – evaporation and moisture fluxes,
respectively – in producing precipitation variability were examined. The main finding of that study is the dominance of remote sources over local ones in nature and quite the opposite in simulations.

In the present study, largely motivated and based on the authors’ previous research, the diagnostic analysis of hydroclimate variability during the warm-season is carried out on coupled simulations. Specifically, the realism of North American hydroclimate variability is evaluated in the coupled simulations of the current climate. At issue are the relative contributions of the atmospheric water-balance terms in producing precipitation variability over central US. The models in the present analysis are state-of-the-art coupled general circulation models (GCM) participating in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Models analyzed include four American models, a British model, and a Japanese model. The American models are the Climate Community System Model, version 3.0, (CCSM3), and the Parallel Climate Model (PCM) from the National Center for Atmospheric Research (NCAR); the Geophysical Fluid Dynamics Laboratory coupled model, version 2.1, (GFDL-CM2.1) from the National Oceanic and Atmospheric Administration (NOAA); the Goddard Institute for Space Studies model E-H (GISS-EH) from the National Aeronautics and Space Administration (NASA). The United Kingdom model is the Hadley Centre for Climate Prediction and Research coupled model, version 3, from the Meteorological Office (UKMO-HadCM3). The Japanese model is the high resolution Model for Interdisciplinary Research on Climate, version 3.2, (MIROC3.2(hires)) from the Center for Climate System Research of the University of Tokyo (CCSR), the National Institute of Environmental Studies (NIES) and the Frontier Research System for Global Change (FRSGC).

The data sets used in hydroclimate validation are described in section 2. The annual cycle of precipitation is briefly described in section 3. The Great Plains precipitation variability is discussed in section 4; additionally the frequency of anomalous events is compared. The accompanying spatial patterns of precipitation, stationary moisture-fluxes, and evaporation linked
to precipitation variability over the region are the focus in section 5; the relative contributions from moisture flux convergence and evaporation to precipitation variability are also compared in this section. The validity of the results is further investigated in section 6 via auto-correlation analysis. Concluding remarks are presented in section 7.

2. Data Sets

The North American Regional Reanalysis (NARR) data set, from the National Centers for Environmental Predictions (NCEP), is used in the models assessment. The studies by Ruiz-Barradas and Nigam (2005a, 2005b) set up the basis of the methodology to follow, as well as the target data set to use for the present analysis. The regional reanalysis is a long-term, consistent, data assimilation-based, climate data suite for North America (http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/; Mesinger et al. 2004). The regional reanalysis is produced at high spatial and temporal resolutions (32-km, 45-layer, 3-hourly) and spans a period of 25 years from October 1978 to December 2003; it is based on the April 2003 frozen version of NCEP’s mesoscale Eta forecast model and its data assimilation system (EDAS). NARR assimilates precipitation unlike the global reanalyses from NCEP (Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasting (ERA-40, http://www.ecmwf.int/products/data/archive/descriptions/e4/). The assimilation is, in fact, successful with downstream effects, including two-way interaction between precipitation and the improved land-surface model (e.g., Mitchell et al. 2004) this implies an observationally constrained evaporation field that is in line with some other observationally constrained products.

Evaluation of the NARR data set was already done in Ruiz-Barradas and Nigam (2005b), and Nigam and Ruiz-Barradas (2005) and gives confidence on the consistency of the data set to be used as target of the simulations, especially in the context of interannual variability over North America. For purposes of the present examination, the analysis on NARR is repeated on the same resolution used in the simulations, that is, an R30 (96X80) Gaussian grid for the 1979-1998 period.
The regional reanalysis is limited in time so an ancillary, longer precipitation data set is also used. The data set of choice for US-Mexico precipitation is NOAA/Climate Prediction Center (CPC)’s retrospective analysis of daily station data (http://www.cpc.ncep.noaa.gov/products/precip/realtime/retro.shtml; hereafter, referred as the US-Mexico data set), which was extensively used for validation in Ruiz-Barradas and Nigam (2005a, 2005b).

As mentioned earlier, simulations from six models are assessed. However, there were three other models analyzed as well\(^1\) which are not included due to space limitations and redundancy of the results in the context of the present paper. The six models, CCSM3 (http://www.ccsm.ucar.edu/publications/jclim04/Papers_JCL04.html), GFDL-CM2.1 (Delworth et al., 2004), GISS-EH (Schmidt et al., 2005), PCM (Meehl, et al., 2004), UKMO-HadCM3 (Gordon et al., 2000; Pope et al., 2000), MIROC3.2(hires) (http://www.ccsr.u-tokyo.ac.jp/kyosei/hasumi/MIROC/tech-repo.pdf), are representatives of major climate research centers in the world.

Historical simulations of the 20th century climate are analyzed. Those are simulations where coupled GCMs are being forced by observed solar irradiance, volcanic and anthropogenic aerosols, and atmospheric concentrations of ozone, carbon dioxide and other well mixed greenhouse gases (ftp://sprite.llnl.gov/pub/covey/IPCC_4AR_Forcing/README). In general the model simulations are century-long starting in the second half of the 1800’s and ending in 1999.

The analysis period will focus on the more recent 48 years (1951-1998) of the century-long coupled simulations. Interannual variability is analyzed using monthly anomalies, calculated with respect to the 1951-1998 monthly climatology\(^2\). Simulated fields were homogenized for all models extrapolating them to an R30 (96x80) Gaussian grid. Stationary moisture fluxes are calculated as in Ruiz-Barradas and Nigam (2005a), by computing the mass-weighted vertical integral from the

\(^1\)GFDL-CM2.0: GFDL’s coupled model version 2.0, GISS-ER: GISS’ E-R coupled model, and GISS-AOM: GISS’s 4 x3° coupled model.

\(^2\)Monthly climatology using the suggested “1981-2000 mean climate”, or more properly, the one for the 1979-1998 period as in NARR, does not change the main results of the study.
surface to 300 hPa in both regional reanalysis and simulations\textsuperscript{3}. The warm-season months of June, July, and August are the focal point of the analysis.

3. Precipitation Annual Cycle

The annual march of monthly precipitation is analyzed here through harmonic analysis of the 12-month climatology\textsuperscript{4}. The interest is on the annual cycle so the analysis is focused on the first harmonic as in Nigam and Ruiz-Barradas (2005). Attention is paid to the amplitude and timing of the annual cycle in the different data sets over the continent; mean annual precipitation (i.e., mean of the 12-month climatology) is also compared as background to the harmonic analysis plots (Fig. 1). Amplitude of the annual cycle is indicated by the length of the vector while phases are indicated by the orientation of the arrows according to the inserted scaling vector; an arrow pointing to the south indicates a maximum on 1 January, one pointing to the west means a maximum on 1 April, one pointing toward the north indicates a maximum on 1 July, and one pointing to the east means a maximum on 1 October.

In general the amplitude of the observed annual cycle diminishes and peaks earlier in summer from tropical Mexico to the central US (arrows in Fig. 1a). Notable observed features include the following: the maximum over northwestern US in January, maximum over central US during June-July, a weak maximum over the southern states during the late winter/early spring months, and weak seasonal variability over the Atlantic states. Additionally, in August there are maxima over northwestern Mexico as well as over central and southern Mexico; those amplitudes diminish from south to north. The structure of the observed mean annual precipitation (contours in Fig. 1a) is given by seasonal contributions in both northwestern and southern US during winter, and central US and Mexico during summer; please, see Nigam and Ruiz-Barradas (2005) for

\textsuperscript{3}UKMO-HadCM3 does not provide data at the 925 hPa standard level but does it at the 950 hPa level instead.

\textsuperscript{4}Climatologies are calculated for the common 1979-1998 period for both NARR and simulations. Minimum, and negligible, differences appear if the 1951-1998 period is used for the simulations.
further details.

Models display differing degree of accuracy when portraying the annual cycle of precipitation (Figs. 1b-g). While all the models capture the timing of the winter maximum over northwestern US, they exhibit some difficulty in capturing the timing of the summer maxima over central US and Mexico. The annual cycle from tropical Mexico to central US peaks erroneously from late spring to early summer in both CCSM3 and PCM but with amplitudes being more realistic in the former than in the latter; the rest of the models have a better timing in that region, specially MIROC3.2(hires). The observed weak late winter/early spring maximum over southern US and the weak annual cycle over the eastern US coast pose additional problems for the models as well. Those features are captured a bit late and too strong in spring, in particular for GISS-EH which peaks even later in summer.

The structure of the mean annual precipitation by the models has similar results than those in the annual cycle. Simulations are reasonable over northwestern US, with a winter maximum, but problematic to the east of the Continental Divide, which has winter (over southern US) and summer (over central US and Mexico) maxima. The UKMO-HadCM3 model has the best reproduction of the observed features. Figures not displayed for winter and summer means show the difficulty the rest of the models have in reproducing the winter maximum of precipitation over southern US as well as the distribution of precipitation over central US during summer.

4. Precipitation Variability

A first look to precipitation variability is made through a glimpse of the mean standard deviation of precipitation during the warm-season months (June-August, Fig. 2). Emphasis is made on the continental features of the field, although considerable differences exist over the oceans. North America is characterized by two regions of maximum precipitation variability (>1.5 mm day⁻¹), one over central US and the other over eastern Mexico (Fig. 2a).

Models have limited success locating these maxima of precipitation variability (Figs. 2b-g).
The maximum over central US is present but shifted to the southwest in all the simulations, while the maximum over eastern Mexico is almost absent, with the exception of the UKMO-HadCM3 and GISS-EH simulations. Precipitation variability over the US reaches a maximum in the GFDL-CM2.1 simulation, and a minimum in the PCM simulation\(^5\).

Knowing the relative success of the models in simulating the maximum of variability over central US, the study now will focus on this region.

**Great Plains Precipitation Index**

The area exhibiting the local maximum in observed precipitation variability over central US (Fig. 2a) defines a coherent domain that can be used to study the temporal variability of the region (Ruiz-Barradas and Nigam, 2005a, b). The 10° longitude-latitude box (100°W-90°W, 35°N-45°N) encompasses the region. The areal average of precipitation anomalies in the box defines the Great Plains Precipitation (GPP) index for the warm-season months (June, July, August).

The GPP index in simulations is also defined in terms of area-averaged precipitation anomalies over the 10° longitude-latitude region defined from observations. Although the box does not entirely enclose the local maximum of standard deviation in the individual simulations, it is not much of a problem for the analysis. The alternate 10° box draw in the GFDL-CM2.1 panel (dashed box in Fig. 2c) is used for a sensitivity analysis to test the dependence of the results on the choice of the region defining the GPP index; please, refer to the **Appendix** for the analysis.

Realistic monthly precipitation variability over the Great Plains is difficult for models to capture. Correlation between observed and simulated monthly GPP indices is almost non existent (-0.13 the highest). A compact, and more favorable measure of the variability is given by the mean standard deviation (SD) of the monthly GPP index. In this comparison the US-Mexico data set is

\(^5\)Large variability over the northwestern coast of Mexico and southwestern US seems to be a problem for PCM and GFDL-CM2.1 models and probably, as suggested by the massive incursion of precipitation from the Pacific ocean over the continent, due to a very active Inter-Tropical Convergence Zone in the eastern Pacific.
preferred to the NARR data set because of the shorter period of the latter\(^6\). With an observed variability over the Great Plains region of 0.91 mm day\(^{-1}\), \textbf{Table 1} summarizes variability over the region: large variability in the GFDL-CM2.1 simulation (SD=1.12 mm day\(^{-1}\)), low variability in the PCM simulation (SD=0.63 mm day\(^{-1}\)), and nature-matching variability in the UKMO-HadCM3 simulation (SD=0.92 mm day\(^{-1}\)); CCSM3 simulation is the second closest to observed variability (SD=1.00 mm day\(^{-1}\)).

Proximity of simulated SD to the observed one is not a guarantee of an exact match of observed distribution of wet and dry months. Frequency of months with precipitation above (wet) or below (dry) climatology is calculated from monthly GPP indices and displayed as a histogram in bins of 0.5 mm day\(^{-1}\) (\textbf{Fig. 3}). The observed US-Mexico data set (dark blue bar) indicates a higher number of dry months (76) than wet months (68), largely confined to the ±1.5 mm day\(^{-1}\) range. The number of dry and wet months partially holds for the simulations, except for PCM (green bar) which has more wet (77) than dry (67) months, and UKMO-HadCM3 which has an equal number of wet and dry (72) months. It is apparent that the smaller the warm-season SD, the larger the number of months concentrated in the ±0.5 mm day\(^{-1}\) range: PCM (green bar), GISS-EH (light blue bar), MIROC3.2(hires) (light brown bar). Large warm-season SD, as in the GFDL-CM2.1 simulation (red bar), imply the presence of months with large negative (>|3| mm day\(^{-1}\)) and positive (>4 mm day\(^{-1}\)) precipitation anomalies. Alternatively, UKMO-HadCM3 (fuchsia bar), and CCSM3 (yellow bar) perform better than the other models in the ±1 mm day\(^{-1}\) range, but do not show the observed marked decline in wet months from the 0.5-1 mm day\(^{-1}\) to the 1.5-2 mm day\(^{-1}\) range.

\textbf{Season-mean GPP Index}

It is expected that season-mean indices will demonstrate better correspondence with observations than the monthly indices. Attention is now shifted to smoothed versions of the monthly indices (\textbf{Fig. 4}). The smoothing is done via a 1-2-1 filter of the summer-mean index

\(^6\)Correlation between NARR and US-Mexico GPP indices is 0.99 for the common 1979-1998 period.
anomalies; in this way, the preceding, current and subsequent summer means are included in the calculation of the smoothed index enhancing interannual variability in them. Plotted indices come from the US-Mexico data set (continuous black line), the NARR data set (dashed black line) and simulations (color lines).

Temporal variability of the smoothed GPP index from observations is not easily reproduced by simulations. The proximity between indices from US-Mexico and NARR data sets is evidence of the successful assimilation of precipitation in NARR\(^7\). Both indices capture the 1993 flood event and 1998 dry event over central US; other dry episodes are also evident during the mid 1950’s and first half of the 1970’s in the index from the US-Mexico data set. The only model capturing the 1993 wet event, as well as the 1988 and early 1970’s dry events is the UKMO-HadCM3 (purple line).

Temporal correlation between the smoothed indices is displayed in Table 2. It summarizes the synchronous temporal evolution of the GPP indices contained in Figure 4: simulations by GFDL-CM2.1 (dark green line), CCSM3 (red line), and MIROC3.2(hires) (yellow-green line) have very limited correlation with observations; PCM (orange line), and GISS-EH (blue line) have modest correlation, and UKMO-HadCM3 (purple line) has a reasonable high correlation of 0.54. Correlations among the simulated indices are also low, except by those between MIROC3.2(hires) with CCSM3 and GFDL-CM2.1, and UKMO-HadCM3 with CCSM3.

5. Structure and linkages of precipitation variability

In this section the structure and linkages of precipitation variability with the atmospheric water-balance components over the Great Plains in the models are contrasted with observations as in Ruiz-Barradas and Nigam (2005a). At stake is the comparative significance of those components (and processes) in models and observations. The monthly GPP index is regressed

\(^7\) Differences between GPP indices from US-Mexico and NARR data sets are minimum, or non-existent, if the index from the US-Mexico data set is calculated with respect to the 1979-1998 climatology.
against monthly precipitation, stationary moisture fluxes (from winds and specific humidity), and evaporation (from surface latent heat) for the warm-season months (June-August) during the 1979-1998 period for NARR, and for the 1951-1998 period for simulations.

Precipitation

The GPP index regressions against precipitation anomalies from the regional reanalysis and simulations are displayed in Figure 5 with a contour interval of 0.3 mm day$^{-1}$. Due to the definition of the GPP index it is not surprising that the structure of precipitation anomalies in the regional reanalysis is confined to the Great Plains region without detriment to precipitation over other continental regions$^8$ (Fig. 5a). Regressed simulated precipitation anomalies show a consistent and confined structure in precipitation anomalies with a maximum over the focus region of the Great Plains (Fig. 5b-g). The exception to this is the CCSM3 simulation whose precipitation structure extends meridionally too far to the south into Mexico; the meridional elongation is also present in the PCM simulation, although to a much lesser extent (a signature of the common atmospheric component in both models?). It is also interesting to note that, except for the UKMO-HadCM3, all the models imply a decrease of precipitation over northwestern Mexico.

Moisture fluxes

Vertically-integrated stationary moisture fluxes$^9$ and their convergences associated with the regressed precipitation anomalies from the regional reanalysis and simulations are shown in Figure 6; as in precipitation regressions, the contour interval of 0.3 mm day$^{-1}$ is used for moisture flux convergence. Great Plains precipitation variability in the regional reanalysis is largely

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$^8$The significance of precipitation anomalies over oceanic regions is beyond the scope of the present study.

$^9$Stationary fluxes refer to moisture transports by the monthly-mean circulation.
supported by the convergence of stationary moisture flux; this apparently accounts for up to three-fourths of the precipitation over the Great Plains (Fig. 6a). A coherent, anti-cyclonic circulation carries moisture northward from the Gulf of Mexico and the Caribbean Sea. A cyclonic circulation over the US prompts a weaker connection to the Pacific, via westerly fluxes over the southwestern states.

Regressed simulated moisture flux anomalies, and their convergences, have less in common (Fig. 6b-g) than the precipitation anomalies but still manage to have a maximum of moisture flux convergence over the focus region. Moisture fluxes from the Gulf of Mexico into central US are apparent in GISS-EH, PCM, UKMO-HadCM3, and MIROC3.2(hires) simulations; the Caribbean connection, although weak, is present only in the UKMO-HadCM3 simulation. The connection to the Pacific via westerly fluxes over the southwestern states in NARR is also weak in simulations; none of the models simulate the cyclonic circulation over the US, with the exception of MIROC3.2(hires) but not with the extension present in the regional reanalysis. However, CCSM3 and, in particular, GFDL-CM2.1 simulations put a premium on moisture fluxes from the Pacific into the central US; while GFDL-CM2.1 has no moisture fluxes from the Gulf of Mexico at all, CCSM3 has them but they are driven by activity in the Pacific!

The structure of the simulated moisture flux convergence in the models is less consistent among the different simulations than it was in the simulated precipitation. Distributions of moisture flux convergence over the Great Plains range from the noisy and very large in GISS-EH, to the almost identical to the regional reanalysis by MIROC3.2(hires); simulated moisture flux convergence by UKMO-HadCM3 is also larger than that in NARR, while those by CCSM3, GFDL-CM2.1 and PCM are slightly weaker than in the regional reanalysis. Note that the simulated moisture flux divergence over northwestern Mexico seems to explain the simulated (and not observed) reduced precipitation over that region, especially in CCSM3, GFDL-CM2.1 and PCM.
Evaporation

The GPP index regressions on surface evaporation from the regional reanalysis and simulations are displayed in Figure 7. In this case, the 0.1 mm day$^{-1}$ contour interval is a third of that used for precipitation and moisture flux convergence. Evaporation anomalies in the regional reanalysis are modest over the Great Plains region (Fig. 7a) and noticeably smaller than precipitation and moisture flux convergence anomalies.

Regressed simulated evaporation anomalies also have few similarities among them (Fig. 7b-g). Great Plains evaporation anomalies span from zero, or close to zero, in GISS-EH to very large anomalies in CCSM3 and GFDL-CM2.1; evaporation anomalies in PCM, UKMO-HadCM3 and MIROC3.2(hires) are modest. The maximum in evaporation anomalies in regional reanalysis and simulations is shifted toward the southwest, with respect to the maximum in precipitation anomalies. Note the closeness of the structures between precipitation and evaporation anomalies simulated by CCSM3 and GFDL-CM2.1.

Relative Contributions

The previous description of regressed anomalies of the main water-balance components in the atmosphere indicates a different hierarchy of processes that are important for precipitation variability over the Great Plains in observations (NARR) and the different models. Although it is important to have a well simulated structure of anomalies, it is even more important to have the relative contributions of the processes responsible for precipitation variability as identified in observations. Observations, via the regional reanalysis, indicate that precipitation anomalies over this region are mostly due to convergence of remote moisture fluxes, and to a smaller extent due to local evaporation of previous precipitation. Thus, attending to the magnitude of the maximum anomalies, models seem to emphasize different processes as follows. In the first type of models (CCSM3, GFDL-CM2.1), the emphasis is on the large local recycling of evaporation. In the second type of models (GISS-EH), the emphasis is on the remote sources of water inducing large moisture
flux convergence. In the third type of model (UKMO-HadCM3, MIROC3.2(hires), PCM), the emphasis is still on the remote sources of water converging over the region but the local recycling of evaporation increases its role, similar to observations.

Another way to see these contributions is by taking an area-average of the regressed anomalies of precipitation, vertically integrated moisture flux convergence, and evaporation over the Great Plains region (100°W-90°W, 35°N-45°N) as seen in Table 3. Note that taking the area-average of the anomalies with different sign in the region can generate the wrong impression, as it is the case for moisture flux convergence from GFDL-CM2.1, evaporation from UKMO-HadCM3, and especially, from PCM (which has comparable negative and positive anomalies). In observations (NARR row), moisture flux convergence dominates over modest evaporation in the generation of precipitation; the former accounts for up to three-fourths of precipitation, while the latter for up to a quarter of the precipitation.

Area-averages of the regressed simulated anomalies (Table 3) also highlights the three different kind of models. However, models are distributed in a slightly different manner than before. 1) Those where large evaporation dominates over moisture flux convergence in the generation of precipitation: CCSM3, and GFDL-CM2.1. 2) Those where moisture flux convergence dominates over reduced evaporation: GISS-EH, PCM, and MIROC3.2(hires). 3) Those were moisture flux convergence dominates over modest evaporation in the generation of precipitation, as in observations: UKMO-HadCM3.

6. Precipitation Recycling

The local recycling of precipitation via evaporation depends on previous precipitation over the region. The higher the correlation between previous and current monthly precipitation, the stronger is the local recycling; this auto-correlation analysis will help to corroborate the outlined division of the models and their distribution. The analysis is carried on the monthly GPP indices calculating the correlation between July’s precipitation anomalies and the rest of the monthly
anomalies for the 1951-1998 period (Fig. 8). July’s precipitation dependence on previous months’ precipitation in observations from the US-Mexico data set (black line) indicates a low correlation (~0.2 with June and lower with earlier months); August’s precipitation dependence on July’s precipitation is almost nonexistent (~0.02). The observed low dependence on the previous month’s precipitation defines a narrow spike-like graph suggesting weak recycling via evaporation over the Great Plains. Thus a broader/narrower spike than the one from observed data will indicate even higher/lower correlations and recycling of the previous month precipitation via local evaporation.

The dependence of precipitation on that of the previous month in simulations helps to clarify the discussion of the previous section. The auto-correlation of the GPP indices simulated by GFDL-CM2.1 (dashed dark green line) and CCSM3 (dashed red line) have a broader spike than that of the observed index. It is not clear why the spike from the GFDL-CM2.1 index is broader than that from the CCSM3 index when mean evaporation is larger in the latter; correlations are at least 0.3 on both sides of the maximum in July. The auto-correlation of the GPP indices simulated by GISS-EH (dashed blue line), and MIROC3.2(hires) (yellow-green line) have narrower spikes than that from the observed index; correlations are around -0.1 on both sides of the maximum in July. Finally, the auto-correlation of the GPP indices simulated by UKMO-HadCM3 (purple line) and PCM (orange line) have comparable spikes to the spike from the observed index, even though PCM has low mean evaporation.

7. Concluding remarks

The present study has sought to ascertain the structure of warm-season hydroclimate variability over the US Great Plains and the extent to which the observed variability features are represented in the state-of-the-art climate simulations of the 20th century. The focus is on the analysis of interannual variability where models are more challenged, however, attention is briefly focused on the simulated annual cycle of precipitation too.
The analysis is largely based on, and driven by, previous research from the authors warm-season hydroclimate variability studies over North America in AMIP simulations and observations at seasonal and interannual time scales. Curiosity arises because the difficulties that state-of-the-art atmospheric GCMs show in capturing the annual cycle of precipitation (Nigam and Ruiz-Barradas, 2005), and the relative contributions by moisture fluxes and evaporation to the generation of precipitation variability over the Great Plains (Ruiz-Barradas and Nigam, 2005a, b).

There is a big interest in identifying those potential problems in fully coupled GCMs over the season and region because a confidence or reliability issue of the simulations for future climate change scenarios. In the current study four American models from NCAR (CCSM3, PCM), NOAA (GFDL-CM2.1), and NASA (GISS-EH), a British model (UKMO-HadCM3), and a Japanese model (MIROC3.2(hires)) are analyzed in the context of Great Plains hydroclimate variability during the warm-season (June-August). Comparisons are made against NCEP’s North American Regional Reanalysis, and the US-Mexico analyzed precipitation data set.

The annual cycle of precipitation, and mean annual precipitation present a surprising challenge to the models (considering that model tuning is usually made with the observed annual cycle).

- Climatological winter precipitation is reasonably well simulated over the US northwest. Models simulate reasonably well the annual cycle over northwestern US and its mean annual precipitation while they fail to capture the weak annual cycle over southeastern US and its mean annual precipitation; precipitation in those regions peaks during middle and late winter respectively.

- Climatological summer precipitation is more demanding. Models have problems capturing both mean precipitation and its annual cycle over central US and Mexico which peaks in summer. Models like CCSM3, GFDL-CM2.1, and PCM have the annual cycle in central US and Mexico markedly ahead of time. In general, UKMO-HadCM3 is closer to observations than the others but it is not perfect, especially in regards of the features over southeastern US where the annual cycle
is a bit stronger than observations indicate.

Interannual variability of precipitation and its links to the atmospheric water-balance components are centered around the Great Plains precipitation index. The index is objectively constructed on the basis of the standard deviation distribution of monthly precipitation in the warm-season months. This maximum in standard deviation of precipitation in general is displaced southwestward in the simulations with respect to the observed maximum. While the region defining the Great Plains (100°W-90°W, 35°N-45°N), and the GPP index, is based on the position of the maximum of standard deviation in observations, it is shown (in the Appendix) that using the region defined by the maximum in standard deviation of simulated precipitation only strengthens the validity of the results summarized in the following paragraphs.

- Model evolution is problematic. Simulated monthly GPP indices are temporally uncorrelated with the observed monthly GPP index. Smoothing of the indices, to enhance interannual variability, increases only marginally the correlation between observed and simulated smoothed indices, except for the UKMO-HadCM3 model that has a high correlation of 0.54!

- Large precipitation variability is consequence of the occurrence of rare extreme wet and/or dry events (as in GFDL-CM2.1), while reduced precipitation variability is the consequence of the lack of those extreme events and the increased number of small wet and/or dry events (as in PCM).

The relative importance of processes contributing to the generation of interannual variability of precipitation over the Great Plains in the warm-season is compared in observations and simulations. Auto-correlation analysis of the monthly GPP indices and their regressed water-balance components indicate the following hierarchy of processes in the models:

- In models like UKMO-HadCM3 and PCM, moisture flux converging from the Gulf of Mexico

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10 Evaluations of GFDL-CM2.0, GISS-AOM and GISS-ER models indicate that in the first two models the local recycling of evaporation is the main process of precipitation variability, while in the third model convergence of moisture fluxes is the most important and overwhelming process for generating precipitation variability over the Great Plains in the warm-season months.
into the region is more important than local evaporation of preceding precipitation, as in observations. Precipitation variability as well as the structure of anomalies of the water-balance components in the UKMO-HadCM3 model are closer to observations than those in the rest of the models.

- In models like GISS-EH and MIROC3.1(hires) the gap between contributions by moisture flux convergence and local evaporation is increased by means of increasing moisture flux convergence from the Gulf of Mexico, and diminishing (reducing to near zero in GISS-EH) the local recycling of preceding precipitation via evaporation.

- In models like CCSM3 and GFDL-CM2.1, the local recycling of preceding precipitation via evaporation is larger than the convergence of moisture fluxes from remote regions. Those models emphasize more moisture fluxes from the Pacific than from the Gulf of Mexico —not an observed feature.

This study emphasizes the importance of remote water sources (moisture fluxes) over evaporation in the generation of Great Plains precipitation variability during the warm-season months. This is clearly evident in observations represented by the regional reanalysis but only in some global models. It is motivating that not all models are tailored in the same way and that the emphasis on the local recycling of precipitation by evaporation is not wide-spread. An enhanced (neglected) recycling of precipitation implies substantial (reduced) energy going into the regional land surface component of the models. Investigation of this issue is already underway as well as analysis of precipitation variability during the cold-season months, where evaporation plays less of a role and models seem to be doing better (at least over the US northwest). This will improve understanding of the water and energy cycles over the region.

The Hadley Center’s model is the one that better approaches the observed hydroclimate variability over the Great Plains during the warm-season. This model will be used to assess the impact of global climate change scenarios over the region in a soon to start analysis.
Aknowledgements

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Appendix

The region of maximum precipitation variability as defined by observations (Fig. 2a) has been used to study simulated precipitation variability over the very same region in the warm-season months. However, this region is not necessarily the region of maximum precipitation variability in simulations (Fig. 2b-g), which opens the question about the generality of the results. To address this issue, and as an example, the analysis is repeated for the GFDL-CM2.1 model whose westward shift of the region of maximum precipitation variability (as compared with observations) is typical of the simulations. The region of maximum precipitation variability of this model can also be enclosed in a 10° longitude-latitude box (Fig. 2c, dashed box 105°W-95°W, 33°N-43°N), as the original definition of the Great Plains region. The precipitation index is generated from area-averaged precipitation anomalies over this shifted box of maximum precipitation variability during the warm-season months. Then it is regressed on precipitation, moisture fluxes and evaporation anomalies.

The new index does not improve the structure of anomalies associated to the precipitation variability of the region. As expected, the regressed precipitation anomalies (Fig. 9a) are centered over the region of definition of the index and are larger than those with the original GPP index (Fig. 5c). The regressed vertically-integrated moisture flux anomalies and their convergence (Fig. 9b) are also larger than before (Fig. 6c); the artificial link with the Pacific basin via moisture fluxes is even stronger than it was before, and the connection with the Gulf of Mexico is still absent. Evaporation anomalies (Fig. 9c) remain of the same magnitude as before (Fig. 7c). It is also clear that according to this displaced region, maximum anomalies are more centered over the region than they were over the Great Plains region.

The relative importance of the water-balance components over the shifted region does not change or the significance of precipitation recycling via local evaporation. In the mean, area-averaged anomalies are larger than before: mean precipitation increases from 1.13 to 1.28 mm day$^{-1}$, mean moisture flux convergence increases from 0.40 to 0.50 mm day$^{-1}$, and evaporation increases.
from 0.59 to 0.67 mm day$^{-1}$. This picture of a larger control by evaporation on precipitation variability is further corroborated by obtaining the auto-correlation of the shifted index (as it was done before for the GPP index, Fig. 8). Now the dependence of July’s precipitation on previous’ months precipitation is larger than before, with correlations of 0.5 for May, and 0.8 for June.

Thus, it is apparent that focusing on the individual regions of maximum precipitation variability of the different models, in contrast to the region identified by observations, does not change the main results of the present study but further strengthens them.
References

Delworth, T.L. and co-authors, 2004: GFDL’s CM2 global coupled climate models -- Part 1:
Formulation and simulation characteristics. Submitted, J. Climate.

Wood, 2000: The simulation of SST, sea ice extents and ocean heat transports in a version
of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16: 147-
168.

Soc., 77, 437-471.

Combinations of natural and anthropogenic forcings and 20th century climate. J. Climate,
17, 3721-3727.

Mesinger, F, G. DiMego, E. Kalnay, P. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, M. Ek, Y. Fan,
Change and Climate Variations, Combined Preprints CD-ROM, American Meteorological

precipitation assimilation and land surface are two hallmarks. GEWEX News, 14, 9-12.

Nigam, S., and A. Ruiz-Barradas, 2005: Seasonal hydroclimate variability over North America in
ERA-40, Regional Reanalysis and AMIP simulations. Submitted to J. Climate.


Table 1. Monthly JJA Standard Deviation (SD) of the GPP index in the 1951-1998 period.

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<tr>
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<th>US-MEX</th>
<th>CCSM3</th>
<th>GFDL-CM2.1</th>
<th>GISS-EH</th>
<th>PCM</th>
<th>UKMO-HadCM3</th>
<th>MIROC3.2 (hires)</th>
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<td>1.00</td>
<td>1.12</td>
<td>0.72</td>
<td>0.63</td>
<td>0.92</td>
<td>0.78</td>
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Table 2. Correlations among smoothed GPP indices in the 1951-1998 period.

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<th>GFDL-CM2.1</th>
<th>GISS-EH</th>
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Table 3. Area-averaged regressed precipitation (P), vertically-integrated moisture flux convergence (MFC), and evaporation (E) over the Great Plains (100°W-90°W, 35°N-45°N) in mm day⁻¹.

<table>
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<th>MFC</th>
<th>E</th>
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<td>0.14</td>
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<tr>
<td>MIROC3.2 (hires)</td>
<td>0.78</td>
<td>0.66</td>
<td>0.06</td>
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Figure Captions

Figure 1. First harmonic of climatological precipitation and mean annual precipitation in reanalysis and coupled simulations (1979-1998): a) NARR, b) CCSM3, c) GFDL-CM2.1, d) GISS-EH, e) PCM, f) UKMO-HadCM3, and g) MIROC3.2(hires). Vectors represent the first harmonic while background isolines display the mean annual precipitation in mm day$^{-1}$. The insert vectors at the top of the figure indicate the scaling of the magnitude in mm day$^{-1}$ and phase of the annual cycle: vectors pointing to the south indicate a maximum on 1 January, one pointing to the west means a maximum on 1 April, one pointing toward the north indicates a maximum on 1 July, and one pointing to the east means a maximum on 1 October. Only magnitudes of the annual cycle equal or larger than 0.5 mm day$^{-1}$ are displayed. Mean annual precipitation is contoured at the 1, 2, 3, 4, 6, 9 mm day$^{-1}$ isolines. Shading indicates mean annual precipitation equal or larger than 2 mm day$^{-1}$.

Figure 2. Standard deviation of monthly precipitation anomalies during summer (June-August) in reanalysis (1979-1998) and coupled simulations (1951-98): a) NARR, b) CCSM3, c) GFDL-CM2.1, d) GISS-EH, e) PCM, f) UKMO-HadCM3, and g) MIROC3.2(hires). The marked box with continuous lines delineates the Great Plains region defined by the maximum in observed precipitation variability in panel a). The box made of dashed lines in panel c) contours the region of maximum precipitation variability for the GFDL model that is used for a sensitivity analysis. Contour interval is 0.3 mm day$^{-1}$ and values greater than 1.2 mm day$^{-1}$ are shaded.

Figure 3. Histogram of precipitation events over the Great Plains as portrayed by the GPP index from: US-Mexico, blue bars; CCSM3, yellow bar; GFDL-CM2.1, red bar; GISS-EH, light blue bar; PCM, green bar; UKMO-HadCM3, violet bar; MIROC3.2(hires), light pink bar. The x-axis represents the anomalous events by categories of 0.5 mm day$^{-1}$ and the y-axis shows the number of months that a given category of anomalies occurs.

Figure 4. Smoothed Great Plains Precipitation index anomalies during the warm-season (June-August) in observations and coupled simulations: US-Mexico (observed rain-gauge), continuous black line; NARR, dashed black line; CCSM3, red line; GFDL-CM2.1, dark green line; GISS-EH, blue line; PCM, orange line; UKMO-HadCM3, purple line; MIROC3.2(hires), yellow-green line. The smoothed index is obtained from a 1-2-1 averaging of the seasonal-mean anomalies. The monthly, warm-season standard deviation, and correlations among the smoothed precipitation indices are displayed in Table 1.

Figure 5. Warm-season regressions of the Great Plains precipitation index on rainfall from: a) NARR, b) CCSM3, c) GFDL-CM2.1, d) GISS-EH, e) PCM, f) UKMO-HadCM3, and g) MIROC3.2(hires). The index and regressions are from the same monthly JJA data set, in each case. Contour interval is 0.3 mm day$^{-1}$; dark (light) shading denotes areas of positive (negative) rainfall in excess of 0.3 mm day$^{-1}$ magnitude; the zero contour is omitted.
Figure 6. Warm-season regressions of the Great Plains precipitation index on stationary moisture fluxes from: a) NARR, b) CCSM3, c) GFDL-CM2.1, d) GISS-EH, e) PCM, f) UKMO-HadCM3, and g) MIROC3.2(hires); moisture flux convergence is displayed as contours. Moisture fluxes and corresponding flux convergences are vertically integrated (300 hPa - surface). Contour and shading are as in figure 4; positive/negative anomalies represent moisture flux convergence/divergence anomalies.

Figure 7. Warm-season regressions of the Great Plains precipitation index on evaporation from: a) NARR, b) CCSM3, c) GFDL-CM2.1, d) GISS-EH, e) PCM, f) UKMO-HadCM3, and g) MIROC3.2(hires). Contour interval is 0.1 mm day$^{-1}$; dark (light) shading denotes areas of positive (negative) evaporation in excess of 0.1 mm day$^{-1}$ magnitude; the zero contour is omitted.

Figure 8. Correlation between July’s Great Plains precipitation index with preceding and succeeding monthly precipitation from the same index in the 1951-1998 period. Correlations from the retrospective U.S.-Mexico precipitation analysis is shown using filled black circles; CCSM3, open red circles; GFDL-CM2.1, open green squares; GISS-EH, open blue diamond; PCM, orange plus sign; UKMO-HadCM3, purple multiplication sign; MIROC3.2(hires), open yellow-green triangle.

Figure 9. Warm-season regressions of a shifted Great Plains precipitation index on a) precipitation, b) stationary moisture fluxes, and c) evaporation from the GFDL-CM2.1 simulation. This shifted index is defined along the maximum of standard deviation in the GFDL-CM2.1 simulation (fig. 2c, dashed line box), and noted in this figure by the enclosed dashed box. The index is displaced southwestward with respect to the region of maximum observed in NARR (noted here as the continuous line box). As in previous figures precipitation and moisture-flux convergence are contoured with the same 0.3 mm day$^{-1}$ interval, and evaporation with a 0.1 mm day$^{-1}$ interval; dark (light) shading denotes areas of positive (negative) anomalies as in figs. 5-7.
Figure 2
Figure 4
Figure 5
Figure 6
Figure 9