Improving Seasonal Forecasting Capability of the North American Monsoon System Using the WRF Regional Climate Model

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Retrospective CFS Ensemble Hindcasts

Official U.S. seasonal climate forecasts by the National Oceanic and Atmospheric Administration (NOAA) are issued by the Climate Prediction Center (CPC), a branch of the National Center for Environmental Prediction (NCEP). CPC uses the Climate Forecast System (CFS) global coupled ocean-atmosphere model as the numerical modeling component of these forecasts. Recently, NCEP has produced a comprehensive long-term retrospective hindcast ensemble forecasts for the years 1980-2005, as described in Saha et al. (2006), for climate research purposes. For each hindcast year, an ensemble of approximately 10-15 members is produced, generated by different initializations by NCEP Reanalysis 2 at the beginning of each month.

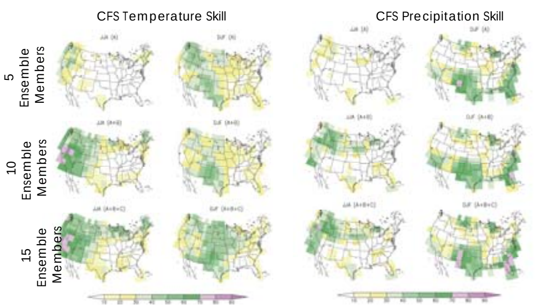

Figure 1: Spatial distribution of retrospective CFS model forecast skill (% anomaly correlation) of the ensemble forecasts of 2-m temperature (left) and precipitation (right) for JJA and DJF. Forecasts made at 1 month lead. The number of ensemble members increases as shown in the panels (From Saha et al. 2006).

The overall strengths and weaknesses of the CFS model are well illustrated by evaluation of retrospective skill for forecasting temperature and precipitation for the winter and summer seasons, as shown in Fig. 1. The CFS model demonstrates an increase in skill when: 1) a greater number of ensembles members are used; 2) an ability to forecast tropical Pacific SSTs and large-scale teleconnection patterns, at least as evaluated for the winter season; and 3) greater skill in forecasting winter than summer climate. Winter climate is largely dependent on synoptic-scale mid-latitude storms. The decrease in CFS skill during the warm season is due to the fact that the physical mechanisms of rainfall at this time are more related to mesoscale processes, such as the diurnal cycle of convection, low-level moisture transport, propagation and organization of convection, and surface moisture recycling. In general, these are poorly represented in global atmospheric models.

Description of WRF and Downscaling of CFS Hindcasts

The Weather Research and Forecasting (WRF) model has been developed as a collaborative effort among numerous research institutions, most notably the Mesoscale and Microscale Meteorology (MMM) Division at the National Center for Atmospheric Research (NCAR) and NOAA NCEP. Similar to other regional atmospheric models, WRF is designed primarily for mesoscale and cloud-scale atmospheric phernomena. The version of WRF we use is the Advanced Research WRF (ARW) developed at NCAR. The ARW solver is fully three dimensional; nonhydrostatic; includes telescoping, interactive grid capabilities; and has schemes for initial and boundary conditions. Model physical parameterizations in this work are consistent with those of the existing WRF numerical weather prediction system at the University of Arizona. Using WRF ARW, Warm season CFS hindcasts for the entire 1980-2005 period are being dynamically downscaled. The hindcasts specifically start at the beginning of May of the given year and last approximately the duration of the warm season (through at least August). Data from NCEP reanalysis 2 is also being dynamically downscaled to assess the performance of the RCM assuming "perfect" boundary forcing. The domain for these simulations covers the contiguous U.S. with a grid spacing of 32 km. Here we focus discussion to preliminary results of dynamically downscaling a single CFS ensemble member and the corresponding global reanalysis for the summer of 1993, which was very anomalous in terms of high rainfall in the central U.S. and a very dry and delayed onset of the monsoon in the Southwest U.S.

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Spectral Nudging in WRF

RCMs loose synoptic scale variabilty from the driving GCM when forced only at its lateral boundaries, affecting mesoscale processes. An alternative approach is spectral nudging, in which selective nudging at only the largest sales takes place throughout the whole domain of the model for prognostic fields like geopotential height, winds, and temperature. The nudging is confined to the upper-levels of the atmosphere above the boundary layer. In this way, the variability of the synoptic scale circulation features may be maintained during the model integration, while allowing the RCM to still add value at the smaller scales. A RCM simulation with spectral nudging is typically more realistic with respect to observations, if global reanalysis data are used as the driving data. For this work, we use the spectral nudging technique in Miguez Macho et al. (2005) recently implemented in the WRF model. Spectral nudging is applied to wavelengths greater than the smallest physically resolved wavelength in the driving model.

Traditional Davies nudging
Only at model lateral boundaries

Model variables
Observations (reanalysis)

$$\frac{dQ}{dt} = L(Q) - K(x,y)\cdot\left(Q - Q_o\right)$$

model operator
Relaxation coefficient

WRF Spectral nudging by G. Miguez Macho
Throughout model domain.

$$\sum_{|n|\le N}\sum_{|m|\le M}\frac{dQ_{mn}}{dt}\cdot e^{ik_m x}\cdot e^{ik_n y} = L(Q) - \sum_{|n|\le N}\sum_{|m|\le M}K_{mn}\cdot\underbrace{\left(Q_{mn}-Q_{omn}\right)}_{D_{mn}}\cdot e^{ik_m x}\cdot e^{ik_n y}$$

Utility of Spectral Nudging for Improving Warm Season RCM Precipitation

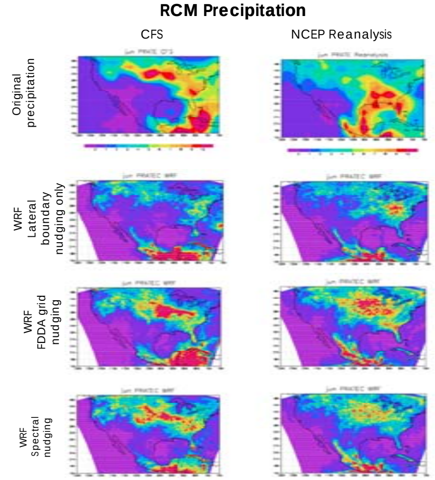

Figure 4: Total monthly precipitation representations for June 1993 (mm) for CFS (left) NCEP/NCAR Reanalysis right) for: Original coarse-resolution data, default WRF simulation without nudging, default WRF simulation with FDDA grid nudging, and WRF simulation with spectral nudging, as labeled.

We have executed several dynamical downscaling tests with WRF using one CFS ensemble member and the corresponding NCEP Reanalysis to demonstrate the utility of spectral nudging. Figure 4 shows the original precipitation solutions for June 1993 along with WRF-simulated precipitation utilizing the different nudging approaches. The precipitation for the CFS ensemble member demonstrates that the CFS model is able to capture warm season teleconnections that lead to increased rainfall in the central U.S., consistent with the precipitation observations at this time. The WRF experiments with only lateral boundary nudging produce comparatively little precipitation in this region. The large-scale circulation patterns in these experiments are significantly different that in the driving CFS or reanalysis data, so the RCM is actually taking away value from its driving model. This is consistent with Castro et al. (2005).

By an improved representation of the large-scale circulation, WRF experiments with internal nudging dramatically improve the representation of June precipitation (bottom two panels of Figure 4). Interior grid nudging at all wavelengths (FDDA) improves the continental-scale representation of precipitation. In the WRF-CFS simulation, spectral nudging further improves the representation of precipitation by retaining more local-scale variability.

Preliminary Dynamical Downscaling Results for Summer 1993

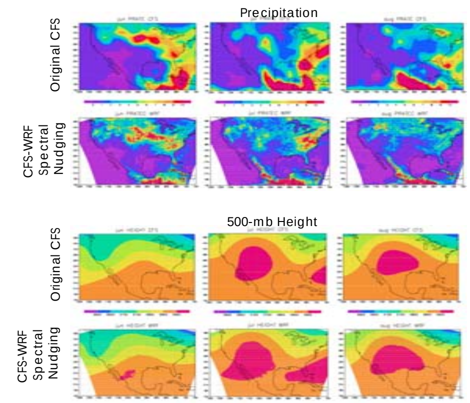

Figure 5: Top: June to August 1993 precipitation (mm) for original CFS ensemble member and WRF-CFS downscaled with spectral nudging. Bottom: Same for 500 mb geopotential height (m).

A RCM can provide a more realistic representation of convective rainfall processes because it better resolves mesoscale circulation features tied to land surface forcing. Thus it can potentially add significant value for simulation of the warm season. However, spectral nudging is necessary to preserve the variability in the large scale circulation while still permitting the development of smaller-scale variability in the RCM, particularly the diurnal cycle of convection. Our preliminary WRF simulation with spectral nudging dynamically downscaling a single CFS ensemble member shows that the RCM produces: 1) A continental-scale pattern of precipitation variability similar to what actually occurred and 2) A reasonable representation of the North American monsoon in the southwest U.S. and northwest Mexico. WRF-CFS downscaled precipitation provides the best hindcast precipitation for Tucson, Arizona, where the monsoon accounts for approximately 60% of summer rainfall (Figure 6).

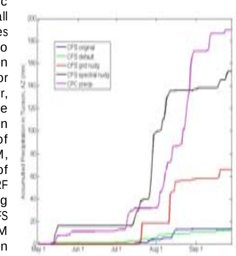

Figure 6: Accumulated Precipitation (mm) for the warm season in Tucson, AZ. The different lines correspond to: Original CFS coarse resolution data (blue), (green) Downscaled CFS with default configuration and no nudging (green), Downscaled CFS with FDDA grid nudging (red), Downscaled CFS with spectral nudging (black) and observed CPC precipitation data (magenta)

Conclusions and Ongoing Work

The preliminary results of dynamically downscaling a CFS ensemble member with WRF for the warm season in North America are quite promising. Provided that the regional model is able to retain the variability in the large-scale circulation fields, WRF used a RVM can potentially add value to representation of the warm season climate. This is primarily realized by an improved representation of convective precipitation. These results appear to validate the hypothesis posed by Castro et al. (2007) that RCMs can add value to the representation of the warm season climate provided the driving global model produces reasonably accurate teleconnection patterns and these are retained in the RCM. We are currently downscaling the entire CFS hindcast period with WRF using the same methodologies described here.

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