

AN ENHANCED ARCHIVE FACILITATING CLIMATE IMPACTS AND ADAPTATION ANALYSIS

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An expanded archive of downscaled model-based projections of future changes in regional climate is described, with a user-friendly web interface, to facilitate analysis of climate change impacts and adaptation.

As humanity and our environment experience increasing impacts of a disrupted climate, exploration of the range of possible future impacts becomes more urgent. While substantial advances have been made through the standardization

of simulations for projecting future climate, there remain many gaps between climate projections and the needs of climate impacts scientists and decision makers, for obtaining higher-resolution climate projections and in making them useful and meaningful for stakeholders (e.g., Bates et al. 2008; Lemos et al. 2012; Tang and Dessai 2012). The focus here is solely on the scale mismatch between large-scale climate model output and the smaller scale at which many management decisions are made, recognizing that climate projections are only one aspect of the complex challenge faced by those attempting to anticipate and adapt to a changing future (Wilby and Dessai 2010).

Prior to the creation of large archives of publicly available climate model output, impacts and adaptation analysts would obtain global climate model (GCM) output from modeling groups for variables of interest, typically temperature or precipitation, downscale these data to a spatial and temporal resolution appropriate for the impact being studied, and use these downscaled data to drive an impacts model (Downing et al. 2001). This sequence of data manipulation and modeling required expertise and computational resources that presented a challenge to many impacts modelers and decision makers, resulting in early studies relying on simple methods such as

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perturbations to historical meteorology, sometimes based on mean GCM projections (e.g., Gleick 1987), and later projects using only a few projections (e.g., Hayhoe et al. 2004). While it was often argued that these few scenarios represented a range of potential futures, using results from only a few GCMs limits investigators to exploring scenarios with no context of where they lie relative to the range of projections. An assessment could be performed using a few climate projections that include changes in temperature or precipitation, for example, that are outliers compared to the larger consensus of projections, and there would not be the means to distinguish this.

With the availability of the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset, archived at the Program for Climate Model Diagnosis and Intercomparison (PCMDI; Meehl et al. 2007), it became standard practice to use an ensemble of GCMs in impacts and adaptation studies (Carter et al. 2007). Using a multimodel ensemble of projections permits the quantification of aspects of model uncertainty by representing the variability among GCM projections, and the ensemble mean generally shows better skill than any individual GCM (Tebaldi and Knutti 2007).¹

While the CMIP3 archive at PCMDI has proved invaluable to many climate scientists and impacts investigators, there remains a disconnect between the spatial scale of typical GCM output and the scales at which impacts are important to society and ecosystems. For example, the precipitation that provides California's water supply is largely driven by orographic effects as moist air moves inland from the Pacific and encounters the Sierra Nevada range. The GCM scale is inadequate to resolve these mountains, limiting the direct use of GCM output for studying impacts on water resources (Hayhoe et al. 2004). This is overcome by employing downscaling techniques that translate the large-scale climate signal from the GCM, at a typical spatial scale of 100 km to several hundred kilometers, to an impacts-relevant scale of a few to dozens of kilometers (Fowler et al. 2007). A common downscaling approach for impacts and adaptation studies is to use empirical relationships between large-scale climate features and local climate. Alternatively, dynamical modeling at a finescale using a limited-domain climate model driven by GCM results can be employed for downscaling to capture changing feedbacks, without the empirical

downscaling assumption of stationary relationships between large- and small-scale climate features. However, dynamical modeling carries a much larger computational burden, and biases in regional model output often require statistical treatment before being used in impact models. For these reasons, empirical statistical downscaling is much more widely used in climate change impacts studies, especially those including projections of long time periods by many GCMs (Benestad 2004).

There has been considerable effort in developing shared tools to enable statistical downscaling by impacts modelers and decision makers, some aimed at generating meteorological projections at a point and others formulated to produce finescale gridded regional data (Benestad 2004; Gudmundsson et al. 2012; Wilby et al. 2002). However, the approach where each impacts study includes a downscaling exercise is an inefficient use of resources that often duplicates the efforts of others. The sharing of downscaled data across disciplinary impacts studies can ameliorate this (e.g., Hayhoe et al. 2004). In the Hayhoe study, downscaled precipitation and temperature projections for California were applied to water resources, urban air quality, wildfire, and other impacts models to produce a coherent cross-sectoral analysis. The data were later shared with other groups studying impacts ranging from agricultural production (Schlenker et al. 2007) to water supply reliability (Vicuna et al. 2007). In this way, GCM output was downscaled once and distributed to many others, allowing them to focus on quantifying impacts of projected changes and facilitating the cross-discipline comparison of impacts produced by a consistent set of projections.

An institutional demand for climate data, downscaled to a level at which it would be useful for water resources impacts studies in particular, provided the initial interest in producing an archive of downscaled climate projections. In 2005 several National Environmental Policy Act (NEPA) environmental compliance studies in California were challenged in part because they failed to address climate change, and the Bureau of Reclamation saw a growing need to address climate change in its environmental compliance studies as well as other long-term planning assessments. This and our experiences with other climate impacts studies motivated a team of us to develop and distribute an easy-to-use downscaled climate projections resource, building on the GCM output at

¹ Most importantly, the PCMDI example of freely distributing climate change projections promoted the emergence of other sites (in addition to ours) distributing regional climate model output (e.g., Mearns et al. 2009) and other regionally focused climate change scenario archives (e.g., Dalton and Jones 2010; Mote and Salathé 2009).

the widely used PCMDI archive and utilizing a well-tested and peer-reviewed downscaling technique. While the work motivating the new archive creation was regionally focused, fully covering the contiguous United States would ensure the new archive's broad geographic applicability to serve federal agencies with different focus areas, programs such as the National Oceanic and Atmospheric Administration (NOAA) Regional Integrated Sciences and Assessments, state and local decision makers, and the broader climate impacts community.

Here we announce new additions to a publicly available archive of downscaled climate and hydrology projections for the United States. We present this in the context of six years of experience in developing and distributing downscaled climate data, highlighting some of the impact the archive has had and lessons learned in the process of providing this data to a wide spectrum of users.

DEVELOPMENT AND DISTRIBUTION OF ARCHIVE CONTENT.

Maurer et al. (2007) used the bias correction and spatial disaggregation method (BCSD; Wood et al. 2004) to downscale monthly projections from 112 GCM simulations to a $1/8^\circ$ spatial resolution across the conterminous United States (plus small portions of Canada and Mexico). The downscaling methods are summarized in appendix A of the technical memorandum on the website for the downscaled data archive (Brekke et al. 2013). The archive included essentially all those GCM runs that, at the time, had valid (not flagged on the PCMDI errata list), complete monthly data in the CMIP3 archive for the three future greenhouse gas emissions scenarios: A2, A1B, and B1, providing a higher, midrange, and lower emissions trajectory, respectively, through the twenty-first century.

In response to user demands, daily data were added by downscaling daily GCM output for the same spatial domain using a technique developed for daily data, bias corrected–constructed analogs (BCCA; Maurer et al. 2010). CMIP3 GCM daily output was available for a smaller subset of models as compared to the original monthly archive, resulting in nine GCMs contributing a total of 53 sets of daily projections. In addition, for daily output only selected time slices were available (1961–2000, 2046–65, and 2081–2100). Notwithstanding these limitations, the inclusion of daily data allows the analysis of daily extremes in precipitation and maximum and minimum temperatures, as well as some assessment of the sensitivity of results to the choice of downscaling technique (e.g., Pierce et al. 2013).

Using output from the new GCM projections conducted as part of the CMIP5 project (Taylor et al. 2012), the archive has been expanded to include downscaled monthly maximum and minimum temperatures and monthly precipitation for 73 historical model runs and 234 projections. This includes four representative concentration pathways (RCPs) of atmospheric greenhouse gas concentrations and other climate drivers, which, although developed separately from those used in CMIP3 simulations (Meinshausen et al. 2011), still allow higher (RCP8.5), midrange (RCP6.0), and lower (RCP4.5) pathways to be represented. These are broadly comparable to the three emissions scenarios used in CMIP3 (designated A2, A1B, and B1) in the archive, though RCP8.5 includes somewhat greater greenhouse gas concentrations and thus greater warming than A2, and RCP6.0 includes slightly lower concentrations and warming than A1B (Rogelj et al. 2012). A fourth CMIP5 pathway is included, RCP2.6, that represents the most aggressive mitigation pathway, aimed at maintaining a global temperature increase to 2°C above preindustrial (van Vuuren et al. 2011). Besides differences in specified external forcings, the CMIP5 projections were performed using newer models typically characterized by improved and more complete representations of physical processes, finer spatial resolution, and/or more complete representations of external forcings than CMIP3 (Knutti and Sedlacek 2013). Because both model formulations and greenhouse gas concentration pathways differ between CMIP3 and CMIP5, it is difficult to attribute any differences in projected climate to one cause or the other using the downscaled data alone.

Recognizing that many societal impacts are sensitive to submonthly climate and weather variations, the latest CMIP5-based additions to the archive include many more daily downscaled products. This allows for the investigation of effects of extremes in daily temperature and precipitation. A total of 44 historical runs and 134 projections (total for all four RCPs) have been downscaled to $1/8^\circ$ spatial resolution at the daily time scale using BCCA.

Downscaled CMIP3 temperature and precipitation have been used to drive a hydrology model to produce distributed projections of soil moisture, snow water equivalent, evapotranspiration, and surface runoff for the western United States (Gangopadhyay and Pruitt 2011). These variables are being served by the archive as they are generated for the CMIP5 projections. While not produced specifically for this archive, a similar $1/2^\circ$ dataset of downscaled monthly average temperature and precipitation projections

was developed for global land areas and is also distributed through the archive interface.

One of the first issues facing users of raw GCM output is the challenge of downloading and storing many large files when only a small geographical domain or short time period may be of interest. The interface serving the downscaled data allows users to select a time period and geographic domain of interest as well as the temporal resolution prior to downloading data. Figure 1 shows the current web interface for the archive, which serves both CMIP3 and CMIP5 downscaled projections.

Any number of projections can be selected (Fig. 2), corresponding to different emissions pathways or GCMs. A subsequent page allows the specification of summary statistics (spatial or temporal mean or standard deviation) for the projections.

The underlying data are stored in netCDF format, a standard for climate and weather data that retains both multidimensional data and the metadata that describe it, and data retrievals may retain this format. This allows users to display and manipulate the downloaded data with the same tools used for the original climate model output obtained from the PCMDI, for example. Files in netCDF format can also be imported directly into some GIS software packages for spatial analysis and display. For some requests the data can also be delivered in a comma-delimited text format, which can then be imported into a spreadsheet, facilitating rapid assessment of the climate projections.

IMPACT OF DATA USE. Since its launch in 2007, 21,675 requests were made by 1,414 different users (based on unique e-mail addresses) through September 2013. These data deliveries amounted to approximately 55 TB of data (Fig. 3). While the original intent of the dataset was to facilitate the use of CMIP3 climate projections in water resources planning and management, the applications have been much wider than that. A survey conducted among data users found 54% used the data for research, 29% for management and planning, and 17% for education, which illustrates the broad utility of a publicly accessible clearinghouse of climate projections. The announcement of the dataset release (Maurer et al. 2007) has been cited by over 120 articles as of June 2013, covering such wide-ranging topics as species migrations under different climate trajectories (Early and Sax 2011), changing frozen-soil dynamics (Sinha and Cherkauer 2010), impacts of changing climate on ski resort real estate values (Butsic et al. 2011), and erosion and habitat impacts on U.S. military reservations (Lozar et al. 2011). One of the most important uses of the archive is to allow users to study the system that would be affected by climate change without having to begin with obtaining raw GCM output and developing expertise in downscaling. For instance, Brown et al. (2012) use downscaled projections from the archive to focus on how climate information can be used in water system vulnerability assessment. Another set of examples is Urban

et al. (2012) and Islam et al. (2012), who each downloaded projections from the dataset to study the potential for future climate to impact different aspects of maize production. These and other successful uses for conservation planning, water management, and many other applications demonstrate the utility of this online resource for many communities.

Beyond the extensive academic use of the data, the archive has facilitated the use of climate change projections in applied work by managers and decision makers. For example, the data have been used to serve utility-level climate

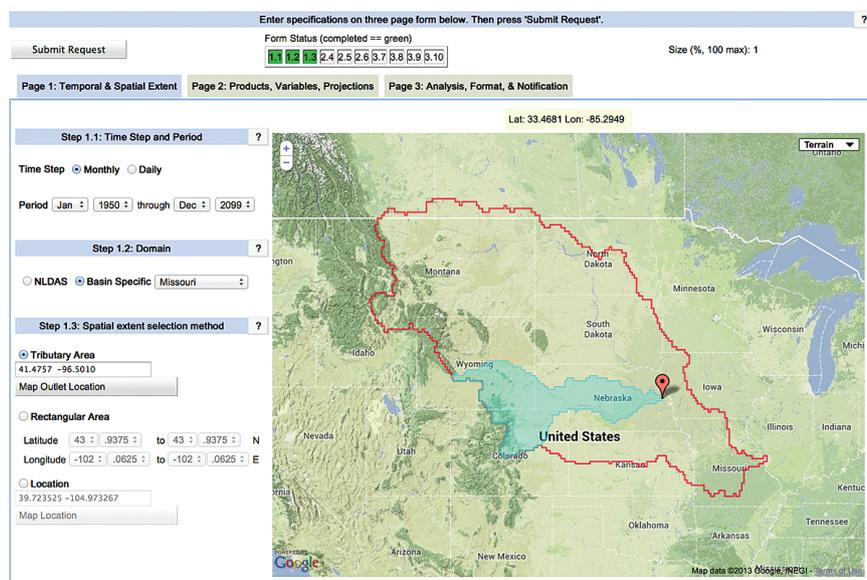


FIG. 1. The web interface for the downscaled data archive. Data are accessible for all stages of the downscaling procedure. Here the Missouri River basin domain has been specified, and within that, the Platte River watershed (shaded in light blue) has been selected as the region for downloading data.

assessments (Woodbury et al. 2012; Barsugli et al. 2009), federal environmental compliance efforts (Bureau of Reclamation 2008), and federal/nonfederal adaptation planning (Bureau of Reclamation 2012). These examples represent agencies using the data archive in developing decision-support information, which is receiving increasing consideration in decision-making activities and will play a role in shaping agency adaptation efforts going forward. This is a key indicator that the archive has satisfied an initial incentive in its development of bridging the gap between the climate science community and the planning community, ultimately bringing pertinent climate change information to bear on locally focused impacts and adaptation efforts.

The archive has also been leveraged by others catering to the specific interests and the needs of other communities. One widely used tool is the ClimateWizard (www.climatewizard.org; Girvetz et al. 2009), which serves a summarized version of the downscaled CMIP3 projections for precipitation and temperature and permits the calculation of summary statistics for ensembles and custom spatial domains and the online preparation of graphics. The archive data from the ClimateWizard has subsequently been used to develop a U.S.-wide index to assess the vulnerability of plant and animal species to climate change (www.natureserve.org; Young et al. 2012). Climate projections from the archive also form the basis for an online water supply

Page 1: Temporal & Spatial Extent | Page 2: Products, Variables, Projections | Page 3: Analysis, Format, & Notification

Step 2.4: Select Projection Sets (Green text indicates projection set form completed) ?

BCSD-CMIP3-Climate-monthly BCSD-CMIP5-Climate-monthly
 BCCA-CMIP3-Climate-daily BCCA-CMIP5-Climate-daily
 BCSD-CMIP3-Hydrology-monthly

BCSD-CMIP3-Climate-monthly **BCCA-CMIP3-Climate-daily** **BCSD-CMIP3-Hydrology-monthly** **BCSD-CMIP5-Climate-monthly** **BCCA-CMIP5-Climate-daily**

Step 2.5: Products & Variables -- monthly projections ?

Products
 1/8 degree BCSD projections
 1/8 degree Observed data (1950-1999)
 2 degree Regridded GCM projections
 2 degree Bias-corrected GCM projections
 2 degree Observed data (1950-1999)

Variables
 Precipitation Rate (mm/day)
 Ave Surface Air Temperature (deg C)

Step 2.6: Emissions Scenarios, Climate Models and Runs ?

De-select all runs	None	None	None
Select all runs	All	All	All
Climate Models:	Emissions Path: A1b	Emissions Path: A2	Emissions Path: B1
bccr_bcm2_0	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
ccma_cgcm3_1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
cnrm_cm3	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
csiro_mk3_0	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
gfdl_cm2_0	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
gfdl_cm2_1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
giss_model_e_r	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
inmcm3_0	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
ipsl_cm4	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
miroc3_2_medres	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
miub_echo_g	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
mpi_echam5	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
mri_cgcm2_3_2a	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
ncar_ccsm3_0	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
ncar_pcm1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
ukmo_hadcm3	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

FIG. 2. An example of the GCM/emission scenario selection options for the archive interface.

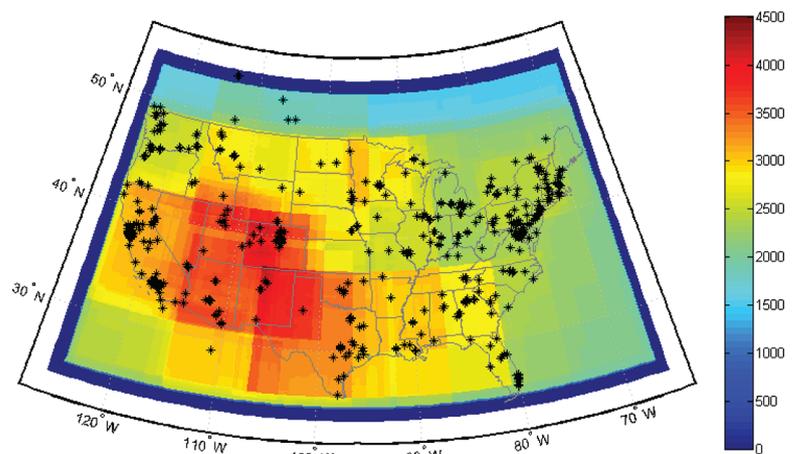


FIG. 3. Summary of archive downloads as of Sep 2013. Color coding indicates the number of times each 1/8° grid cell was downloaded. Each asterisk indicates a unique Internet Protocol (IP) address initiating the request.

sustainability index for the United States (www.nrdc.org/globalwarming/watersustainability; Roy et al. 2012).

CULTIVATING APPROPRIATE DATA USE.

One drawback to the unsupervised distribution of downscaled data is the possibility for inappropriate application of the data. For example, more than one instance has arisen where a user attempted to compare downscaled results for the historical period to observations to gauge the quality of the GCM projections. With the bias correction of all GCMs to the same observed data, the downscaled GCM simulations for the historical period are in many respects statistically indistinguishable. Any slightly closer correspondence of one set of downscaled GCM output to observations could not realistically be interpreted as an indication of better quality. A prominent feedback button on the interface allows users to send questions or concerns directly to the dataset creators, which has allowed these cases (as many as we are aware of) to be addressed before excessive time was spent on a fruitless effort.

The most common question from archive users is how many projections, and which climate models, should be selected to create an ensemble. This is a complex issue without a simple answer. A short summary of some recent findings on this is in Mote et al. (2011) and references therein. In general, to obtain a robust estimate of the ensemble mean, it is preferable to include at least 10–14 climate models (not multiple runs by the same model), with declining returns as more models are added. This can vary with location, variable, and time scale, so including more models is preferable to including fewer. While it seems reasonable to give greater weight to models that capture historic observed climate features that are important for the region of study (Knutti et al. 2010), in practice this often does not better characterize the range of projected mean changes (Sanderson and Knutti 2012; Weigel et al. 2010). There are some exceptional cases where a promising ability to rank models and potentially decrease uncertainty in the ensemble of projections has been demonstrated (Fasullo and Trenberth 2012; Walsh et al. 2008), although other studies (e.g., Pierce et al. 2009; Santer et al. 2009) have in contrast found no such advantages or have highlighted the difficulty in identifying tests that actually accomplish this (Coquard et al. 2004; Raff et al. 2009).

With the addition of CMIP5 output to the archive, users are unsure whether downscaled CMIP5 output should be preferred over CMIP3 output. The climate models in CMIP5 represent much

advancement achieved since the CMIP3 simulations were completed. Despite the inclusion of more physical processes in the models (e.g., some CMIP5 models having explicit treatment of the carbon cycle), the spread among the GCMs does not appear to be any greater than for CMIP3 (Knutti and Sedlacek 2013), and the representation of some climate features shows improvements (Guilyardi et al. 2012; Polade et al. 2013; Sakaguchi et al. 2012). Despite these promising studies, the CMIP5 GCM output has not been broadly demonstrated as providing more skillful projections of future climate than CMIP3. As long as this is the case, users may want to consider the CMIP5 projections to be an addition to rather than a replacement for the existing CMIP3-based data. This and other issues related to the new CMIP5-based content (including some intercomparison with CMIP3 projections) are discussed in a technical memorandum available on the archive website (Brekke et al. 2013).

CONCLUSIONS. The motivation for creating an archive of downscaled climate projections was to share data originally prepared to aid institutions in anticipating climate change impacts to water resources. Once the downscaled data were placed on a publicly accessible website capable of providing data for user-defined regions, time scales, and projections, the data use grew substantially, sometimes in ways not originally anticipated. While user demands will be met with expanded temporal resolution, variables available, and downscaling techniques represented in the archive, we also increasingly recognize the need to improve our understanding of the performance of different methods so that we can provide better guidance on the use of the downscaled data for examining projections of climate change impacts in different regions.

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