Downscaling climate change information for water resources

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As decision makers evaluate future water resources, they often consider the potential impact of climate change. The inherent challenge of this process involves assessment of general circulation model output from different models, and at inappropriately large spatial scales for measuring climate change impacts. This paper investigates the basic strategies for downscaling general circulation model output. Through examples from the North American Regional Climate Change Assessment Program (NARCCAP) we consider the results of dynamic downscaling in the Southeast United States.

Figure 1 illustrates the summer average air temperature for the model and observed/reanalysis data from 1991-2000 (except for the gridded observed data which encompasses 1990-1999). For the most part, all of the regional climate models do a good job of picking up the general trends across the continental United States. If we consider the University of Washington gridded data as that which was actually observed, we can see that hot spots such as the Death Valley region in southern California/southern Arizona/northern Mexico is depicted well by the Pennsylvania State University/National Center for Atmospheric Research mesoscale model (MM5I), the International Center for Theoretical Physics Regional Climate Model (RCM3) and the Weather Research and Forecasting (WRFP) model. All use the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) Reanalysis data as its boundary conditions. The MM5I model with the Community Climate System Model (CCSM) boundary conditions and the RCM3 model with Geofluids Dynamics Lab (GFDL) boundary conditions fail to capture the full extent of this hot spot. Additionally, the MM5I model (regardless of boundary condition) and the WRFP model depict a hot spot that does not show up in the observed record running from North Texas through most of the Upper Midwest, through the Great Plains, and into the desert Southwest.

The MM5I-CCSM and RCM3-GFDL models do the best at resolving the relative minimum temperatures over the Rocky Mountain region, specifically a local minimum in central Colorado, and over portions of Wyoming, Montana, and Idaho. All of the models do a pretty good job of picking up the temperature minimum over far southwestern British Columbia, Canada. In general, it appears that the MM5I-NCEP combination does the best overall job in reproducing observation across the entire Continental United States (CONUS). The biggest caveat, however, is that each model combination appears to perform better in certain regions of the country. For instance, MM5I-NCEP performs well across the CONUS except for the central Great Plains where temperatures were projected too high. To contrast that, the RCM3-GFDL combination is generally too cool across much of the CONUS, specifically the Upper Midwest, through the Great Plains, and into the desert Southwest.

Figure 2 depicts the average winter temperature for each of the models and observed data from 1991-2000 (again except for the gridded observed meteorology data from University of Washington which covers 1990-1999). Although the gridded observed data did not map as well as we would have liked, we can still pick out the general trends throughout the CONUS. In general, winter temperature prediction is much easier than summer temperature due to the fact that the model does not have to worry (for the most part) about convection within the model which can have a big impact on average temperature. All of the models conform to the observed data except for the MM5I-CCSM and the RCM3-GFDL. The MM5I-CCSM is too warm across the Southeast United States and is too cold across much of the western U.S. with an emphasis on the inner Rocky Mountain region. The likely reason for this discrepancy is that the CCSM boundary conditions must have been significantly different than the NCEP boundary conditions.

The next figures deal with the summer average precipitation. All of the models except for the RCM3-GFDL and the HRM3-HADCM3 model underestimate the average daily precipitation rate in the Upper Midwest (i.e. Minnesota, Iowa, Wisconsin, Illinois, and North and South Dakota). The main
reason for this shortcoming is that this area receives a large amount of their summer precipitation through Mesoscale Convective Complexes moving over the region during the overnight hours. The NCEP boundary conditions downplay this significant phenomenon and does not get picked up and depicted well by the regional climate models.

The RCM3-GFDL combination overestimates precipitation over much of the front range of the Rocky Mountains from Northeast New Mexico all the way through central Montana. We theorize that this overestimate is due to one of two things: 1) too much precipitation generated by overactive upslope flow, or 2) the model, in general, is simply too wet due to its convective parameterization. The second hypothesis appears to be of more truth than the first hypothesis because the rest of the CONUS also appears too wet, especially New England, the Texas and Louisiana coast, and the mountains of Mexico. In general, the RCM3-NCEP and MM5I-CCSM are too dry across much of the CONUS. Interestingly, the MM5I-NCEP combination appears to do well for the western U.S. as well as New England but is much too wet across the entire Southeast U.S.

The winter precipitation pattern displayed in Figure 4 performs much better across each of the models. The primary reason for this is that convective precipitation is at a minimum during the portion of the year and thus the model is not at the mercy of the convective parameterization. Each of the models do a good job of depicting the biggest hot spot which is across the Pacific Northwest. Each model resolves slightly different maximum precipitation values over this region; however, the general trend is present in each of the models. The Hadley Centre Model (HRM3-HADCM3) appears to capture this best.

The other area of maximum precipitation occurred over the southern U.S. with an emphasis on the southeastern quarter of the U.S. The MM5I-CCSM, RCM3-GFDL, and HRM3-HADCM3 models do the best at depicting a maximum precipitation value over this region, however, the magnitude of all three models is less than what was observed. Additionally, with the exception of the HRM3-HADCM3 model, the other two models shift the precipitation maximum too far to the east. The MM5I-NCEP model hints at a precipitation maximum over the Southeast U.S., however the magnitude is much too small as where the RCM3-NCEP model does not depict this phenomenon at all.
The next step of analysis was done to determine how different boundary conditions impact the regional climate models. Figure 5 illustrates the difference in average summer temperature for the RCM3 model using the GFDL and NCEP general circulation models (GCMs) as well as the MM5I model using the CCSM and NCEP GCMs. The NCEP GCM is warmer than the GFDL across the entire CONUS by anywhere from 1K to approximately 5K. The biggest discrepancy occurs west of the Mississippi River with the central Great Plains and southern Texas/northern Mexico showing the greatest difference. For the MM5I RCM, the NCEP boundary conditions are slightly warmer over the western U.S. including the desert Southwest. The CCSM GCM is warmer than the NCEP boundary conditions for over two-thirds of the U.S., stretching from the front range of the Rocky Mountains to the Atlantic coast. The biggest difference between the two boundary conditions encompasses the Upper Midwest through the Great Lakes. Figure 6 illustrates the difference in the average winter temperature; a pattern which is very similar to the summer pattern just described. With the RCM3 model, the NCEP GCM is warmer than the GFDL across the entire CONUS. Similarly to the summer pattern for the MM5I model, the western U.S. is warmer for the NCEP GCM as were the CCSM GCM is warmer in the eastern two-thirds of the U.S. The precipitation patterns illustrated in Figure 7 prove to be somewhat interesting. For the RCM3 model there are relatively big discrepancies between the Great Plains/front range of the Rockies as well as the Southeast U.S. In the Great Plains/front range region, the GFDL GCM is wetter than the NCEP GCM as where in the Southeast U.S., the NCEP GCM is wetter than the GFDL. For the rest of the U.S. the differences in precipitation rate are less than 1 millimeter per day, not a significant difference. Another interesting difference between the two boundary conditions can be observed in western Mexico over the mountains. One the east side of the mountains, the NCEP GCM is wetter as were on the west side of the mountains the GFDL model is wetter. This phenomenon may be a result of the GFDL's ability to resolve monsoonal conditions over this region but fails to resolve inter-mountain precipitation. Although slight differences can be noted between the CCSM and NCEP boundary conditions for the MM5I model, they vary by less than 1 millimeter per day and again are not considered significant. The biggest differences between the two occur along the Gulf coast where the NCEP model is wetter and in the southern Appalachian Mountains where the CCSM model is wetter. We currently cannot explain why this difference is occurring, let alone why the difference occurs in such close proximity to each other. One plausible explanation is that the NCEP boundary conditions may have led to increased tropical activity over the Gulf coast. Within the Appalachian Mountains, the CCSM model may have been able to resolve the complex terrain better (140 km spacing for CCSM compared with 250 km for NCEP) which may have resulted in more orographic related precipitation. Figure 8 illustrates the difference in winter precipitation for the RCM3 and MM5I regional models. For the RCM3 model, the difference between the GFDL and NCEP boundary conditions is generally less than 1 millimeter per day from the interior Rocky Mountains eastward to the Ohio River Valley. Over the Southeast U.S. and along the California and Oregon Pacific coastlines, the GFDL is wetter than the NCEP GCM. The only place where the NCEP GCM is significantly wetter than the GFDL GCM is in extreme southwestern British Columbia, Canada. These differences can be explained by the GCM's treatment of the mid-latitude cyclones which move onshore from the Pacific Ocean. Similarly in the Southeast U.S., the models probably differ in the generation and subsequent track of mid-latitude cyclones from the Gulf of Mexico.
Figure 1. Average summer temperature for various regional climate models with differing boundary conditions from 1991-2000. The upper left image in the UW gridded observational data which is an average from 1990-1999.
Figure 2. Average winter temperature for various regional climate models with differing boundary conditions from 1991-2000. The upper left image in the UW gridded observational data which is an average from 1990-1999.
Figure 3. Average summer precipitation for various regional climate models with differing boundary conditions from 1991-2000. The upper left image in the UW gridded observational data which is an average from 1990-1999.
Figure 4. Average winter precipitation for various regional climate models with differing boundary conditions from 1991-2000. The upper left image in the UW gridded observational data which is an average from 1990-1999.
Figure 5. Difference in average summer temperature for RCM3 and MM5I regional climate models under different boundary conditions from 1991-2000.
Figure 6. Difference in average winter temperature for RCM3 and MM5I regional climate models under different boundary conditions from 1991-2000.
Figure 7. Difference in average summer precipitation for RCM3 and MM5I regional climate models under different boundary conditions from 1991-2000.
Figure 8. Difference in average winter precipitation for RCM3 and MM5I regional climate models under different boundary conditions from 1991-2000.