US National Oceanic and Atmospheric Administration
Climate Test Bed Joint Seminar Series
NCEP, Camp Springs, Maryland, 19 March 2012

Can a Regional Climate Model Improve the Ability to Forecast the North American Monsoon?

Christopher L. Castro

Department of Atmospheric Sciences, University of Arizona, Tucson, Arizona

1. Introduction

Official seasonal forecasts for the U.S. are issued by the National Center for Environmental Prediction (NCEP), Climate Prediction Center (CPC) within NOAA. These seasonal forecasts are important for natural resource decision making within the United States. Skillful cool season seasonal forecasts are possible because atmospheric teleconnection responses associated with ENSO (El Niño Southern Oscillation) can be resolved by global seasonal forecast models (Livezey and Timofeyeva 2008) and are present as statistically robust features in observational data. Producing skillful operational seasonal forecasts for the warm season, including the North American monsoon system (NAMS), however, has been more challenging.

Can the operational modeling component in the CPC seasonal forecasts be potentially improved to provide better NAMS seasonal outlooks? A CFS reforecast product (1981-2004) has been recently created, with the primary intent to assess the characteristic behavior and biases in the modeling system (Saha *et al.* 2006). The CFS represents large-scale circulation anomaly patterns well in the winter (*e.g.* in 200-mb or 500-mb geopotential height), as these are tied to remote Pacific SST forcing. Therefore, it has demonstrable skill in forecasting precipitation for the cool season which increases when a greater number of ensemble members are used in the forecast. However, the NAMS in CFS is not represented as a salient climatological feature, in terms of a dramatic increase in rainfall in late summer, and this still true even at T126 resolution (Yang *et al.* 2009). Schemm *et al.* (2009) demonstrated that an experimental version of the CFS model at T382 resolution, with 5 ensemble members initialized in late spring for the period 1982-2000, improves NAMS climatology and interannual variability To represent the NAMS in a dynamic modeling system, two requisite conditions must be reasonably satisfied. First, the mesoscale-physical processes that lead to precipitation must be present in the model simulation to some degree. Second, the model should reasonably represent the climatology and interannual variability of the large-scale (or synoptic scale) circulation during the warm season. This study evaluates the use of the Weather Research and Forecasting (WRF) model to dynamically downscale CFS reforecast data for the period 1982-2000. The primary objective is to demonstrate potential for an improved seasonal forecast capability of the NAMS during the warm season, addressing one of the major scientific objectives of North American Monsoon Experiment (NAME, Higgins *et al.* 2006; Higgins and Gochis 2007).

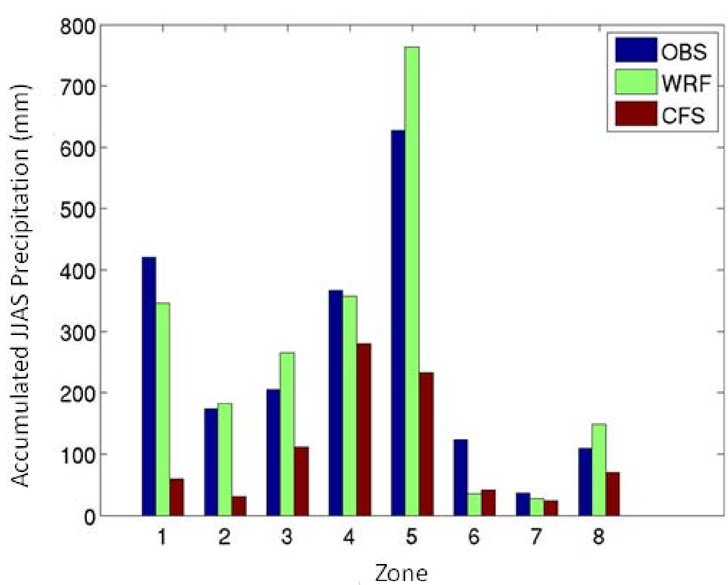

Figure 1 Average annual warm season (JJAS) accumulated precipitation (mm) in the NAME precipitation zones for the period 1982-2000, considering CPC observed precipitation (blue), CFS GCM model (dark red) and WRF dynamically downscaled CFS ensemble members (light green).

2. Data and methods

The regional climate model (RCM) that used is the Advanced Research version of the

Correspondence to: Christopher L. Castro, Department of Atmospheric Sciences, University of Arizona, Tucson, Arizona; E-mail: castro@atmo.arizona.edu

Weather Research and Forecasting (WRF) Model, (ARW Version 3.1) (Skamarock *et al.* 2005). The specific model physical parameterizations used are consistent with those of the existing WRF NWP system at the University of Arizona that produces quasi-operational forecasts for Arizona during the summer at grid spacing of 1.8 km. RCM simulations are performed for a single grid, contiguous U.S.-Mexico domain at 35 km grid spacing, with spectral nudging to maintain the variability of large-scale circulation features from the driving global model (*e.g.* von Storch *et al.* 2000; Miguez-Macho *et al.* 2005; Rockel *et al.* 2008). Two types of data are dynamically downscaled. The first is CFS nine model ensemble members from the reforecast (Saha *et al.* 2006), initialized in the prior spring months from March through May. In this study, the base period of 1982-2000 is used to establish a WRF-CFS RCM climatology and evaluate performance of the modeling system. Initial WRF model soil moisture is specified from the North American Regional Reanalysis (NARR, Mesinger et al. 2006). The WRF-CFS simulations are compared with equivalent Type 2 dynamical downscaling using the NCEP-NCAR Reanalysis as boundary forcing (WRF-NCEP).

Regional model simulation results were compared with several different observational proxy data: NCEP-NCAR global reanalysis, a newly developed precipitation dataset developed at NOAA by Drs. Russ Vose and Ed Cook (P-NOAA), and temperature data from the University of Delaware dataset. To compute anomaly correlations, both model simulated and proxy observed temperature and precipitation have been normalized at each grid point on their respective grids. The normalization of temperature simply considers a normal distribution for a defined time period. Precipitation anomalies are defined using the standardized precipitation index (SPI). Dominant modes of SPI variability are determined using rotated EOF (REOF) analysis and these are linearly regressed on large-scale atmospheric circulation anomalies and global sea surface temperature anomalies. A Pearson correlation of the observed and model-simulated precipitation and surface temperature anomalies is considered for early summer (JJ) and late summer (AS) periods for the entire regional model domain of the contiguous U.S. and Mexico.

3. Analysis of Results

a. RCM climatology

Before considering seasonal forecast performance of CFS vs. WRF-CFS, it is necessary to establish that the seasonal forecast RCM simulations add value in terms of representing the climatology of the NAMS. Both reanalysis and CFS show a well-defined monsoon ridge that develops in June in northern Mexico, advances north and westward toward the Southwest U.S. in July and August, and then retreats back into Mexico by September (not shown). Though the CFS model gives a good representation of the climatology of the large-scale circulation, it has a poor representation NAMS rainfall. The annual warm season (JJAS) average precipitation for the NAME precipitation zones is shown in Fig. 1. CFS consistently underestimates NAMS precipitation overall, but it is especially the

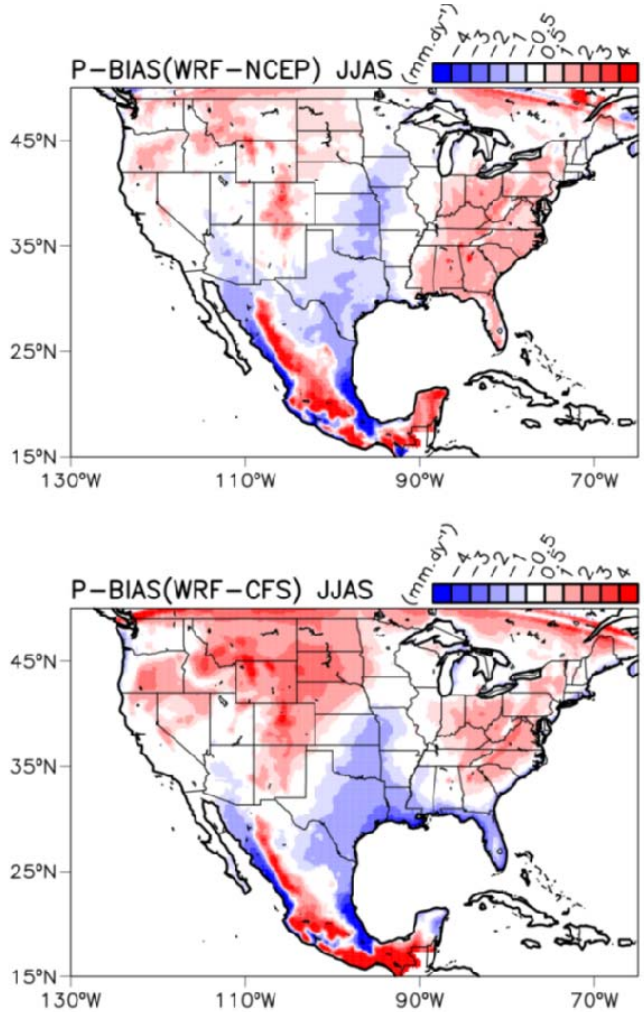

Figure 2 Average warm season (JJAS) precipitation bias (mm day^{-1}) for WRF-NCEP (top) and WRF-CFS (bottom) [P-BIAS=RCM minus P-NOAA observation]. Red (blue) colors indicate precipitation overestimation (underestimation) by WRF.

case in the zones 1 and 2, as the CFS precipitation is about 10-20% of the actual total in Sonora and Arizona. WRF is also able to capture the rapid increase in precipitation that occurs during monsoon onset (not shown). Fig. 2 shows the RCM-simulated climatological precipitation bias for WRF-NCEP and WRF-CFS, considering P-NOAA observations. WRF dynamical downscaling overestimates precipitation directly over complex terrain, such as the Rocky Mountains or Sierra Madres. Precipitation is underestimated in zones where more organized, propagating convection accounts for the majority of warm season rainfall, such as west of the Sierra Madres or east of the Rockies in the southern Great Plains. The regional model produces a better climatology of warm season precipitation primarily because of a better representation of the diurnal cycle of convection.

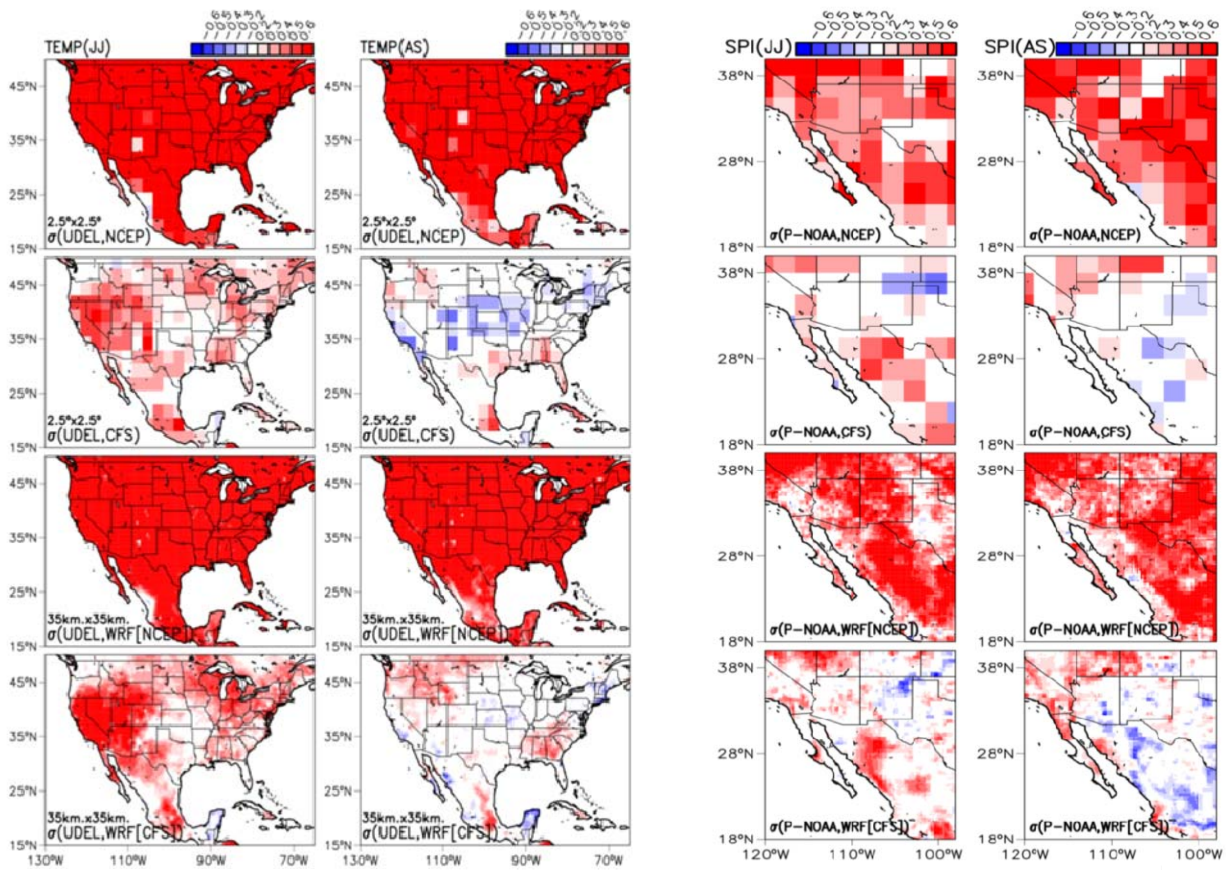

Figure 3 Left panel: Anomaly correlation (σ) of normalized temperature for early summer (JJ) and late summer (AS). Normalized observed UDEL temperature anomalies correlated with those from corresponding NCEP-NCAR Reanalysis (top panel), CFS model (upper middle panel), WRF-NCEP (lower middle panel), and WRF-CFS (bottom panel). The magnitude of anomaly correlation is indicated by the color bar. Results shown at native model resolution indicated on the plots. Right panel: Same for two month SPI for early and late summer, for the NAME Tier 2 region. Observed SPI derived from P-NOAA data.

b. Anomaly correlations for precipitation and temperature: early vs. late warm season

The anomaly correlations are considered for the early part (JJ) and late part (AS) of the warm season, as it is known a priori that precipitation variability behaves very differently with respect to Pacific SST forcing as the summer progresses. The surface temperature anomaly correlation for the NCEP reanalysis and WRF-NCEP shown in Fig. 3 (left panels), not surprisingly, is high (above 0.6) nearly everywhere in the model domain throughout the warm season, except in central Mexico probably owing to uncertainties in the UDEL dataset with elevation. Considering CFS in JJ (upper middle panel on left), the highest surface temperature anomaly correlation generally occurs in the Southwest. The RCM tends to improve the temperature anomaly correlation in those locations where it is already positive in the global model (bottom panels. During AS, the temperature anomaly correlation is generally much lower everywhere in CFS, and even negative in the central U.S. Notably, the strong anomaly correlation present earlier in the Southwest vanishes. Though the AS RCM temperature anomaly correlation is also worse than for the corresponding JJ, it is still improved from CFS, especially in the Pacific Northwest and southeast.

The precipitation (two-month SPI) anomaly correlation for early vs. late summer is also considered in Fig.3 (right panels) for approximately the NAME Tier 2 region covering the Southwest U.S. and northwest Mexico. The highest relative precipitation anomaly correlation in the WRF-NCEP simulations occurs on the crest of the mountains, such as the Mogollon Rim in Arizona (in range of 0.2 to 0.4) and Sierra Madre Occidental in northwest Mexico (greater than 0.6). The precipitation anomaly correlation then decreases rapidly in the lowland desert regions toward the Colorado River Valley and Gulf of California. The spatial differences in the precipitation anomaly correlation in the WRF-NCEP simulations have a very important implication for higher orders of dynamical downscaling like seasonal forecasting. Even downscaling "perfect" observations from an atmospheric reanalysis, the RCM at 35 km grid spacing is still very challenged to represent the interannual variability of organized, propagating convection that causes the majority of monsoon precipitation away from complex terrain. Comparing the SPI anomaly correlation for CFS vs. WRF-CFS, like for temperature, the RCM tends to slightly increase the anomaly correlation where it is already of positive sign in the CFS model. In AS, the positive precipitation anomaly correlation in the NAMS Tier 2 region quickly deteriorates from JJ, and even becomes negative at some grid points in the RCM domain, reflecting the large difference in potential NAMS predictability from the early to late part of the warm season.

c. Interannual variability in relation to Pacific-SST associated teleconnections

Given the time varying influence of Pacific SST forcing on summer precipitation, the 500-mb height anomaly correlation between CFS and the NCEP-NCAR Reanalysis (Fig. 4) not surprisingly shows a rapid decrease in the ability of CFS to represent the observed large-scale circulation from early to late part of the warm season in the U.S., with the highest anomaly correlation in the United States occurring in the far western U.S. in JJ, near 0.4. As ENSO and Pacific Decadal Variability (PDV) is the dominant influence on the continental scale distribution of NAMS precipitation during the early part of the warm season, how is this represented in CFS and WRF-CFS simulated precipitation? Fig. 5 shows the dominant mode of early warm season precipitation (JJ SPI) in WRF-CFS and its relationship with CFS 500-mb height anomalies and global SSTA. We find that the RCM substantially improves the ability to represent the influence of ENSO-PDV variability on early warm season precipitation, as WRF-CFS shows a more well-defined reverse relationship between central U.S. and NAMS precipitation and a stronger relationship to 500-mb height anomalies and Pacific SSTA.

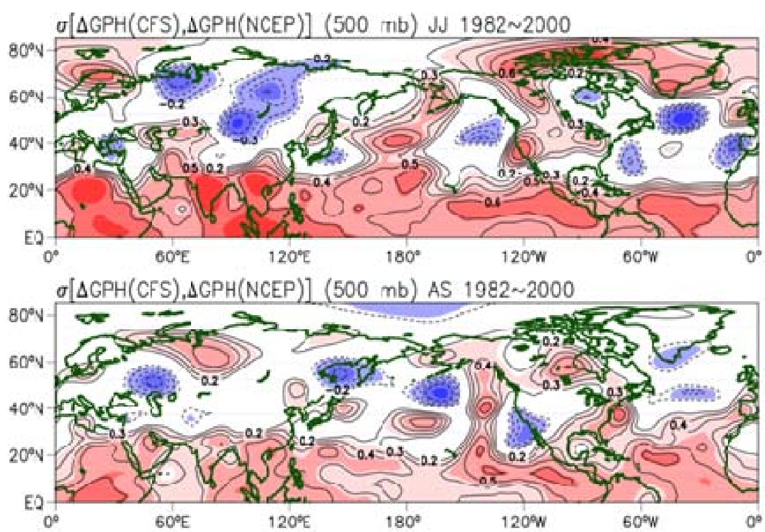

Figure 4 500-mb height anomaly correlations between CFS and the NCEP-NCAR Reanalysis in early (JJ, top) and late (AS, bottom) parts of the summer. Shaded is local significance, and line contour is correlation between CFS and NCEP-NCAR Reanalysis.

4. Concluding remarks

In order to represent the NAMS as a salient climatological feature within a dynamical modeling system, a RCM, or a global model with an equivalent resolution of at least 10s of km, is required. At this resolution, the physical processes related to the development of monsoon thunderstorms can be more realistically represented, particularly the diurnal cycle of convection. However, even downscaling an atmospheric reanalysis, a RCM is still quite challenged to represent the propagating, more organized convection that causes monsoon precipitation at a distance from mountainous terrain. In terms of representing interannual variability of precipitation and temperature anomalies during the warm season, the WRF-CFS simulations tend to slightly increase the anomaly correlation in those geographic areas where it is already positive in CFS but do not significantly change the overall spatial patterns in anomaly correlation. Both CFS and WRF-CFS perform better in forecasting temperature and precipitation in the western U.S. and NAMS region during the early part of the warm season (JJ), owing to the relatively stronger teleconnectivity between Pacific SSTs and the large-scale atmospheric circulation over North America at this time. For geographic locations where Pacific SST variability has a greater influence on monsoon rainfall, as indicated by the spatial loadings of dominant modes of early warm season SPI shown in the previous section, a RCM may potentially add some value for seasonal forecasting. Namely for the core NAMS region, where WRF-CFS correctly represents a dry (wet) monsoon in association with El Niño-like (La Niña-like) conditions in the Pacific, the early warm season SPI correlations do slightly increase from the driving CFS model. As Pacific-SST teleconnectivity to North American climate diminishes in late summer, so too do the precipitation and temperature anomaly correlations over the entire RCM domain, especially in the NAMS region. Realizing the full potential to improve NAMS seasonal forecasts with a dynamical downscaling approach depends both on the driving forecast GCM and RCM. In the case of the North American warm season, the driving forecast GCM must reasonably represent the atmospheric teleconnection responses associated with ENSO-PDV variability, as Pacific SST forcing drives the dominant mode of early warm season precipitation variability in the U.S. We have only highlighted the influence of Pacific SST forcing because it heavily governs CFS predictability in the cool season. We hope this work will be helpful in planning the next phase of the Multi-RCM Ensemble Downscaling (MRED) of Multi-GCM Seasonal Forecast project to consider North American warm season precipitation, further supporting the incorporation of RCMs as a component in NCEP operational seasonal forecasts in the near future.

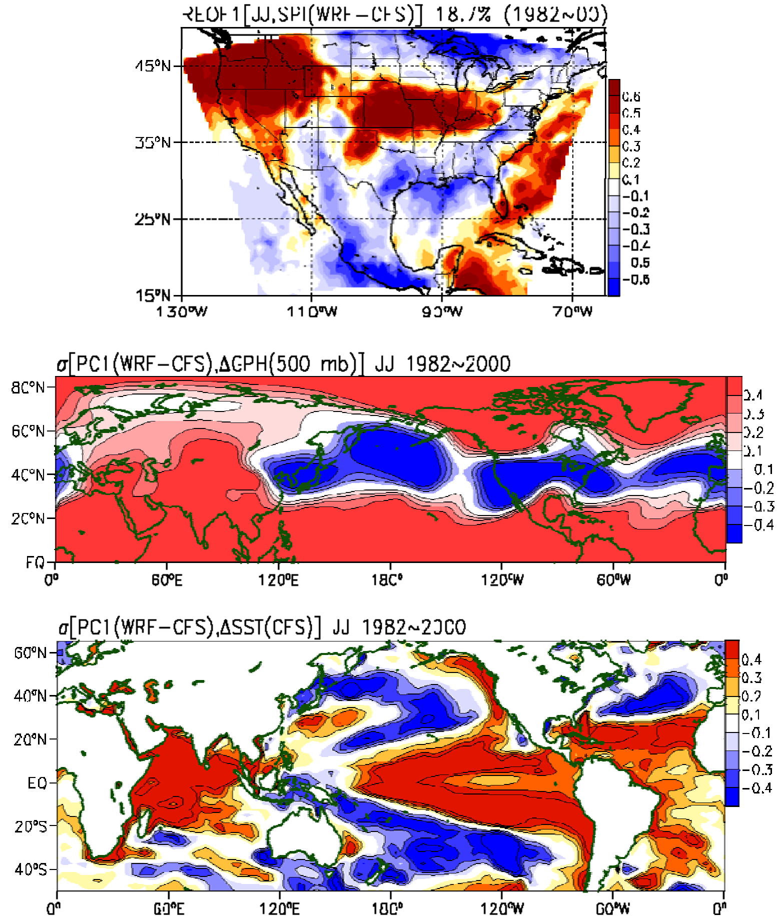

Figure 5 Top: Dominant REOF mode of early warm season (JJ) precipitation (SPI) in WRF-CFS associated with ENSO variability. Middle: corresponding PC correlation on normalized 500-mb geopotential height anomalies from CFS. Bottom: Corresponding PC correlation on CFS SSTA.

Acknowledgements. This work was supported by the National Science Foundation, grant ATM-813656. NCEP collaborators Drs. Jae Kyung-Schemm and Henry Juang are gratefully acknowledged for their contributions to this research. Mr. Matthew Switanek provided assistance in obtaining the CFS model data from NCEP and Drs. Russ Vose and Ed Cook provided access and guidance in the use of the P-NOAA data.

Other observational datasets used in this study were provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA from their website http://www.esrl.noaa.gov/psd.

References

Higgins, R.W., and Coauthors, 2006: The NAME 2004 Field Campaign and Modeling Strategy. *Bull Amer. Meteor. Soc.*, **87**, 79-94.

Higgins, W., and D. Gochis, 2007: Synthesis of Results from the North American Monsoon Experiment (NAME) Process Study. *J. Climate*, **20**, 1601-1607.

Livezey, R.E., and M.M. Timofeyeva, 2008: The First Decade of Long-Lead U.S. Seasonal Forecasts. *Bull. Amer. Meteor. Soc.*, **89**, 843-554.

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.*, **87**, 343-360.

Miguez-Macho, G., G.L. Stenchikov, and A. Robock, 2005: Regional climate simulations over North America: Interaction of local processes with improved large-scale flow. *J. Climate*, **18**, 1227-1246.

Rockel, B., C.L. Castro, R.A. Pielke, Sr., H. von Storch, and G. Leoncini, 2008: Dynamical downscaling: Assessment of model system dependent retained and added variability for two different regional climate models .*J. Geophys. Res.*, **113**, D21107, doi:10.1029/2007JD009461.

Saha, S., and Coauthors, 2006: The NCEP Climate Forecast System. *J. Climate*, **19**, 3483–3517.

Schemm, J-K., R.W. Higgins, L. Long, and W. Shi, 2009: The North American Monsoon Forecast Forum at CPC and Assessment of the NCEP CFS GCM. *5th Symposium on Southwest Hydrometeorology*. Albuquerque, New Mexico, Sep. 30-Oct.1.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF Version 2. *NCAR Tech Notes-468+STR.*

von Storch, H., H. Langenberg and F. Feser, 2000: A spectral nudging technique for dynamical downscaling purposes. *Mon. Wea. Rev.*, **128**, 3664-3673.

Yang, S., Y. Jiang, D. Zheng, R.W. Higgins, Q. Zhang, V.E. Kousky, and M. Wen, 2009: Variations of U.S. Regional Precipitation and Simulations by the NCEP CFS: Focus on the Southwest. *J. Climate*, **22**, 3211-3231.