Hydrologic Response of the Columbia River Basin to Climate Change

The short version: *Climate change is expected to affect temperature and precipitation in the Pacific Northwest and change the region's hydrology. This web site provides streamflow information for the Columbia River and coastal drainages in Washington and Oregon State for the 21st century based on a large number of climate scenarios and model experiments. Detailed information about the study can be found under **Documentation**, while model results can be found under **Data**. The **project team** consisted of researchers in the UW Hydro | Computational Hydrology research group at the University of Washington and the Oregon Climate Change Research Institute at Oregon State University.*

The slightly longer version: The Pacific Northwest presents a mosaic of regional hydro-climates. While for many it conjures images of snow-capped peaks, emerald forests, and roaring rivers, it is also home to open plains and inland deserts. Water availability in our region affects local ecosystems, energy generation, water supply, fisheries, agriculture, navigation, and recreation.

The Columbia River, which drains much of the Pacific Northwest, is the fourth-largest river by volume in the United States. Hydroelectric facilities on its main stem and tributaries are responsible for nearly half of total U.S. hydroelectric power generation. Pacific Northwest rivers are also home to anadromous fish, such as salmon, that sustain environmentally, economically, and culturally important fisheries. Northwest rivers provide irrigation water for economically valuable crops and support barge transportation on the lower reaches of the Snake and Columbia Rivers. Northwest forests have important ecological functions and provide lumber and other natural products. Water-dependent recreational activities range from fishing and boating to downhill and cross-country skiing.

These competing uses can result in conflict at times. For example, as a result of habitat degradation, dam construction, reservoir operation, and other interventions, many salmon, trout, and sturgeon populations in the Pacific Northwest are now listed as threatened or endangered. With a rapidly increasing human population in the Pacific Northwest, careful management of water resources is necessary to ensure that the Columbia and other northwest rivers can support a diverse range of uses for the decades to come, from power generation to fisheries, and from recreation to ecosystem services. To this end, Pacific Northwest natural resources agencies and water managers need information about future patterns of water availability in the region, both in time and space.

Much of the Pacific Northwest experiences dry summers and wet winters. Combined with our mountain ranges and generally cold winters east of the Cascades, this winter-dominant precipitation regime has historically resulted in large amounts of snow (Mount Baker still holds the unofficial world record for the greatest recorded snowfall in a single season). Hydrologically, the snow pack acts as a large reservoir, retaining moisture during the winter and releasing it in spring and summer when rainfall amounts in the Pacific Northwest are low.

Climate change can affect the hydrology of the region in a number of ways. Even without changes in precipitation, changes in temperature will affect snow accumulation and melt. Temperature increases will result in more rainfall in winter, less water stored as snow, and earlier melt of these thinner snow packs. For some rivers, peak flows may no longer occur in spring, but may occur in fall and winter instead. Warmer summers may increase drought conditions, especially if less spring and summer runoff is available from mountain snow packs. Changes in precipitation may alleviate or worsen some of these impacts.

This web site provides streamflow information for the Columbia River and coastal drainages in Washington and Oregon State for the 21st century based on a large number of climate scenarios and model experiments. Detailed information about the study can be found under Documentation, while model results can be found under Data. The project team consisted of researchers in the Computational Hydrology group at the University of Washington and the Oregon Climate Change Research Institute at Oregon State University.

The River Management Joint Operating Committee released a report on the general findings of the study, which provides a synopsis of methods as well as results for different regions around the Pacific Northwest.

Funding: This study was partly funded by the Bonneville Power Administration as part of its Technology and Innovation Program (project BPA TIP304 to the University of Washington and Oregon State University), with additional funding to the University of Washington from the United States Bureau of Reclamation and the United States Army Corps of Engineers.

Acknowledgements: While the data sets produced as part of this study are the responsibility of the project teams at the University of Washington and Oregon State University, many people provided input and evaluated successive data set versions. We would like to acknowledge the contributions of the following persons and groups: the UW Hydro | Computational Hydrology Group at the University of Washington, in particular Joe Hamman, Yixin Mao, Mu Xiao (now at UCLA), and Katie Knight; Naoki Mizukami and Martyn Clark at the National Center for Atmospheric Research, Research Applications Laboratory for providing VIC model parameters; Shih-Chieh Kao, Bibi Naz, and Moetasim Ashfaq at Oak Ridge National Laboratories for providing VIC model parameters and dynamically downscaled meteorological data; Ming Pan at Princeton University for providing code and guidance for VIC model calibration; Katherine Hegewisch and John Abatzoglou at the University of Idaho for help with the MACA downscaling method; Eric Salathé for providing code and guidance for the BCSD downscaling method; the members of the technical review team, including Bruce Glabau, Kari Hay, Mariano Mezzatesta, Arun Mylvahanan, Eric Nielsen, Erik Pytlak, Nancy Stephan, and Rick van der Zweep at the Bonneville Power Administration; Pete Dickerson, Keith Duffy, Chris Frans, Jeremy Giovando, Kristian Mickelson, and Jason Ward at the United States Army Corps of Engineers; Bob Lounsbury, Jennifer Cuhaciyan, and Jennifer Johnson at the United States Bureau of Reclamation; and the participants in the many RMJOC-II Transboundary Workshops.

Contents

Front matter

- Attribution
- Project Report
- Funding
- Acknowledgements
- Copyright and license

Attribution: Chegwidden, O. S., B. Nijssen, D. E. Rupp, P. W. Mote, 2017: Hydrologic Response of the Columbia River System to Climate Change [Data set]. Zenodo. doi:10.5281/zenodo.854763.

Project report:

Columbia River Management Joint Operating Committee, 2018: 2018 Climate Change Study, Part I: Hydroclimate Projections and Analyses. Available online.

Funding: This study was partly funded by the Bonneville Power Administration as part of its Technology and Innovation Program (project BPA TIP304 to the University of Washington and Oregon State University), with additional funding to the University of Washington from the United States Bureau of Reclamation and the United States Army Corps of Engineers.

Acknowledgements: While the data sets produced as part of this study are the responsibility of the project teams at the University of Washington and Oregon State University, many people provided input and evaluated successive data set versions. We would like to acknowledge the contributions of the following persons and groups: the UW Hydro | Computational Hydrology Group at the University of Washington, in particular Joe Hamman, Yixin Mao, Mu Xiao (now at UCLA), and Katie Knight; Naoki Mizukami and Martyn Clark at the National Center for Atmospheric Research, Research Applications Laboratory for providing VIC model parameters; Shih-Chieh Kao, Bibi Naz, and Moetasim Ashfaq at Oak Ridge National Laboratories for providing VIC model parameters and dynamically downscaled meteorological data; Ming Pan at Princeton University for providing code and guidance for VIC model calibration; Katherine Hegewisch and John Abatzoglou at the University of Idaho for help with the MACA downscaling method; Eric Salathé for providing code and guidance for the BCSD downscaling method; the members of the technical review team, including Bruce Glabau, Kari Hay, Mariano Mezzatesta, Arun Mylvahanan, Eric Nielsen, Erik Pytlak, Nancy Stephan, and Rick van der Zweep at the Bonneville Power Administration; Pete Dickerson, Keith Duffy, Chris Frans, Jeremy Giovando, Kristian Mickelson, and Jason Ward at the United States Army Corps of Engineers; Bob Lounsbury, Jennifer Cuhaciyan, and Jennifer Johnson at the United States Bureau of Reclamation; and the participants in the many RMJOC-II Transboundary Workshops.

Copyright and license:

Contents

Introduction

Climate change, largely a result of anthropogenic greenhouse gas emissions, is expected to lead to significant warming of the planet over the coming decades (IPCC, 2014). This increase in temperature will be accompanied by changes in other aspects of the climate system, such as atmospheric circulation and precipitation. Resulting changes in hydrological fluxes (i.e. streamflow, evapotranspiration) and states (i.e. snow water equivalent, soil moisture) are likely to change the flow regime of many rivers around the world. The Columbia River, whose flow regime is heavily dependent on seasonal snow melt, will likely experience significant changes in the timing of the streamflow and possibly in total flow volume.

In 2013, The Bonneville Power Administration (BPA) solicited proposals as part of its Technology and Innovation Program to develop *"[...] a new set of temperature, precipitation, snowpack, and streamflow forecast projections for the entire Columbia River System, based on the new Global Climate Model datasets being published in conjunction with IPCC-5"*, where IPCC-5 refers to the global climate model experiments performed in support of the fifth assessment report of the IPCC (2014). In addition to updated global climate models, BPA was interested in an evaluation of the effect of methodological choices in the modeling process on the range of projected future hydrological conditions. Other requirements were:

- output at a daily time step for the period 1950-2100
- at least two Representative Concentration Pathways (RCPs)
- at least two downscaling techniques
- at least two hydrological models to generate unregulated flows
- account for glacial melt
- provide streamflow projections that are unbiased in the 1950-2010 (historic) period relative to best-available, estimated natural streamflows
- provided in a format usable by all three River Management Joint Operating Committee (RMJOC) members to run hydroregulation studies.

The work would be an update to the previous Columbia River climate change study performed for the RMJOC by the Climate Impacts Group at the University of Washington (Hamlet, 2011). Coloquially, this new iteration can be referred to as the **Columbia River Climate Change** study or **CRCC**.

The work presented here is the outcome of the project that was awarded to the UW Hydro | Computational Hydrology group at the University of Washington and the Oregon Climate Change Research Institute at Oregon State University. As detailed in the Methods section, the resulting data set takes advantage of advancements in climate models, downscaling methods, and hydrological modeling. The dataset is intended to be used for long-range planning by a variety of stakeholders in the region.

The general methodology that was used in the production of this data set follows that used in the production of the previous dataset (Hamlet, 2011). Specifically, we evaluated, downscaled and bias-corrected output from CMIP5 global models, so that the output could be used as input for regional-scale hydrological models, which cover the Columbia River Basin at a spatial resolution of 1/16°. Multiple hydrological models were then used to simulate the hydrology of the Columbia River Basin. The resulting spatial runoff was routed through the channel network to selected flow locations to produce daily streamflow sequences which were bias-corrected to produce daily natural flow records for the period 1950-2100. These streamflow time series are intended for use in impact studies. This procedure was applied to global climate model output based on two RCPs (RCP 4.5 and RCP 8.5). In accordance with the Opportunity Announcement, we produced transient streamflow time series for the entire 1950-2100 period.

Improvements and changes relative to the existing streamflow dataset (Hamlet, 2011) consist of the following:

- latest CMIP5 global climate model output, which also form the basis for the IPCC AR5 climate change assessments, as well as recent regional climate modeling
- multiple downscaling methods
- multiple hydrological models
- newer versions of GCMs, hydrologic models and streamflow bias-correction method.

While we have done our best to ensure consistency and quality across all permutations and locations, errors and/or problems do pop up on occasion. We keep track of known issues and their resolution.

Contents

Methods

Study domain and temporal extent

The dataset represented here provides projections of streamflow at 396 sites throughout the Pacific Northwest. Most of the sites are located within the Columbia River basin but the dataset also includes selected sites within the coastal drainages in Washington and Oregon.

The hydrological models were implemented at a spatial resolution of 1/16°, which corresponds to roughly rectangular grid cells that are 6 km or 3.5 mi on a side, resulting in 23,929 individual hydrological model elements (or grid cells) over the domain.

Most of the climate change simulations were run from water year 1950 through 2099. The exceptions are (1) the historical simulation which runs from 1960 through 2011; and (2) the time series resulting from the dynamically-downscaled meteorological forcings produced by collaborators at Oak Ridge National Laboratory.

Products

The main product of this project consists of streamflow time series for 396 locations. Because of the different **methodological choices**, there are 172 individual time series for each of these locations. In addition, for a subset (190) of these locations, we provide both **raw and bias-corrected versions** of these time series. All told, the streamflow dataset includes 100,792 individual streamflow time series. While this number may be overwhelming in aggregate, many users may only use a selected subset or slice from that large ensemble. We provide separate streamflow time series for every location in the domain for each climate scenario, global climate model, downscaling method, and hydrologic model set-up.

The River Management Joing Operating Committee released a **report** on the general findings of the study, which provides a synopsis of methods as well as results for different regions around the Pacific Northwest.

Methodological choices

One purpose of this study is to evaluate the impact that methodological choices have on streamflow projections under climate change. To construct a dataset that could probe that question, we devised a modeling tree which involved four decision points where we could choose among multiple options. These methodological choices were made with respect to:

- Representative concentration pathway
- Global climate model
- Downscaling method
- Hydrological model

Representative concentration pathway (RCP)

The Representative concentration pathways (RCPs) describe four different 21st century pathways of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions and land use (**IPCC 2014**). The RCPs are described in detail by **Vuuren et al. (2011)** and are available **online**. In turn, these RCPs were used by the Coupled Model Intercomparison Project Phase 5 **(CMIP5)** to create climate projections associated with each RCP.

As explained by **IPCC (2014)**), *"The RCPs include a stringent mitigation scenario (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0) and one scenario with very high GHG emissions (RCP 8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5 (Figure SPM.5a). RCP2.6 is representative of a scenario that aims to keep global warming likely below 2°C above pre-industrial temperatures."* In this project, we elected to evaluate climate projections associated with the lower intermediate scenarios and the highest scenario: RCP 4.5 and RCP 8.5. For the study domain, both scenarios produce a warmer future than historically observed, with RCP8.5 warmer than RCP4.5. It is important to keep in mind that the RCPs are possible concentration pathways and that actual greenhouse gas emissions may be lower or higher. The projected streamflow time series in this dataset are predicated on our choice of RCP 4.5 and RCP 8.5.

Global climate model (GCM)

Global climate models (GCMs) use the RCPs to supply boundary conditions to simulate different realizations of the future of the Earth's climate. Outputs from ten different global climate models were used in this study to investigate the uncertainty within hydrologic projections owing to choice of GCM. The **CMIP5 experiment** involved 31 GCMs, but this project uses outputs from 10 of them. The models were chosen based upon a variety of metrics detailed in **Rupp et al (2013)**. While the earlier Columbia River climate change project (**Hamlet, 2013**) used GCMs from many of the same modeling groups, these models have been significantly enhanced and updated.

Downscaling method

Downscaling is a technique which translates meteorological information at a relatively coarse spatial scale (~150 km) to the scale of the hydrologic model implementation (~6 km). Downscaling methods often incorporate a bias-correction step which removes systematic biases that the GCMs have in their simulations of the 20th century. For example, a particular GCM may be wetter and warmer than observed climatology when compared for a historical period. In climate change studies, we are predominantly concerned with the change in climate over a period of time. Therefore, we are interested in the change signal and correct the model output for historic biases. After all, if we use the GCM output that is too wet and too warm as input to a hydrology model, then we may not be able to simulate hydrological processes such as snow accumulation and melt with sufficient realism.

Three different downscaling/bias-correction methods were used to create the meteorological data for this project:

- The bias-correction, spatial-disaggregation (BCSD) technique **(Wood et al, 2004)**. This method uses a monthly quantile mapping approach to remove systematic biases at the GCM grid scale. It then uses an inverse square weighting method to map the GCM outputs onto the fine scale spatial variability of the domain. These meteorological forcings are available for 1950-2099. This is the method which was used in the RMJOC-I project.
- The multivariate adaptive constructed analogs (MACA) technique **(Abatzoglou and Brown, 2012)**. This method was developed and implemented by John Abatzoglou and Katherine Hegewisch at the University of Idaho. Like BCSD, it uses a training historical dataset to remove GCM biases. However, unlike BCSD, MACA uses an analog approach to match spatial patterns in global climate model output to map them to the fine scale variability of the domain. Another key difference is that the MACA approach uses daily output from the GCMs, while BCSD uses only monthly output. Like the BCSD forcings, these are available from 1950-2099.
- For a subset of GCMs and scenarios, we were able to use a set of dynamically-downscaled outputs developed by Moetasim Ashfaq and Shih-Chieh Kao at Oak Ridge National Laboratory **(Ashfaq et al., 2016)**. This method involved running a regional climate model to dynamically downscale the GCM output to an 18 km resolution. This output was then statistically bias-corrected to the resolution that is used as input for the hydrologic model. It is important to note that these forcings were trained to a different historical meteorological forcing dataset. Further, unlike the two statistical techniques described above, these forcings are only available from January 1966-November 2005 and January 2010-November 2050.

Hydrologic models

Four different hydrologic models were used in the development of the dataset. Three were distinct implementations of the **Variable Infiltration Capacity (VIC) model** and a fourth was an implementation of the **Precipitation Runoff Modeling System (PRMS)**. The VIC model used in this project involved a novel implementation of a simple glacier model. In the naming conventions of the dataset, the four different model set-ups are denoted by the hydrologic model followed by "PX" where X=1,2,3 set-ups are denoted by the hydrologic model followed by "PX" where X=1,2,3.

- VIC-P1: This implementation of VIC uses parameters calibrated by the University of Washington to the NRNI flow dataset provided by the RMJOC.
- VIC-P2: This implementation of VIC uses parameters calibrated by collaborators at Oak Ridge National Laboratory **(Naz et al., 2016)**.
- VIC-P3: This implementation of VIC uses parameters calibrated by collaborators at the Research Applications Laboratory at the National Center for Atmospheric Research.
- PRMS-P1: This implementation of PRMS uses parameters calibrated by the University of Washington to the NRNI flow dataset provided by the RMJOC.

Routing model

The streamflow from all hydrologic model setups was routed through a stream network using the same routing model and set-up. The RVIC model is a source-to-sink model developed originally by Lohmann et al. with improvements by (**Hamman et al. 2017**). See **rvic.readthedocs.io** for detailed documentation on the model.

Streamflow bias-correction

At 190 sites throughout the basin, the RMJOC provided time series of **no-regulation, no-irrigation (NRNI) streamflow**. These reference streamflows were used, where available, to adjust the modeled streamflow time series to remove systematic biases. The method uses the preservation of ratio technique described by **Pierce et al. (2015)**, with a number of adaptations to ensure that any change in annual volumes (i.e. a 15% increase or decrease in overall streamflow at a given site) is preserved between the raw and bias-corrected time-series. It is important to note that, as with most streamflow bias-correction procedures, the method breaks the water balance of the hydrologic modeling system, adding or removing water from the system such that there can be discontinuities between upstream and downstream locations. In addition, all flow locations are bias corrected independently, which may result in inconsistencies between upstream and downstream locations at short time scales.

Contents

Data sets

The main product of this project consists of streamflow time series for 396 locations. These come in both raw and bias-corrected forms for 190 of these locations.

Raw streamflow time series

Every one of the 396 locations throughout the domain includes **172 ensemble members** each representing a distinct realization of both the 20th century and the future 21st century. These time series are each unique both in their representation of the control period (the 20th century) and the future period.

The time series have not undergone any post-processing and so reflect exactly what the given hydrologic model set-up produces. This is a key point: the raw streamflow time series are directly synced with the hydrologic states of the modeling set-ups. Also, all of the streamflow time series within a stream network are consistent (a.k.a. streamflows increase monotonically from any given location to a downstream location).

However, accordingly, using streamflow time series directly from the hydrologic model results in systemic biases in the modeling set-up are carried through to each of the time series. For example, if streamflow at a given location is systematically too high given a poor calibration or errors in meteorological forcing information, that systematic bias will likely occur across all simulations. In general, these systematic biases are more pronounced for smaller basins.

Bias-corrected

For a subset of locations (190), we have produced **bias-corrected flows**. For these sites, RMJOC supplied no-regulation, no-irrigation time series which provide a record of what streamflow would have been without human impacts on the system. These time series were used to adjust the modeled streamflow time series to account for systematic model biases.

It is important to note that this additional modeling step breaks the water balance of the entire model set-up: streamflow is added or subtracted systematically. Further, unlike in the raw simulations described above, there may be discrepancies between upstream and downstream locations along a stream network.

Contents

How to find a sample time series

Hypothetical scenario: You want to better understand how streamflow on the Yakima River is projected to change by the end of the 21st century. You are curious about the change at two locations: Kiona and Troy.

1. Navigate to the `Data` tab in the upper-right corner of the website.
2. Locate your desired site for the Yakima River either:
   - in the dropdown menu by scrolling to `Yakima River` and selecting the location along the river you want or
   - Selecting the blue icon in the inset map corresponding to the location you want. After clicking on the blue pin, click the link below `Website` which will take you to the website housing that location's data.
3. After arriving at the website for **Yakima River at Kiona**, scroll down to find tables including the different modeling options. There is a different table for each downscaling method and RCP.
4. Select the hydrologic model parameter set within the table. Then choose which GCM you would like to select.
5. The desired cell within the table will include a `Raw` hyperlink which will take you to a link with a timeseries of streamflow. At 190 sites (including the Yakima River at Kiona location) there will also be options within the table with `BC` links to bias-corrected streamflow time series. At other locations (for example **Yakima River at Troy**) there will only be `Raw` timeseries available.
6. Click on the desired time series and a download will automatically begin. There is a separate file for every site and every permutation of modeling options. The top of each timeseries file includes a large section of metadata describing the file contents. Each of those lines begins with a `#` symbol. The time series then includes a date stamp and a set of daily instantaneous streamflow in cubic feet per second.
7. For analysis, the selected time series in this dataset is equivalent to the transient time series as produced in the RMJOC-I project. Every time series includes a control simulation in the 20th century which reflects the climate as modeled by the GCM for the past. A key note is that the control simulation reflects *statistically* the same climate as the past, but does not align with the same recorded weather as was observed. So, for example, the same total amount of precipitation occured in the past for the GCM simulation, but the drought of 1976-1977 does not necessarily exist within the control simulation. The climate change impacts take effect starting in 2006. Between 2006 and the end of the 21st century the streamflow time series experiences the changes in temperature and precipitation as modeled by the RCP-GCM-downscaling method selected.

Contents

References

Abatzoglou J.T. and Brown T.J., 2012: A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology*, doi:10.1002/joc.2312.

Ashfaq, M., D. Rastogi, R. Mei, S.-C. Kao, S. Gangrade, B. S. Naz, and D. Touma, 2016: High-resolution Ensemble Projections of Near-term Regional Climate over the Continental United States, *Journal of Geophysical Research*, 121, 9943–9963, doi:10.1002/2016JD025285.

Columbia River Management Joint Operating Committee, 2015: No Regulation, No Irrigation Flows 1928-2008 Corrected 03-2015. Bonneville Power Administration. Available online.

Columbia River Management Joint Operating Committee, 2018: 2018 Climate Change Study, Part I: Hydroclimate Projections and Analyses. Available online.

Gergel, D. R., B. Nijssen, J. T. Abatzoglou, D. P. Lettenmaier, M. R. Stumbaugh, 2017: Effects of climate change on snowpack and fire potential in the western United States. *Climatic Change*, doi:10.1007/s10584-017-1899-y.

Hamlet, A.F., M.M. Elsner, G. Mauger, S-Y Lee, I.M. Tohver, 2013: An overview of the Columbia Basin climate change scenarios project: Approach, methods, and summary of key results. *Atmosphere-Ocean*, doi:10.1080/07055900.2013.819555.

Hamman, J., B. Nijssen, A. Roberts, A. Craig, W. Maslowski, and R. Osinski, 2017: The coastal streamflow flux in the Regional Arctic System Model. *Journal of Geophysical Research: Oceans*, doi:10.1002/2016JC012323.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. Available online.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983: Precipitation-runoff modeling system-User's manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207 p. Available online.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994: A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models. *Journal of Geophysical Research - Atmospheres*, doi:10.1029/94jd00483.

Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K. Andreadis, E.P. Maurer, and D.P. Lettenmaier, 2013: A long-term hydrologically based data set of land surface fluxes and states for the conterminous United States: Updates and extensions. *Journal of Climate*, doi:10.1175/JCLI-D-12-00508.1.

Lohmann, D., E. Raschke, B. Nijssen, and D. P. Lettenmaier, 1998: Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model. *Hydrological Sciences Journal*, doi:10.1080/02626669809492107.

Naz, B. S., S. Kao, M. Ashfaq, R. Deeksha, R. Mei, L. Bowling, 2016: Regional hydrologic response to climate change in the conterminous United States using high-resolution hydroclimate simulations. *Global and Planetary Change*, doi:10.1016/j.gloplacha.2016.06.003.

Pierce, D. W., D. R. Cayan, E. P. Maurer, J. T. Abatzoglou, and K. C. Hegewisch, 2015: Improved bias correction techniques for hydrological simulations of climate change. *Journal of Hydrometeorology*, doi:10.1175/Jhm-D-14-0236.1.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, P. W. Mote, 2013: Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. *Journal of Geophysical Research: Atmospheres*, doi:10.1002/jgrd.50843.

Taylor, K.E., R.J. Stouffer, G.A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-D-11-00094.1.

Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith, and S. K. Rose, 2011: The representative concentration pathways: an overview. *Climatic Change*, doi:10.1007/s10584-011-0148-z.

Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D.P., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic Change*, doi:10.1023/B:CLIM.0000013685.99609.9e.

Contents

Known issues

This is a large data set, summarizing about 25 thousand model years (across all RCP, GCM, downscaling method and hydrologic model permutations) for nearly 400 locations. While we have done our best to ensure consistency and quality across all permutations and locations, errors and/or problems do pop up on occasion.

We keep a record of known issues and will report on these here. We will do our best to fix outstanding problems as soon as possible. Note that poor performance of the raw model simulations at some locations is unavoidable and something we cannot fix. However, spurious spikes in model out or in the bias-corrected files, negative numbers in the streamflow files other than blocks of `-9999` in the dynamically-downscaled simulations, formatting errors, etc. are things we would like to hear about.

Please consult these pages before filing a report by sending an e-mail to orianac@uw.edu. Use the subject line **Problem report for the CRCC streamflow data set**. Please be as specific as possible when filing a report, at minimum clearly stating:

1. the version of the data set in which you encountered the issue
2. the specific files including the issue
3. the specific issue

We will not be able to respond to generic queries and will not be able to support requests for help with data ingestion and formatting. Please use the suggested e-mail subject to ensure that the e-mail is not overlooked.

date filed	dataset version with found issue	date resolved	dataset version with issue resolved	issue	notes	action
2017-09-20	v1.0	2018-01-11	v1.1	Spurious spikes and `-9999` values in bias-corrected streamflows for some models at `COT` and `DOR` locations	This appears a result of multi-day sequences of `0` streamflow in the simulated streamflow for these locations	Added a very small, but inconsequential, offset to the simulated streamflows to remove `0` s from the record.
2017-12-05	v1.0	2018-01-11	v1.1	Spurious spikes and `-9999` values in bias-corrected streamflows for some models at `HAH` and `AUB` locations	This appears a result of the NRNI record for these two sites not extending the length of the period used for training the bias-correction.	For these two sites, the streamflow bias-correction used a training period constrained between WY 1963 and 2002.

Bart Nijssen
Oriana Chegwidden

UW Hydro | Computational Hydrology
Civil and Environmental Engineering
University of Washington

David E. Rupp
Philip Mote

Oregon Climate Change Research Institute
Earth, Ocean, and Atmospheric Sciences
Oregon State University