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Examining Regional Climate Model (RCM) projections: What do they add to our picture of future climate in the region?

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Introduction

To prepare for future climate change, land and water resource managers want to know how key climate variables, such as temperature and precipitation, may change in the future relative to the present. The principal tools for investigating potential future climate changes on global-to-regional scales are global climate models (GCMs). Because of the relatively coarse spatial resolution of GCM output (100-300 km), many user applications of GCM climate projections require processing of the GCM output to bring the effective scale of the data to a more local level. This process is called *downscaling.*

In this article, we first provide an overview of GCMs and dynamical approaches to downscaling. We then present an analysis of dynamically downscaled climate projections for the San Juan Mountain region in southwestern Colorado based on the regional climate model (RCM) output available from the North American Regional Climate Change Assessment Program (NARCCAP). Then we place the RCM projections for Intermountain West in the context of raw GCM output and statistically downscaled projections, and examine some of the uncertainties and limitations common to the different climate projections for the region.

The NARCCAP RCM results as described below don't fundamentally alter the overall picture of future climate change for our region provided by GCM projections without downscaling, or by other downscaled GCM projections. All of these datasets indicate that significant warming of 3-7 ^{o}F is likely to occur in all seasons by the mid-21st century, while precipitation changes are much more uncertain in terms of direction, magnitude, and spatial patterns—though with some tendency towards more precipitation in winter and less in summer. By representing the physical processes of climate at a finer scale, the NARCCAP RCMs allow for new insights into regional climate change. They represent an evolutionary step towards more robust projections of climate at yet finer spatial scales that are more consistent with the complex topography of our region.

GCMs and RCMs

GCMs are sophisticated computer models that mathematically represent how the different components of the Earth System—primarily the atmosphere, oceans,

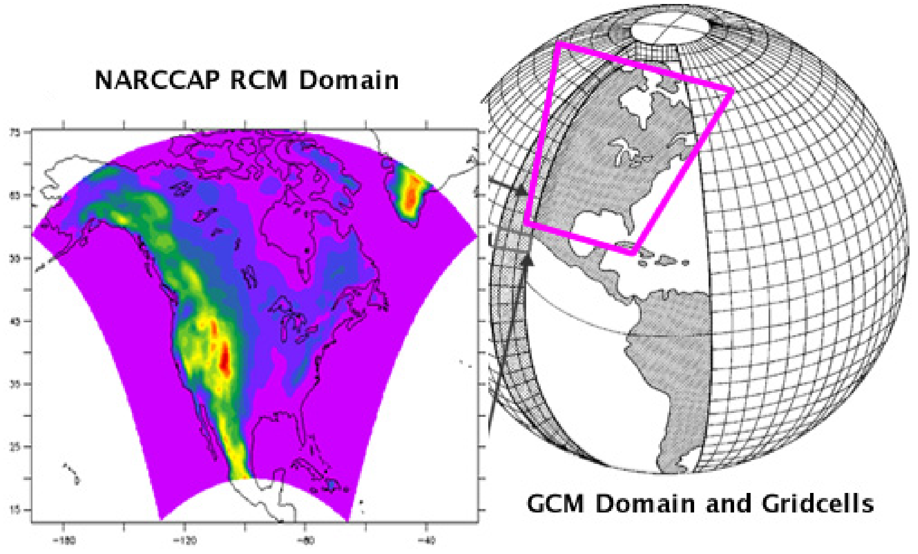

Figure 1. The model grid for the atmosphere component of a typical GCM (right) and the domain and topography of the NARCCAP RCMs (left) that were run "nested" within a GCM. Sources: NOAA and NCAR.

land surface, ice sheets and sea ice—interact to create weather and climate. To effectively simulate the global nature and spatial complexities of the climate system, GCMs subdivide the earth's surface into a three-dimensional grid in the atmosphere and the ocean, creating many thousands of grid cells (Figure 1).

When GCMs are run, standard physical equations for the transfer of heat, water, and momentum (i.e., wind speed) are solved for each grid cell. Many relevant processes are well represented at the scale of these grid cells, such as the large-scale westerly flow of moisture from the Pacific Ocean. Other processes that occur at a spatial scale much smaller than the grid cells, such as the formation of individual clouds, are *parameterized*—that is, they are represented by values which reflect the observed relationships among climate variables. For example, a parameterization can determine the coverage of clouds and their total water content in a grid cell based on the temperature, water vapor, and winds, even when it is not possible to model the individual clouds.

GCMs have been developed by over a dozen research groups around the world, including the National Center for Atmospheric Research (NCAR) in Boulder, Colorado (the Community Climate System Models, or CCSM). The latest Intergovernmental Panel on Climate Change (IPCC) assessment report made use of projections from 24 different GCMs; the archive of these projections is known as CMIP3 (Coupled Model Intercomparison Project 3).

The size of the GCM grid cells, and thus the spatial resolution of the climate projections, is limited by the enormous computing power necessary to solve the equations for all of the grid cells at hourly (or shorter) time steps for runs which may span 100 years or more. Thus, the climate models at the time of the latest IPCC report in 2007 produced output at spatial scales of roughly 200-300 km (120-180 miles).

Particularly in mountainous regions like the Intermountain West, this scale is too coarse to capture the many important effects of topography on climate (Figure 2). For example, because mountain ranges are averaged with adjacent valleys, the Rocky Mountains, as represented in the GCMs, top out at around 8,000'. The scale of GCM output is also too coarse to use as input for many models predicting environmental impacts, such as basin-scale hydrologic and water system models, or wildlife habitat models. Therefore, techniques to reduce the spatial scale of the GCM output (that is, downscaling) are needed for most user applications.

Dynamical Downscaling with RCMs

Dynamical downscaling typically involves nesting a regional climate model (RCM) inside a GCM over the region of interest. An RCM is very similar to a GCM but covers a smaller spatial domain (e.g., North America), at a higher resolution (Figure 1). The GCM provides the environmental conditions, typically for every 3 or 6 hours, at the boundaries of the RCM domain. RCMs provide both better topographical representations than GCMs and better local- to regional- scale atmospheric dynamics that may, for example, improve the simulation of warm-season convective precipitation. Dynamically downscaled projections can be produced at a variety of spatial scales, sometimes as small as 1 km. However, these efforts are generally constrained to the 25-50 km range because of computational limitations.

One of the main advantages of dynamical downscaling over statistical downscaling that the former represents the physical processes of climate—thus linking spatial

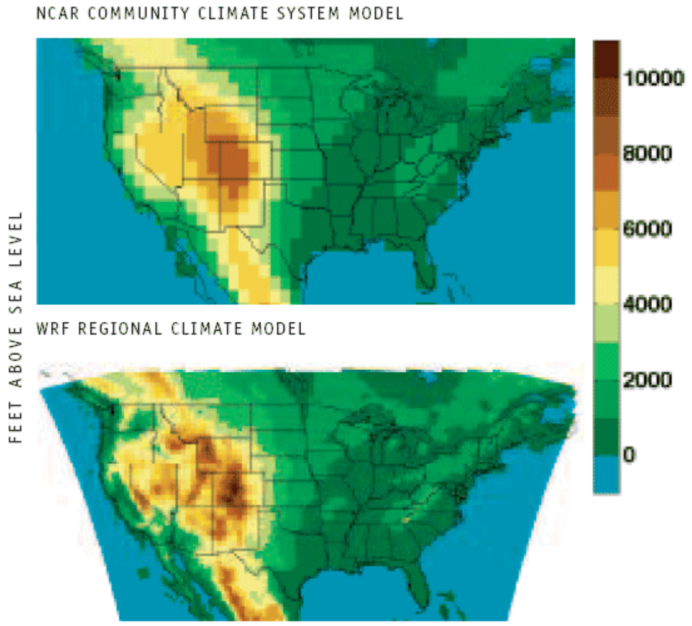

Figure 2. The spatial resolution and the representation of topography across the US of a typical GCM (top; NCAR CCSM 3.0) and a typical RCM (bottom; WRF Model). The RCM depicts individual mountain ranges and intermontane basins while the GCM does not. Source: NCAR.

scales of climate in a manner that can vary as the the future climate changes. By contrast, statistical downscaling is based on fixed historically-based assumptions regarding the spatial relationships of climate variables. In addition, a greater number of output climate variables from these RCMs relevant to resource managers, are being archived at sub-daily timescales. For example, the RCMs simulate the individual terms in the water and energy budgets at the Earth's surface, so that projected trends in evapotranspiration, solar radiation, and snowcover can be investigated at sub-GCM scales.

A major disadvantage of dynamical downscaling is that, as with GCMs, the process is computationally intensive and there are biases, or systematic errors, in the simulation of the present-day climate. And if modelers of water and ecosystem impacts require data at a yet finer spatial resolution than is provided by the RCMs, they would still need to make use of statistical methods to further downscale the data.

When making use of downscaled climate projections, as with the underlying GCM output, one should consider a range of projections rather than one or two. In the case of statistical downscaling, several or more GCM projections are typically downscaled using the same method. Likewise with dynamical downscaling, it is important to consider projections produced by multiple RCM-GCM combinations. Each RCM, like each GCM, varies in how it represents climate processes. In addition, there are significant differences among RCMs in how they interact with the specific GCMs that provide their boundary conditions. Because each model has strengths and weaknesses, there is no one "best" RCM, nor one "best" RCM-GCM combination.

About the NARCCAP dynamically downscaled projections

The North American Regional Climate Change Assessment Program (NARCCAP) is an international program, led by the National Center for Atmospheric Research (NCAR), to produce high-resolution climate projections in order to investigate the uncertainties in regional-scale projections of future climate, and generate future climate projections for use in studies of climate impacts. NARCCAP researchers at several modeling centers are collectively running a set of RCMs driven by multiple GCMs, over a domain that covers the conterminous United States and most of Canada, Alaska, and northern Mexico. The GCM runs are all driven by the A2 emissions scenario, which describes a future with continued high rates of greenhouse gas emissions. All of the RCMs were run at a 50 km (~30 mi.) spatial resolution (Figure 2; bottom panel).

Assessment of the NARCCAP results for the San Juan Mountain region

Researchers with the Western Water Assessment (authors Cozzetto and Rangwala, along with Jason Neff and Joe Barsugli) have examined in detail the dynamically downscaled temperature and precipitation projections available from the NARCCAP for southwestern Colorado for two 30-year periods: a historic period (1971-2000) and a future period (2041-2070). The area of investigation extends from 36.0° to 38.5° North latitude and 105.5° to 110° West longitude, and was centered on the San Juan Mountains (Figure 3). The projections from a total of six different combinations of RCMs and GCMs are discussed here.

Projections for three climate variables were analyzed: maximum daily air temperature (T_{max}), minimum daily (nighttime) air temperature (T_{min}), and total precipitation. T_{max} and T_{min} were selected because they were considered to be more relevant than average daily air temperature to ecological processes and impacts. For instance, changes in T_{min} will likely affect the cold-season survival of bark beetles, while changes in T_{max} will affect stream temperatures and the viability of coldwater species such as cutthroat trout. At the time of the analysis, temperature

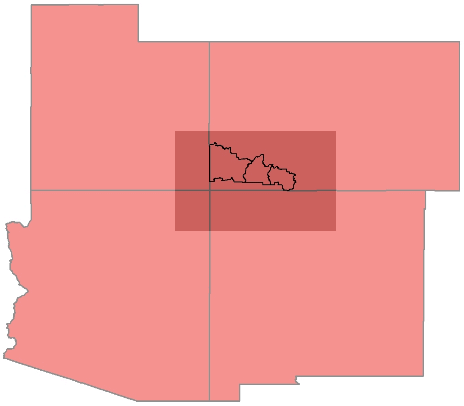

Figure 3. The study area for the NARCCAP analysis is shaded in dark red. The boundaries of BLM and US Forest Service lands managed by the San Juan Public Lands Center are outlined in black. (Source: Daniel Fernandez, University of Colorado)

(T_{max} and T_{min}) data were only available for analysis for four different RCM-GCM combinations. Precipitation data were available and analyzed for those same four RCM-GCM combinations and for two additional RCM-GCM combinations.

Mid-21st century changes in temperature and precipitation were determined as the average changes over the 2041-2070 time period relative to the average for the 1971-2000 time period. Changes in both temperature and precipitation were examined on a seasonal (3-month) basis, and precipitation changes were also analyzed on a monthly basis because some of the key precipitation features in southwestern Colorado occur at that timescale. For instance, June is generally the driest month, while July and August are the wettest owing to the intrusion of moist air associated with the arrival of the North American Monsoon.

The projected changes between now and 2040 were not examined because these outputs were not available from NARCCAP. However, based on the results from the GCMs used in the latest IPCC report, it would be reasonable to assume roughly linear increases in annual and seasonal temperatures between now and 2040. However, abrupt shifts in temperatures at monthly-to-seasonal scales could occur because of changes in certain climatic features, for example, those associated with changes in snow cover or shifts in precipitation regimes and atmospheric circulation.

Temperature projections

Figure 4 shows the projected changes, by season, in the average daily maximum (daytime) and minimum (nighttime) temperatures across the San Juans by the middle of the 21st century relative to the late 20th century for the median of the 4 RCM-GCM combinations. The results for the individual RCM runs are similar to the median changes, except for minimum temperature during winter. Overall, the results show at least 4^o F warming in all seasons. Summer has the highest warming in maximum (daytime) temperatures (>6^o F), with greater increases at higher elevations (>8,000'). By the mid-21st century, the normal daytime summer temperatures are projected to be similar to those observed in 2002, the year with the highest observed summer temperatures in the San Juans. Preliminary analysis suggests that high summer temperatures are caused by the reduction in summer precipitation and an increased drying of the land surface. Several models also show large nightime warming (>6^o F) during winter, particularly at lower elevations (<8,000'). The confidence in model estimates of temperature are generally greater than for other climate variables, such as precipitation.

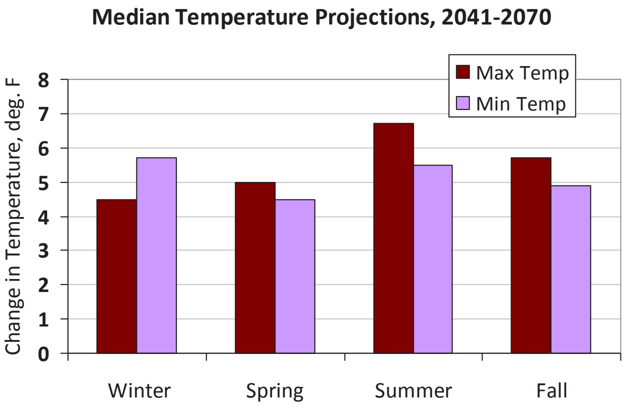

Figure 4. Median projected change in daily minimum and maximum temperature for 2041-2070, by season, relative to 1971-2000, as projected by 4 RCM-GCM combinations for the San Juan Mountain region.

Precipitation projections

GCM and RCM projections of precipitation are known to be less reliable than air temperature, because precipitation is more strongly affected by non-linear processes in atmospheric and oceanic circulation, which are not yet well represented in current climate models. The under-representation of topographic features in these models for the San Juan Mountain region is an additional challenge for reliable projections of precipitation. The difficulty that the models have in representing precipitation processes in the region is seen in the NARCCAP simulations of the historic period. None of the RCM simulations reproduced well the observed seasonality of precipitation in the region. Wintertime precipitation, which is dominated by large-scale storm systems, is better simulated than summertime precipitation. Because no single model was clearly better than the others in reproducing the historic precipitation patterns, all six RCM simulations were considered in assessing the future changes in precipitation.

Figure 5 shows the differences between mid-21st century and late-20th century precipitation in southwestern Colorado for six RCM runs. The consensus among the runs is that southwestern Colorado can expect near-average precipitation or a slight increase during

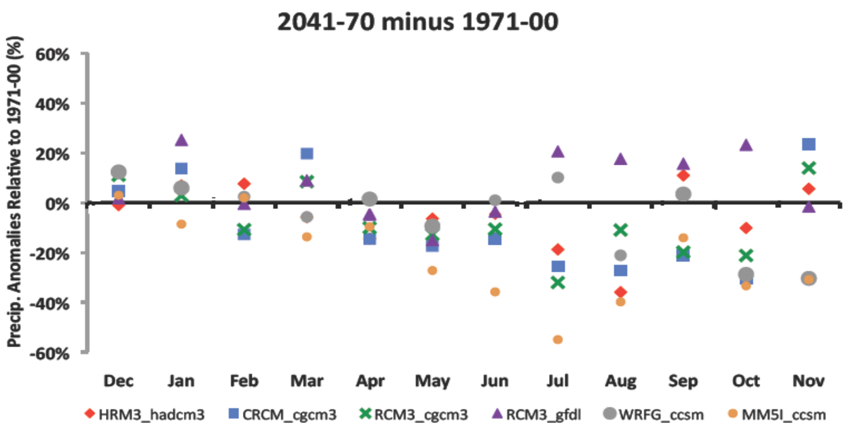

Figure 5. Projected changes (%) in monthly precipitation for the study area for 2041-2070, relative to 1971-2000, as projected by 6 RCM-GCM combinations (colored icons)

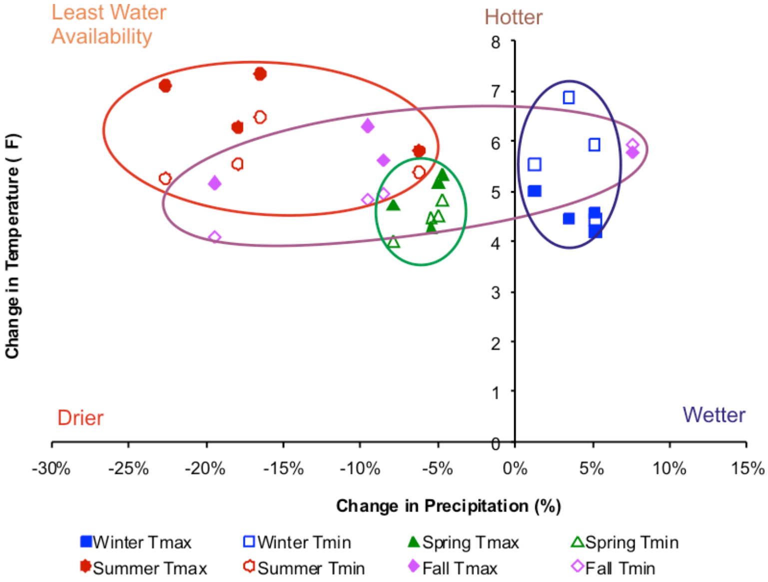

Figure 6. Projected changes in temperature (minimum and maximum) and precipitation, averaged for each season, from 4 RCM-GCM combinations, for the 2041-2070 period relative to the 1971-2000 period. Each RCM-GCM combination is represented by one open icon (T_{min}) and one filled icon (T_{max}) for each of the four seasons. The colored ovals encompass the range of projections for each season.

December and January, near-average precipitation or a decrease from April to June, and a decrease in precipitation in July and August. These changes qualitatively agree with the GCM projections for the region. Again, none of the models adequately captured the dry to wet transition associated with the onset of the North American Monsoon, and so only very limited confidence can be placed on the projections of summer precipitation.

It is also important to note that changes in the water availability for plants, streams and human uses are not determined by precipitation alone. A large fraction of rain and snow (50-80%) is lost to the atmosphere via evapotranspiration (ET) and this process is highly sensitive to temperature. Evapotranspiration will increase as a result of rising air temperatures and will reduce overall water availability. The higher maximum and minimum daily air temperatures projected for the mid-21st century will, all else being equal, result in less available water. So an assessment of the impacts on water availability should jointly consider the temperature and precipitation projections (Figure 6).

Limitations and uncertainties in the NARCCAP results

The NARCCAP data are useful in that they facilitate comparison among the results of multiple RCMs and GCMs and allow examination of the additional information that dynamical downscaling can provide about future climates at smaller spatial scales. However, the four GCMs used by NARCCAP to provide boundary conditions for the RCMs represents only one-sixth of the GCMs available in the CMIP3 archive. Thus, the analysis for the San Juans presented here does not capture the full range of available GCM climate projections.

Also, while the 50-km resolution of the NARCCAP data is a large improvement over the resolution of the GCMs, resulting in 20 to 40 times more grid cells, it is still inadequate to fully resolve both the horizontal and vertical scales of local topographic features. For example, the RCM representations of the San Juan Mountains only reach 3300 m (11,000’) instead of the actual 4300 m (14,000’), thus constraining the climatic influence of topography (e.g., on the terrain-induced lifting of air masses above the condensation level).

And as noted above, none of the RCM simulations captured the monthly precipitation climatology of the region. In particular, all of the models had trouble reproducing various features of the North American Monsoon from July through September. In most cases, no monsoon was simulated, and in the remaining ones, the monsoon was not maintained for a long enough period. Additionally, a majority of the RCM simulations had problems reproducing the observed trend of increasing precipitation with elevation during the fall, winter, and spring months, the period during which the snowpack is accumulated. This analysis indicates that climate model projections of changes in precipitation have much greater uncertainty than temperature and, therefore, should be treated with greater caution. That said, there is no clear evidence for a future trend toward greater annual precipitation in this region that would be large enough to counterbalance the drying effect of the projected increase in temperature. Thus, it is likely that water availability will decline in the future.

How do NARCCAP RCM projections compare with GCM Projections for Intermountain West?

When an RCM is nested within a GCM, as with the NARCCAP dataset, the RCM's output will reflect both the GCM's representation of large-scale processes that determine the boundary conditions driving the RCM, and the RCM's own representation of regional-scale processes. The relative influence of the GCM boundary conditions should vary seasonally, with less influence expected during the summer as regional-scale convective dynamics become important in the RCMs.

For the Intermountain West, the projections of future temperature and precipitation changes from NARCCAP RCMs as reported above are generally similar to those of their driving GCMs, with the exception of summer-time precipitation. For a majority of NARCCAP runs, the RCMs project a greater reduction in precipitation during summer than do those same GCMs when run without downscaling. In fact, there are instances where the sign of change (increase vs. decrease) for summer precipitation is different between the RCM and GCM.

The causes for this difference in projections of summer precipitation projections are unclear and research is underway to elucidate them. It would be important to know if the dissimilar response in the RCM is arising from real physical processes that the RCM is better able to simulate due to its higher spatial resolution, or if these differences are an outcome of misconstrued formulations in the RCM that affect the correct modeling of convective processes and monsoonal flows.

A broader, though preliminary, analysis has been performed for the Upper Colorado River Basin, comparing five of the NARCCAP RCM projections with the full set of CMIP3 GCM projections (34 different model runs) for the same A2 emissions scenario used in the NARCCAP runs. (These 34 GCM projections are also the basis for one-third of the LLNL-Reclamation-Santa Clara 112-projection statistically downscaled dataset that has been used in recent Reclamation and state agency reports.) This analysis indicates that the NARCCAP projections for the mid-21st century for the Upper Colorado Basin all fall within the range of the broader set of GCM projections, in terms of changes in summer and winter temperature, and changes in summer and winter precipitation. Where the NARCCAP data add some useful detail is in showing seasonal differences in the magnitude of climate change, caused by physical processes that become more evident at smaller spatial scales. For example, the NARCCAP data show winter and spring mininum temperatures increasing more than the maxima in the San Juan Mountain study area, particularly at lower elevations. Examination of the NARCCAP snow depth output indicates that the likely cause is the greater future reduction in snow cover at lower elevations.

What's coming: High-resolution dynamical downscaling

To properly simulate precipitation in mountainous regions such as the Colorado Rocky Mountains, where terrain-induced lifting of air masses is dominant, a realistic depiction of the topography is essential. Such orographic processes are almost non-existent in the current GCMs and remain weak in NARCCAP-type RCMs. High-resolution RCMs at spatial scales as low as 1-2 km are now being used, in a limited research mode, to simulate climate over mountainous regions. To properly simulate snowfall over the Colorado Rockies, researchers at NCAR have found that the RCMs need to be run at spatial scales of 6 km or less (Rasmussen et al. 2011). In one climate change experiment, they found the high-resolution RCM simulated a much greater increase in winter precipitation (+26%) for the Colorado Rockies than that projected by the driving GCM (+4%).

Even if we accept that high-resolution RCMs are more realistically simulating winter precipitation in Intermountain West, as appears likely, we would still need several such RCM runs driven by a suite of different GCM boundary forcings to confidently project future precipitation trends from them. These runs would be extremely computationally intensive and it would not be economically viable to perform them over large areas in the near future. And this approach would not necessarily address the poor representation of the North American Monsoon and summer precipitation in the region. Nonetheless, we can expect to see more results from fine-scale RCMs in near future, and it is expected that they will increase our understanding of the complex atmospheric processes over mountains.

Summary

The RCMs bring the physical sophistication of the GCMs down to a finer scale, allowing dynamic simulations of future regional climate not limited by the historic relationships between climate variables. Critically for our region, they represent the topography in a more realistic fashion, so that terrain-induced spatial patterns in climate may be better represented than in the GCMs alone.

As mentioned earlier, in terms of annual temperature and precipitation, the NARCCAP RCM results don't diverge from the overall picture of future climate change for our region provided by GCM projections without downscaling and by the statistically downscaled GCM projections like the LLNL-Reclamation-Santa Clara dataset. But interesting details at the seasonal or monthly time scales, and at smaller spatial scales, do emerge from the NARCCAP data. And for those who need to model the impacts of future climate change on specific resources, the NARCCAP output has over 40 climate variables at 3-hourly and daily time steps, including humidity, wind speed, soil moisture, heat fluxes, and shortwave and longwave radiation. Thus, natural resource planners and agency researchers may benefit from examining the NARCCAP output for their area of interest, alongside other downscaled GCM data—keeping in mind the caveats described above.

Additional Resources

See the Climate Change in Colorado Report (http://wwa.colorado.edu/CO_Climate_Report/index.html) for more information about GCMs, downscaling, and the projections for Colorado and the West from GCMs and statistically downscaled output.

The NARCCAP data as used in the analyses described above are available in NetCDF format through the NARCCAP website (http://www.narccap.ucar.edu).

Readers interested in ongoing analyses of NARCCAP data for the Upper Colorado River Basin can contact Imtiaz Rangwala at imtiaz.rangwala@noaa.gov.

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