Analysis of Precipitation Projections over the Climate Gradient of the Arkansas Red River Basin

LEI QIAO AND CHRIS B. ZOU
Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, Oklahoma

CARLOS F. GAITÁN
South Central Climate Science Center, and College of Atmospheric and Geographic Sciences, University of Oklahoma, Norman, Oklahoma

YANG HONG
School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma

RENEE A. MCPHERSON
South Central Climate Science Center, and Department of Geography and Environmental Sustainability, University of Oklahoma, Norman, Oklahoma

(Manuscript received 31 May 2016, in final form 16 January 2017)

ABSTRACT

Increases in the frequency and intensity of extreme precipitation are projected for most U.S. regions under climate change. There is a high degree of uncertainty, however, in precipitation regime changes across the large precipitation gradient of the Arkansas Red River basin (ARRB). The authors analyzed future precipitation regimes using two statistical downscaling datasets based on the scenarios from phase 5 of the Coupled Model Intercomparison Project (CMIP5). Seasonal precipitation in low-to-high quantiles was calculated and compared for the southern ARRB where the downscaled data were available. The results showed a generally comparable shift in precipitation patterns and amounts between the two datasets. However, some spatial variation of precipitation amount change exists, and the direction of change could be opposite for the summer. Both datasets showed that the top 10% of monthly precipitation amounts could increase for the southern ARRB, mostly ranging from 5–10 mm month$^{-1}$ for the early part of the century (2010–39) to 15–30 mm month$^{-1}$ for the midcentury (2040–69) as compared with the historical period (1968–97). The maximum monthly precipitation could increase by up to 150 mm in both datasets by the midcentury. Precipitation was projected to increase regardless of quantile during both winter and spring but tended to decrease during summer and autumn. More-frequent and higher-intensity rainfall events were expected for the eastern part of the basin, and longer and drier dry periods were expected for the western basin. Conservation strategies and sustainable water management should consider the regional differences in the projected changes in precipitation regimes for the basin under climate change.

1. Introduction

The Arkansas Red River basin (ARRB) spans from subhumid Arkansas to semiarid and arid lands of eastern New Mexico and Colorado, including all of Oklahoma and small parts of Texas, Kansas, and Missouri. The basin encompasses a climate gradient with annual precipitation from more than 1600 mm (62 in.) in the east to less than 200 mm (8 in.) in the west (Fig. 1). The land cover features extensive rangelands and croplands that spread across the U.S. southern Great Plains, and landscape fragmentation has been increasing because of agricultural activities, energy development, and urban sprawl (Shafer et al. 2014). Growing urban areas inside (e.g., Oklahoma City, Oklahoma) and just outside of the basin (e.g., Dallas–Fort Worth, Texas, to the south) have sought to access surface waters from the ARRB in greater quantities as their populations grow (e.g., https://www.waterunityok.com/media/1075/agreement-160808.pdf; https://www.supremecourt.gov/opinions/12pdf/11-889_5ie6.pdf). Food

DOI: 10.1175/JAMC-D-16-0201.1

© 2017 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
and energy production are the major economic engines for this river basin, and water is critically important for both. In the arid and semiarid region of the western basin, agriculture production relies heavily on continued withdrawals of groundwater (e.g., from the Ogallala Aquifer). With limited natural recharge, these groundwater resources are stressed, and climate change could worsen the problem (Ng et al. 2010; Scanlon et al. 2010a,b). In contrast, floods are common in the humid eastern basin, and the flood frequency and severity could increase under climate change (Min et al. 2011).

Knutson et al. (2014) detected record annual and seasonal precipitation wet anomalies for several U.S. regions, including the southern Great Plains, using data from the Global Historical Climatology Network. Past studies have also documented potential climate change impacts on the hydroecological systems within the basin, but these impacts tended to be geospatially located either in semiarid or subhumid zones (Liu et al. 2012; Qiao et al. 2014b). Because of the high degree of uncertainty in knowing how precipitation regime changes will manifest themselves in the ARRB, it is difficult to select appropriate adaptive management approaches for sustainable water resource management under climate change. A specific study focusing on the spatial and temporal variations of precipitation over the precipitation gradient of the Arkansas Red River basin under climate change is timely.

Under climate change, increased frequency of extreme precipitation events is especially concerning because of their potential to severely impact the natural environment and ecosystem services to society. Many studies have focused on understanding historical precipitation trends and future precipitation changes using a combination of historical observational datasets (Douglas et al. 2000; Groisman et al. 2005; McCabe and Wolock 2002) and global climate model (GCM) output (Qiao et al. 2014c; Kharel and Kirilenko 2015; Rosenberg et al. 2003; Stone et al. 2003; Takle et al. 2010; Wang et al. 2009). Past modeling studies were based primarily on model simulations used in the third phase of the Coupled Model Intercomparison Project (CMIP3). Phase 5 of CMIP (CMIP5) included predominantly higher-resolution output and used more updated GCMs (Taylor et al. 2012). Although projected global trends were generally consistent between the CMIP3 and CMIP5 GCM ensembles, the CMIP5 datasets, with their generally higher resolution, differed from those of CMIP3 in regional details, such as North American storm tracks, precipitation patterns, and the spatiotemporal variability of midsummer drought (Maloney et al. 2014). The CMIP5 ensemble represents an opportunity to improve the understanding of climate change and its impacts on the environment.

Uncertainties generated from climate model simulations greatly complicate interpretation of climate change-related studies. Output from a single climate model could be inherently biased and unrepresentative because of its fundamental structure (e.g., computational techniques, parameterizations); thus, an ensemble of simulations from multiple models should be used for better quantification of variables and their temporal and spatial changes, such as seasonal and annual precipitation trends and variability (Haerter et al. 2015; Maurer and Pierce 2014). Statistical or dynamical downscaling techniques can generate even more uncertainties, though higher-resolution historical and projected meteorological datasets facilitate research on regional and local climate change and impacts (Gaitán et al. 2014; Maurer et al. 2007; Mearns et al. 2015; Wilby and Harris 2006).

To reduce bias in the datasets prior to interpretation and application, bias corrections are usually carried out using quantile mapping (QM), which matches quantiles of GCM-simulated historical output to the quantiles of observed climate variables during the same time period. Maurer and Pierce (2014) showed that the QM approach was able to modify the precipitation change/trend simulated by a single GCM; however, there was no effect of the QM method on the trend of the ensemble mean of precipitation from many GCMs (i.e., biases tended to cancel one another). Qiao et al. (2014c) used a QM bias correction technique to improve the hydrological performance of daily climate variables from the dynamically downscaled dataset of the North American Regional Climate Change Assessment Program (NARCCAP). They also compared the bias corrected and the original NARCCAP projections and showed that there was good consistency in shifts in
precipitation intensity and frequency for the lower Missouri River basin. However, recent studies have identified that QM approaches could cause a serious trend deviation from the original GCM simulations. For example, Cannon et al. (2015) found that QM methods can enlarge the relative increase in magnitude of extreme precipitation projected by GCMs as compared with the raw projections. Hence, there is a need to investigate the differences among downscaled future projections from different sources and to understand the potential implications for climate change impacts.

Two sources of downscaled datasets for the southern portion of the ARRB allow us to assess and document any differences and their implications. The bias corrected and spatially disaggregated (BCSD) dataset generated from CMIP5 (BCSD-CMIP5) has $\frac{1}{5}^\circ$ resolution and resulted from the studies of Maurer et al. (2007), Maurer and Pierce (2014), and Wood et al. (2004). This dataset has been widely used for water-related problems in the western and central parts of the United States (Ayers et al. 2016; Das et al. 2013; Venkataraman et al. 2016). In 2015, the South Central Climate Science Center (SCCSC) statistically downscaled projections (SCCSC-CMIP5) for the Red River basin (Gaitán 2016e) to aid water managers within the basin in developing long-term (e.g., 50 yr) water plans. This latter dataset contains downscaled time series of daily maximum and minimum temperature as well as daily precipitation at $\frac{1}{10}^\circ$ resolution over the entire basin for the 1961–2005 (historical) and 2006–99 (future) periods. To broadly explore uncertainties in high-resolution climate projections, the SCCSC-CMIP5 datasets were generated using three statistical downscaling methods, three global climate models, and three representative concentration pathways (RCPs).

The objective of this study is to improve our understanding of the spatial and temporal variations of precipitation across the climate gradient of the ARRB under climate change. We will use the two most recent statistical downscaling datasets BCSD-CMIP5 and SCCSC-CMIP5; the former is available for the entire basin, and the latter is available for the Red River basin, the southernmost part of the ARRB (Fig. 1). While our study scope is the whole ARRB, the direct comparison between datasets will focus on the southern ARRB because of limited data availability. We will quantify the precipitation changes from the historical period to the early twenty-first century, and then to the middle twenty-first century, by examining changes in quantiles and extremes for seasonal and monthly precipitation amounts. We will evaluate and compare precipitation projections from the BCSD-CMIP5 and SCCSC-CMIP5, with particular attention to heavy precipitation amounts across the precipitation gradient of the ARRB, and then discuss the potential impacts for the river basin on water resources and natural hazards related to the precipitation changes.

2. Dataset and methods

BCSD-CMIP5 provided a multimodel ensemble that included 39 of the models that contributed to CMIP5. The datasets were freely downloaded from the Internet (http://gdodcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html). Table 1 details the names and organizations of the climate models used in BCSD-CMIP5.

We used monthly precipitation projections from all 39 BCSD-CMIP5 ensemble members that were driven by the moderate representative concentration pathway 4.5 (RCP4.5) whereby anthropogenic radiative forcing stabilizes at 4.5 W m$^{-2}$ around 2050 and then remains fixed through 2100. The BCSD downscaling approach employed a nonparametric QM to reduce the monthly precipitation bias in historical simulations as compared with a similarly gridded, historical observational 51-yr (1950–2000) dataset (Maurer et al. 2002). That means there was no theoretical probability density fit (PDF) to the precipitation cumulative density functions (CDFs). The CDFs were constructed for all 12 months for both GCM and observation datasets, then the quantiles of GCM CDFs were matched to those of the observations. Maurer et al. (2007) and Maurer and Pierce (2014) detailed the BCSD-CMIP5 downscaling methods. For direct comparison, the RCP4.5 emission scenario was also selected from the SCCSC-CMIP5 datasets. This recently developed dataset only overlaps the BCSD-CMIP5 in the southern part of the ARRB, over the Red River basin. However, the overlapping area extends across a similar wet-to-dry precipitation gradient, providing an intercomparison opportunity between the two different datasets (Fig. 1). The SCCSC-CMIP5 datasets were downscaled from only three GCMs: MPI-ESM-LR (Giorgetta et al. 2013), MIROC5 (Watanabe et al. 2010), and CCSM4 (Gent et al. 2011). These GCMs were selected based on the historical performance evaluation over the region by Sheffield et al. (2013) and are also included in the BCSD-CMIP5 dataset. In contrast to the BCSD-CMIP5 dataset, however, the SCCSC-CMIP5 datasets employed three different downscaling approaches to test the sensitivity of the projections to the QM methods: cumulative density function transform (Michelangeli et al. 2009), equi-distant quantile mapping (Li et al. 2010), and bias correction quantile mapping (Ho et al. 2012). The collection of downscaled daily precipitation, daily maximum and minimum temperatures for the Red River basin (Gaitán 2016e), and the observations used to train the models (Gaitán 2016a) can be freely downloaded from the Internet (http://dx.doi.org/10.15763/dbs.sccsc.rr). In particular, the CCSM4 downscaled
projections (Gaitán 2016b), the MPI-ESM-LR downcaled projections (Gaitán 2016d), and the MIROC5 downscaled projections (Gaitán 2016c) include historical (1961–2005) and future (2006–99) outputs generated using the abovementioned downscaling methods.

For this study, we compared the 39 projections in BCSD-CMIP5 and the 9 projections (three GCM models downcaled by three methods) in SCCSC-CMIP5 for precipitation changes in different quantiles of CDFs for each season. We used climatological seasons, with winter defined as December–February (DJF), spring as March–May (MAM), summer as June–August (JJA), and autumn as September–November (SON). We then tested the significance of the changes using a two-tailed $t$ test at 95% confidence level.

### 3. Results

Both datasets generally showed that the frequency of months with precipitation between 40 and 100 mm...
decreased for the early twenty-first century (2010–39) and the middle twenty-first century (2040–69) over the southern ARRB (Fig. 2) as compared with the historical period. The tails of monthly precipitation distribution (i.e., either >100 or <40 mm) tended to increase. The frequency of months with precipitation greater than 220 mm month$^{-1}$ was projected to double from the historical period to the early twenty-first century in both datasets and becomes much higher in the middle twenty-first century in the BCSD-CMIP5 datasets. For the historical observations, monthly precipitation was mostly frequently 20–40 mm in BCSD-CMIP5 but 40–60 mm in SCCSC-CMIP5. As seen in Fig. 2 (top panel), there was no monthly precipitation amount greater than 280 mm in the BCSD-CMIP5 historical period. As a whole, BCSD-CMIP5 had lower monthly precipitation amounts as compared with SCCSC-CMIP5.

Mean seasonal precipitation increased for winter and spring for both future time periods over the southern ARRB in both datasets (Fig. 3), with small or negligible changes in lower quantiles (Fig. 4). On average, the precipitation amount in the top 10% quantile for these two seasons increased by 5–10 mm month$^{-1}$ in the early twenty-first century and 15–30 mm month$^{-1}$ by the mid-twenty-first century. For summer and autumn, the BCSD-CMIP5 dataset showed that the precipitation amounts in the quantiles below 80% mostly decreased for two future time periods, ranging from 5 to 10 mm month$^{-1}$, while the precipitation amounts in the top 10% quantile substantially increased. SCCSC-CMIP5 showed a similar trend for autumn but not for summer. For summer, SCCSC-CMIP5 precipitation amounts generally increased from the historical periods for all quantiles during the early twenty-first century, while there was no apparent trend by the mid-twenty-first century. Except for summer, the trends (magnitude and direction) of precipitation change were similar between the two ensemble datasets. Different from the seasonal changes in mean total precipitation, shown in Fig. 3, the seasonal changes in different quantiles (Fig. 4) were typically statistically significant in both datasets, especially for the extreme high and the extreme low quantiles.
Figure 5 displays the spatial variations of seasonal changes of mean monthly precipitation for the early twenty-first century from both datasets. In BCSD-CMIP5, the mean monthly precipitation increased for winter and spring and was more prominent across the eastern basin (up to 8 mm month$^{-1}$ higher than the historical period). Mean monthly precipitation decreased for almost the entire basin during summer, with a maximum decrease of 5 mm month$^{-1}$ in the north-central basin and a distinct band of decreased precipitation largely coinciding with the arid western basin. Relatively, the smallest changes in magnitude and spatial variations of precipitation occurred during the autumn. The SCCSC-CMIP5 dataset, only available for the southern ARRB, provided quite different deviations from the historical mean, both in magnitude and spatial pattern from those in BCSD-CMIP5. Spring and summer displayed a relatively uniform increase (around 5 mm month$^{-1}$ on average) in mean monthly precipitation across the precipitation gradient of the Red River basin. In contrast to the BCSD-CMIP5, SCCSC-CMIP5 showed substantial reduction (up to 10 mm month$^{-1}$) in precipitation across the humid east while considerable increases were projected in the arid west for winter and autumn.

Figure 6 shows the spatial patterns of projected changes for the early twenty-first century in mean seasonal precipitation for the highest 10% quantile from both datasets. The BCSD-CMIP5 projections showed the increases in extreme high-precipitation values for all seasons, with larger increases (15 mm month$^{-1}$) across the humid east and lower increases of 2–5 mm month$^{-1}$ (or slight decrease) across the arid west. The SCCSC-CMIP5 projections for the early twenty-first century exhibited more spatial variations and generally larger magnitude changes of the extreme high precipitation than did BCSD-CMIP5 across the precipitation gradient. A relatively uniform increase of $\sim$16 mm month$^{-1}$, though up to 50 mm month$^{-1}$ in the west, was projected across the precipitation gradient for spring. The maximum projected increase occurred near 97°W longitude for summer. For winter and autumn, an approximate doubling of the extreme high precipitation was projected across the western part of the basin, while a moderate reduction was projected in the humid east.

4. Discussion

a. Precipitation projection uncertainties of BCSD-CMIP5 and SCCSC-CMIP5

There are several sources of uncertainty that affect the climate projections. GCM uncertainty is the most important component for climate projections of multiple decades ahead (Hawkins and Sutton 2011), caused
by our incomplete understanding of the Earth system and its interactions and the different approximations used to represent relevant subgrid processes, like convective precipitation. Another major source of uncertainty is derived from the type of downscaling method used, as there are dynamical and statistical methods that could potentially be used to refine the GCM outputs.

In this study, both SCCS-CMIP5 and BCSD-CMIP5 datasets were obtained using statistical downscaling
methods. Furthermore, both datasets used quantile mapping–based approaches to bias correct the GCM output. Moreover, both statistically downscaled products (SCCSC-CMIP5 and BCSD-CMIP5) used National Land Data Assimilation Systems (NLDAS)-derived gridded observation-based datasets as historical period benchmarks. Specifically, BCSD-CMIP5 used the original 1/8° product as observational reference, and SCCSC-CMIP5 used a 1/10° product derived from the 1/8° observation-based dataset by Livneh et al. (2013). All of the abovementioned products are derived from NLDAS data. Therefore, we suggest the potential users

FIG. 6. As in Fig. 5, but for the top 10% quantiles.
of these datasets to include the effect of collinearity in their assessments and to not consider them as strictly independent data products.

The 1/8 product, however, is considered to be a refinement of the original 1/8 observation-based product used to produce the BCSD-CMIP5 projections. It contains significant modifications and postprocessing steps not included in the original 1/8 product, and these modifications could explain in part the differences in the historical period between the datasets. As seen in the PDFs of Fig. 2, the historical monthly precipitation in BCSD-CMIP5 had a skewed distribution toward drier values as compared with the SCCSC-CMIP5. The use of two different spatial scales (1/10 and 1/8) also would account for more differences, as coarser datasets typically are less variable than the finer datasets (Chen and Knutson 2008). Other discrepancies can be accounted for by the temporal scale used in the downscaling (monthly vs daily data aggregation) and by the differences in the bias correction steps used by the different downscaling methods.

Finally, we note that the number of ensemble members used by each product differs considerably, with BCSD-CMIP5 using 10 times more members than the SCCSC-CMIP5. This discrepancy alone creates differences in the mean and variance between the two datasets, as ensemble statistics tend to stabilize with an increased number of ensemble members. Therefore, one expects to see some differences in the precipitation projections, especially when comparing details of magnitude and spatial patterns for different seasons between the two datasets. The direction of area-mean precipitation change was projected to be opposite for summer during 2010–39 between the two datasets (Fig. 3), and spatial differences of the seasonal mean and extreme precipitation change exist during autumn and winter (Figs. 5 and 6).

b. Implications of the precipitation changes on water resources and natural hazards

Intense rainfall events associated with severe thunderstorms, mesoscale convective systems, stationary fronts, and landfalling tropical cyclones are natural elements of the climate of the south-central United States (e.g., Boone et al. 2012; Arndt et al. 2009). With higher water vapor capacity in a warming troposphere, it is expected that more precipitation could be produced. Increases in precipitation intensity have been observed to occur in the subhumid to semiarid climates of the south-central United States (Knapp et al. 2008). More rainfall at higher intensities can cause higher peaks in surface runoff and larger floods (Min et al. 2011; Wentz et al. 2007). In fact, Min et al. (2011) pointed out that climate change has intensified extremely high precipitation events over a large part of the Northern Hemispheric landmasses, including the ARRB. Their study also suggested that the future extreme high precipitation events could be strengthened more than climate models have projected since the historical extremes have tended to be underestimated in the models. Janssen et al. (2016) showed a shift in the seasonality of extreme precipitation events for this region, shifting from summer to spring in CMIP5 scenarios. Our analysis of both BCSD-CMIP5 and SCCSC-CMIP5 datasets showed that these high-precipitation events could become more intense in nearly every season, especially for spring. When precipitation increases in the higher quantiles, the potential for flooding is even greater. Spatial patterns of precipitation change in both datasets indicated a further increase of extreme high-precipitation events and associated higher flooding potential in the humid eastern part of the basin during spring and summer. In the recent past, damaging floods have impacted this region with record streamflow. For example, during 26–30 June 2007, almost one week of heavy rainfall (more than 180 mm day$^{-1}$) occurred in northeast Oklahoma, setting records of streamflow in the Verdigris River basin. During this event, river water breached levees and caused nearly 40 million U.S. dollars in damages throughout the floodplain (Qiao et al. 2014). Even in the semiarid region, extreme rainfall could cause flood hazards. On 19 August 2007, Tropical Storm Erin reintensified as it crossed the Washita River basin (Arndt et al. 2009), producing 187 mm of rainfall in three hours, followed by substantial flooding with the loss of five lives and extensive property damage (Gourley et al. 2010). The SCCSC-CMIP5 datasets essentially showed an approximate doubling of extreme high precipitation across the semiarid and arid western basin during autumn and winter. Although floods are less frequent in this area as compared with the humid/subhumid east, a doubling of the extreme high-precipitation amount would increase flash flooding risks in the arid–semiarid parts of the basin.

Despite increases in precipitation intensity and amount, decreases in the frequency of precipitation days have been observed in this region, resulting in fewer but more intense rainfall events intervened by longer dry spells (Knapp et al. 2008). In the far western area of the basin, limited amount of precipitation falls (i.e., less than 50 mm month$^{-1}$ during summer and less than 10 mm month$^{-1}$ during winter, autumn, and spring). The amount of precipitation represented in the lowest 50% of the quantiles could become even smaller and mostly occur in the seasons of summer and autumn (Figs. 3 and 4), when potential evapotranspiration is the
highest. Even though the projections from the two datasets showed some differences spatially, the greatest decrease in mean monthly precipitation was projected to be located in the semiarid to arid parts of the basin during summer (Fig. 5). Precipitation decreases together with substantial warming of the surface air could produce increasing evaporative demand during the summer growing season (Ruiz Castillo and Gaitán Osipina 2016). The western part of the ARRB is one of the most important crop production regions in the United States. It is very important for water resource managers and agriculture crop producers to consider the projected precipitation change in general, and seasonal changes in particular, to adjust the land-use pattern and implement conservation strategies in order to sustain the socio-economic and ecological fabric of the region.

5. Conclusions

The Arkansas Red River basin, spanning across subhumid, semiarid, and arid climates in the south-central United States, is very sensitive to climate change. Precipitation extremes and associated hazards (such as floods and droughts) are especially concerning under climate change because they can severely impact ecosystems and related services, affecting human society.

Our analysis of two statistically downscaled datasets (following RCP 4.5) revealed that the extreme high precipitation (the top 10% monthly precipitation amounts) could increase during winter and spring seasons, and the magnitude of the increase could be enhanced for the mid-twenty-first century (2040–69) as compared with the early twenty-first century (2010–39). The BCSD-CMIP5 dataset projected higher maximum monthly precipitation values than did the SCCSC-CMIP5 dataset. During summer and autumn, precipitation generally decreased in most quantiles except the top 10%. Both datasets showed comparable precipitation shifts in total precipitation amount for the whole basin in general; however, the datasets displayed different spatial patterns of change. Special attention should be paid to and additional research should be conducted on the projection of precipitation change during the summer for the early twenty-first century, as the SCCSC-CMIP5 data suggested a basinwide increase while the BCSD-CMIP5 data suggested a moderate but basinwide decrease in precipitation amount.

Overall, the results showed that precipitation could increase greatly in spring, coincident with the flooding season in the eastern subhumid basin, thus potentially increasing flooding risk in this part of the basin. The results also show a decrease in precipitation during summer coincident with the dry seasons in the western dry basin. With this pattern of precipitation change, drought would likely occur more frequently and more intensely. Regional conservation strategies and sustainable water resource systems should be developed and enhanced for different parts of the Arkansas Red River basin to adapt to projected changes in precipitation regimes under a changing climate.

Acknowledgments. This study is supported by the National Science Foundation under Grant OIA-1301789 and Grant DEB-1413900. Dr. Lei Qiao is a South-Central Climate Science Center postdoctoral research fellow supported by the U.S. Geological Survey (USGS) through Grant G12AC00002 and by the Oklahoma Agricultural Experiment Station. Funding for Dr. Gaitán was provided by the USGS through Grant G13AC00386 and the College of Atmospheric and Geographic Sciences at the University of Oklahoma. Support for Dr. Gaitán’s workspace and computational environment were provided by NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL). We thank the three anonymous reviewers for their careful review and constructive comments, which helped us greatly in improving the manuscript.

REFERENCES


