Creating Dynamically Downscaled Seasonal Climate Forecasts and Climate Change Projections for the North American Monsoon Suitable for Decision Making Purposes

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Scientific Background: What is the North American Monsoon?

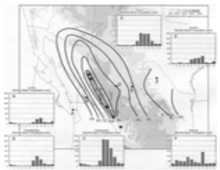

Figure 1: Average North American Monsoon rainfall (mm) in northern Mexico (Douglas et al. 1993).

Figure 2: Air mass monsoon thunderstorms in July 2006 as viewed from the top of Kitt Peak, near Tucson, Arizona, USA. Storms are at their peak intensity here in mid-afternoon with outflow boundaries and gust fronts (photo by C. Castro).

The North American Monsoon is the period of a late-summer maximum in precipitation in the southwestern U.S. and northwest Mexico, and accounts for approximately 50-70% of annual total precipitation in this region (Fig. 1). The monsoon typically begins abruptly in late June to early July when the upper-level flow changes to an south and easterly direction, bringing moist air from the Gulf of Mexico and tropical eastern Pacific. Individual thunderstorm cells are initiated by the diurnal cycle of terrain heating, so the majority of the precipitation occurs in the mountains like the Sierra Madre Occidental in Mexico or Mogollon Rim in Arizona (Fig. 2). Intraseasonally, monsoon "burst" periods occur when convection organizes and propagates off the terrain into the western low deserts of Arizona and Sonora. This typically requires the presence of synoptic-scale disturbance, such as an inverted mid-latitude trough or easterly wave, and a surge of low-level moisture from the Gulf of California (Fig. 3). Interannual variability of the monsoon is primarily controlled by the evolution and positioning of upper-level sub-tropical high pressure (monsoon) ridge over western North America, modulated by ENSO and Pacific Decadal Variability through summertime atmospheric teleconnection responses, per our prior work in Castro et al. (2001) and Castro et al. (2007) as depicted in Fig. 4. Our work herein investigates the ability of the North American monsoon to be represented in the framework of a regional climate model, addressing a major research priority of the North American Monsoon Experiment (NAME) to improve monsoon seasonal forecasts and climate change projections.

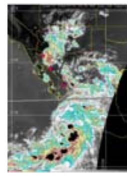

Figure 3: Enhanced infrared satellite image of organized, propagating convection in a monsoon burst period in mid-July 2004, associated with an upper level disturbance over northern Mexico and a low-level moisture surge triggered by the passage of a tropical cyclone. This event occurred during the North American Monsoon Experiment (NCAR imagery).

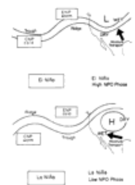

Figure 4: Idealized Pacific – SST related quasi stationary Rossby wave teleconnection responses in early summer (June, July) that affect the North American monsoon (Castro et al. 2001).

Research Motivation: Societal Importance of the Monsoon and Stakeholder Engagement

Severe Weather Hazards

The monsoon has a myriad of societal impacts with respect to both extreme weather and seasonal climate (Ray et al. 2007), so an ability to generate improved seasonal forecasts and climate change projections is of benefit to diverse number of natural resource stakeholders. Specifically, in addition to U.S. federal government funding from the National Science Foundation and Department of Energy, our research is supported by Arizona water resource and power providers, specifically the City of Phoenix, Salt River Project, and U.S. Bureau of Reclamation. Though the Climate Assessment for the Southwest (CLIMAS), we are providing our local stakeholder partners dynamically downscaled climate change projection information to generate water supply projections for the near future (next twenty years) and briefing them and the general public on the issue of climate change. The urgent issues with respect to climate change in our region that have been recently observed are a long-term increase in temperature and dryness, especially right before the monsoon in late June and early July, and possible increase in rainfall intensity. Recent prominent studies based on IPCC AR4 GCM data have projected the Southwest U.S. to experience "permanent dust bowl conditions" by the mid to late twenty-first century (e.g. Seager et al. 2007).

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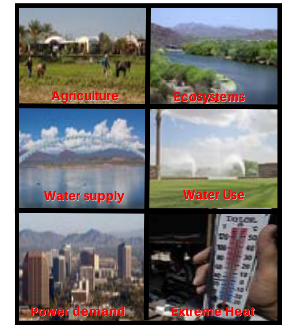
Climate Impacts



Methodology: Dynamically Downscaled North American Monsoon Climate Projections

Figure 5: Monthly evolution of annual average precipitation (mm day^{-1}) in the Southwest U.S. from IPCC AR4 models for the historical period (1970-2000) and observations (Dominguez et al. 2009).

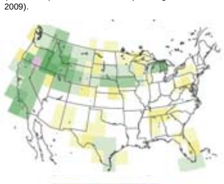


Figure 6: Spatial distribution of retrospective CFS model forecast skill (% anomaly correlation) of the 15 member ensemble reforecasts of JJA. Forecasts made at 1 month lead. (From Saha et al. 2006).

Currently, both operational seasonal climate forecasts and IPCC AR4 climate change projections depend on global climate models (GCMs). Within the GCMs, the North American Monsoon is generally not represented as a salient feature. For example, the suite of IPCC AR4 climate models during the climate control period of the late 20th century show that warm season precipitation in the Southwest U.S. is generally overestimated with an incorrect representation of the late warm season maximum in precipitation (Fig. 5). Similarly, seasonal forecasts GCMs have little to no skill in our region for during the warm season (Fig. 6) The failure of GCMs to get the monsoon "right" is tied to their inability to reasonably represent the development and evolution convective thunderstorms and problems in representing the large-scale circulation, particularly the positioning of the monsoon ridge.

To improve GCM climate projections, the Weather Research and Forecast (WRF) model is used to dynamically downscale: 1) retrospective NCEP-NCAR Reanalyses (Kalnay et al. 1996); 2) nine ensemble member seasonal reforecasts from the Climate Forecast System (CFS) model for the period 1982-2000 (Saha et al. 2006) and 3) several "well performing" IPCC AR4 models (A2 emission scenario) for the period 1967-2081 as described in Dominguez et al. (2009). The specific IPCC models are UKMO-HadCM3, MPI-ECHAM5, and NCAR-CCSM3. The model domain covers the contiguous U.S. and Mexico at 32 km. The implicit assumption in our regional climate modeling methodology, shown in Fig. 7, is that the regional model adds value to the GCM by an enhanced representation of surface-forced processes. The WRF model experimental design is very similar to that used for real time high-resolution numerical weather prediction in Arizona. Of critical importance for regional climate model simulation, our WRF simulations incorporate a recently added spectral nudging capability to the model that ensures the large-scale variability at the spatial scale of driving global model is appropriately retained.

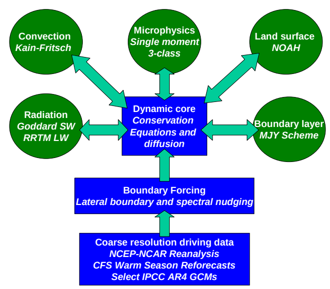


Figure 7: Schematic of WRF model experimental design for regional climate dynamical downscaling. Model parameterized physics and core dynamics, boundary forcing indicated by green bubbles and blue boxes, respectively.

Preliminary Results: Improved Representation of the Monsoon Climatology and Interannual Variability

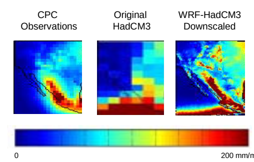


Figure 8: Average July precipitation (mm) over the North American Monsoon region for the period 1970-2000 from observations for gauge-derived gridded (CPC) observations and GCM and RCM products.

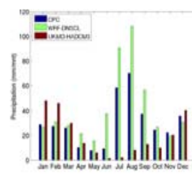


Figure 9: Evolution of average monthly precipitation in Arizona (mm) for the historical period 1970-2000 of gridded gauge (CPC) observations and GCM and RCM products.

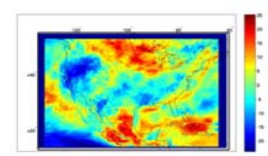


Figure 10: Dominant spatial mode (rotated EOF) of early summer precipitation (JJ 2 month SPI) of HadCM3-WRF simulations (unitless).

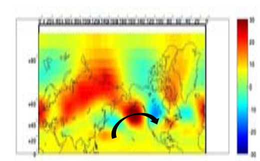


Figure 11: Regression of the dominant rotated principal component of HadCM3-WRF early summer precipitation onto coincident HadCM3 500 hPa height anomalies (m).

To demonstrate the effectiveness of our dynamical downscaling methodologies, preliminary results are shown of analysis of the first complete dynamically downscaled IPCC AR4 model (HadCM3). Fig. 8 and Fig. 9 shows that WRF is better able to capture the spatial and temporal distribution of precipitation over the complex terrain of the North American Monsoon region than the raw HadCM3 data for the late 20th century historical period. The GCM has substantial difficulty simulating topographically induced convection, while WRF captures it and extends the precipitation north into the Southwest United States. WRF clearly improves the monthly precipitation climatology in Arizona by invigorating summer precipitation (Fig. 9). Moreover, considering the climate change period of 2001-2040, regional climate model-simulated warm season precipitation increases (not shown). This result is quite provocative in light of the conclusions of most present climate change studies for the region.

Long-term precipitation variability is considered by analysis of early summer standardized precipitation index (SPI) from the regional climate model. Fig. 11 shows the regression maps of 500-hPa geopotential height anomalies and sea surface temperature anomalies on the first rotated principal component of early summer HadCM3-WRF precipitation in Fig. 10 (2-month SPI ending July). There is a clear quasi-stationary Rossby wave train driven by tropical convection in the western Pacific related to ENSO and Pacific Decadal Variability. The wave train affects the strength and positioning of the monsoon ridge and continental-scale distribution of rainfall (as in Fig. 4). This mode is entirely consistent with prior observational analyses and has a dominant time variability of approximately nine years (Castro et al. 2009). These features are impossible to capture in the original HadCM3 data because of its poor climatology. Nearly identical results were obtained for dynamical downscaling of retrospective CFS seasonal forecasts, as shown in our companion poster.

Selected References

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Summary and Ongoing Work

<u>INADEQUACY OF PRESENT GLOBAL CLIMATE MODELS:</u> Current seasonal climate forecasts and climate change projections for the Southwest U.S. based on global models are not satisfactory. The same is likely to be true for other semi-arid regions of the world with monsoonal climates that are projected to suffer worst drying and warming in the future. Improving the representation of climate in these regions is an urgent need because of its large impact on natural and human systems.

<u>VALUE ADDED BY DYNAMICAL DOWNSCALING:</u> A regional climate model can add substantial value to the representation of warm season climate in North American primarily due to its better representation of convective precipitation. If the driving global climate model has a reasonable representation of large-scale climate variability and this is retained within the RCM, there is much hope for improved representation of the monsoon and forecast products that are appropriate for local stakeholder needs.

<u>TRANSLATION OF REGIONAL MODEL DATA FOR DECISION MAKING</u>: We anticipate that three "well performing" IPCC AR4 models will be dynamically downscaled within the next year and their climate change projection data used for water resource decision making. We also hope to contribute real-time experimental WRF warm season forecasts to the Climate Prediction Center within NOAA as part of their seasonal forecast tools.

Acknowledgements

This work is supported by federal government of the United States under Department of Energy grant DE-SC00001172 and National Science Foundation grant ATM-813656. We also gratefully acknowledge the support of our local water resource stakeholder partners mentioned herein and the Climate Assessment for the Southwest (CLIMAS) for facilitating their engagement in our research.

Global model data used for WRF dynamical downscaling have been provided directly from the individual modeling centers. We particularly acknowledge Dr. Jae Kyung Schemm from the National Center for Environmental Prediction, Climate Prediction Center for providing CFS reforecast data and Mr. Matthew Switanek for his assistance in archival of these data.