Overview of Regional Climate Scenario Development
at the Climate Impacts Group
March, 2010

The University of Washington Climate Impacts Group is an internationally recognized interdisciplinary research team studying the impacts of climate variability and climate change on the Pacific Northwest (PNW). For the last 15 years, members of the CIG have won acclaim for their leadership role in climate impacts research, outreach, and education for the region, conducting cutting-edge research at spatial scales ranging from local communities to the entire western U.S. Their research is funded by federal, state, and local sources including major federal grants from NOAA, NSF, EPA, and DOE. This program has yielded more than 300 publications and created an extensive set of tools and scientific resources used by stakeholders, including people in regulatory agencies, resource managers and policy makers, in addressing issues related to climate in the PNW. Key areas of the group's collective expertise include:

- Development of spatially-explicit meteorological data sets for use in resource impacts models
- Statistical downscaling techniques
- Regional climate modeling and the application of regional climate models to dynamically downscale climate change scenarios
- Seasonal to interannual climate variability and forecasting
- Macro scale and fine scale hydrologic modeling
- Water resources modeling and impacts assessment
- Terrestrial and aquatic ecosystem impacts assessment
- Coastal impacts assessment
- Climate change vulnerability assessment and adaptation planning
- Outreach and education programs

The CIG currently provides a wide range of climate change products and services to PNW stakeholders using a suite of statistically and dynamically downscaled climate projections based on global model simulations from the IPCC Fourth Assessment Report (IPCC AR4). In addition to these well-proven approaches, over the last five years the CIG has also developed an innovative, comprehensive, and well-funded regional climate modeling program that provides the foundation for the CIG's cutting-edge experimental downscaling research.

Current Climate Change Products and Services Based on Statistical Downscaling

In collaboration with the Washington State Department of Ecology and a group of regional stakeholders in Oregon, Washington, Idaho, Montana and British Columbia, the CIG is currently completing a two-year climate change study over the Columbia River basin and coastal drainages in Washington and Oregon. The study, which is one of the most comprehensive of its type in the country, provides detailed projections of future hydrologic conditions for 297 river locations in the PNW as well as a regional database of gridded (i.e., spatially-explicit) projections of climatic and hydrologic conditions over the entire study domain (http://www.hydro.washington.edu/2860/). The study chose the ten best-performing global climate models* for the PNW from the IPCC AR4 and used different global greenhouse gas scenarios and three different statistical downscaling approaches to produce projections for a variety of different future time periods (76 climate change scenarios in all). These scenarios were designed in collaboration with regional decision makers to support water resources planning and terrestrial and aquatic ecosystems research, impacts assessment and planning. The draft study results (which will be finalized this spring) are already being used by a wide range of stakeholders, including the U.S. Geological Survey, Bonneville Power Administration, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, U.S. Forest Service, U.S. Fish and Wildlife Service, Boise Aquatic Research Laboratory, and the National Marine Fisheries Science Center. Upon finalization of the scenarios, CIG will host a series of workshops introducing the scenarios and their potential applications in greater detail.

Overview of CIG's Downscaling Methods and Ongoing Research

The CIG has been developing effective and well-validated methods of downscaling global climate projections for over ten years, and houses leading research programs for both statistical downscaling and regional climate modeling (dynamic downscaling). These downscaling methods have been applied to the global climate model projections produced for the Third and Fourth IPCC Assessments (TAR and AR4) and will be applied to the Fifth Assessment (AR5/CMIP5) simulations as they become available. We are currently collaborating with the Oregon Climate Change Research Institute (OCCRI) at Oregon State University, Oxford University and the Hadley Centre in the United Kingdom to develop a regional version of the Oxford/Hadley global ClimatePrediction.net system for volunteer computing. CIG also uses a variety of publically available regional climate products from other research groups. These include simulations from the North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations and statistical downscaling results (*e.g.,* using the BCSD approach discussed below) from several sources. Although closely related to the downscaling approaches used by the CIG, both typically are of coarser resolution than the current CIG methods.

The CIG's suite of downscaling approaches includes:

1) **Statistical Downscaling.** An improved version of the Bias-Correction Spatial Downscaling (BCSD) method (Elsner *et al.*, 2010; Salathe *et al.*, 2007; Salathé, 2003; 2005; Widmann *et al.*, 2003; Wood *et al.*, 2004) has been developed at CIG and is also used by several other research groups. The current version of this method produces daily minimum/maximum temperature and precipitation on a 1/16-degree grid (roughly 5 km x 6 km; 3 x 3.6 miles) for the Columbia, Missouri, and Colorado basins. Several approaches have recently been developed to temporally downscale the monthly-mean model output to daily time steps, which produce significantly more realistic hydroclimate results than previous methods (Hamlet *et al.*, in prep.). The output from these downscaling approaches can be used directly as input to hydrologic models such as VIC, DHSVM, or those used by other researchers, water resource agencies, etc. As noted above, a large suite of hydroclimate scenarios using AR4 (CMIP3) global climate simulations (10 models and two emissions scenarios) and three statistical downscaling methods

* The 10 best models are selected according to their performance at simulating the observed 20th century climate.

are now available on-line (http://www.hydro.washington.edu/2860/). New simulations for the IPCC AR5 will be downscaled as they become available.

2) **WRF Regional Climate Modeling.** Regional climate model simulations using MM5 and now the WRF model have been underway for the past five years at CIG (Salathé *et al.*, 2007; Salathé *et al.*, 2008; Salathé *et al.*, 2009; Zhang *et al.*, 2009), building on the long-standing mesoscale weather forecasting system at the University of Washington (Mass *et al.*, 2003) and in collaboration with Pacific Northwest National Lab (PNNL) (Leung *et al.*, 1999; Wood *et al.*, 2004). Due to the computational demands inherent in regional climate modeling, only a few global simulations have been downscaled using this method. Currently, we have three 100-year scenarios simulated over the western United States. However, due to recent advances in regional climate modeling and computing power, we are now constructing a larger ensemble of simulations. Results are 3-hourly surface fields (*e.g.,* temperature, precipitation, winds, snow cover, soil moisture) and 6-hourly upper atmospheric fields on a 12-km grid over the Pacific Northwest and 36-km over the western United States. New simulations for the IPCC AR5 and coarse-resolution NARCCAP simulations will be dynamically downscaled using the WRF model as they become available. The high spatial resolution and frequent time step of the output allows the WRF results to be used in a wide range of climate impacts studies such as air quality modeling (Avise *et al.*, 2009; Chen *et al.*, 2009), urban stormwater management (Rosenberg *et al.* 2010), and fine-scale hydrologic modeling. This model is also a valuable tool for research on small-scale climate processes unique to our region.

3) **Regional ClimatePrediction.net** The ClimatePrediction.net (CPDN) project is a joint effort between Oxford University and the Hadley Centre in the United Kingdom to engage volunteers in running a climate model on their personal computers and generate very large climate ensemble experiments. In 2007, Oxford/Hadley Centre formed partnerships to develop regional versions of CPDN (regCPDN). A western U.S. project has been formed as a collaboration between OCCRI at Oregon State University, CIG, and Climate Central. The regCPDN modeling system is still in development; a beta version is expected in Spring 2010 with a full release by Summer 2010. This project will provide a very large ensemble of simulations of the regional climate to allow better understanding of uncertainties in regional climate projections. Volunteers will perform one-year climate simulations for current and future conditions; based on previous CPDN experiments, we anticipate well over 1000 volunteers. Results will include monthly-mean values and annualized statistics on a 25-km grid covering the US West. Output variables have been selected with societal and environmental applications in mind and include parameters for the mean surface climate (minimum and maximum temperature, precipitation, winds, humidity, and pressure), the jet stream, extreme weather (temperature, precipitation, winds), the hydrologic cycle, and coastal upwelling.

Statistical Downscaling and Regional Climate Modeling

While regional climate models (RCMs) allow for significantly better treatment of topographic influences on regional climate when compared with coarser-resolution global climate models, additional uncertainties and biases are introduced by RCMs. Furthermore, it is important to recognize that even the highest-resolution regional climate models are too coarse for many impacts studies. Consequently, as shown in Wood et al. (2004), it is not simply a question of choosing to use either statistical downscaling or dynamical downscaling with RCMs to provide climate change scenarios needed for impacts assessments. For most applications, RCM results must be statistically downscaled and bias corrected to produce climate scenario output appropriate for impacts applications.

Uncertainties in global climate model projections are a major consideration in climate impacts studies. Because dynamical downscaling with RCMs requires a great deal of computer time, few global climate model scenarios have been dynamically downscaled, and the range of scenarios examined this way is currently limited. In contrast, statistical downscaling (*e.g.,* BCSD) requires only modest computing power and therefore allows for downscaling many global climate model projections, which is important for sampling the uncertainty that currently exists in future climate projections. Additionally, the BCSD downscaling method does not add additional uncertainty to the climate projection; this method formally maps the climate change signal from the global model onto the observed regional climate patterns. RCMs simulate fine-scale weather processes that interact with terrain features that are important to local impacts and extreme events, factors that are at best poorly represented in coarse-resolution global climate models in regions with rugged terrain like western North America. Thus, RCMs create more diversity in climate projections by adding more pathways for local climate change to be expressed even when constrained by the output from a coarser-resolution global climate model. In this way, statistical BCSD downscaling and RCMs are highly complementary methods for developing high-resolution regional climate scenarios that are useful for local to regional scale climate change impacts assessments.

In contrast to the Bias-Correction Spatial Downscaling method and the WRF regional climate model, the regCPDN is not a downscaling method, but a system for generating a large ensemble of regional climate simulations using an integrated global atmospheric model (HadAM) and embedded regional model (HadRM). Different ensemble members will be produced by altering initial conditions or numerical parameters in the model. Thus, AR4 or AR5 global climate models will not be downscaled with this method. Output variables will be suitable for many climate impacts applications; however, this project will not produce daily or hourly data and full three-dimensional atmospheric fields that are required for some modeling applications, such as air quality. As such, the regCPDN program complements traditional RCM studies that can produce more detailed results, but for much smaller ensembles.

References

Avise, J., J. Chen, B. Lamb, C. Wiedinmyer, A. Guenther, E. Salathé, and C. Mass, 2009: Attribution of projected changes in US ozone and PM2.5 concentrations to global changes. *Atmos. Chem. Phys. Discuss.*, **9,** 1111-1124.

Chen, J., J. Avise, B. Lamb, E. Salathé, C. Mass, A. Guenther, C. Wiedinmyer, J.-F. Lamarque, S. O'Neill, D. McKenzie, and N. Larkin, 2009: The effects of global changes upon regional ozone pollution in the United States. *Atmos. Chem. Phys.*, **9,** 1125–1141.

Elsner, M. M., L. Cuo, N. Voisin, J. S. Deems, A. F. Hamlet, J. Vano, and D. P. Lettenmaier, 2010: Implications of IPCC 4th Assessment Report climate projections for the hydrology of Washington State in the 21st Century. *Climatic Change*, **in press**.

Hamlet, A.F., E.P. Salathé, P. Carrasco. 2010. Statistical Downscaling Techniques for GCM Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies (in prep) http://www.hydro.washington.edu/2860/products/sites/r7climate/study_report/CBCCSP_chap4_gcm_draft_20100111.pdf

Leung, L. R., A. F. Hamlet, D. P. Lettenmaier, and A. Kumar, 1999: Simulations of the ENSO hydroclimate signals in the Pacific Northwest Columbia River basin. *Bulletin of the American Meteorological Society*, **80,** 2313-2329.

Mass, C. F., M. Albright, D. Ovens, R. Steed, M. MacIver, E. Grimit, T. Eckel, B. Lamb, J. Vaughan, K. Westrick*, et al.*, 2003: Regional Environmental Prediction Over the Pacific Northwest. *Bulletin of the American Meteorological Society*, **84,** 1353-1366.

Rosenberg, E.A., P.W. Keys, D.B. Booth, D. Hartley, J. Burkey, A.C. Steinemann, D.P. Lettenmaier, 2010. Precipitation Extremes and the Impacts of Climate Change on Stormwater Infrastructure in Washington State. *Climatic Change*, **in press**.

Salathe, E. P., P. W. Mote, and M. W. Wiley, 2007: Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States pacific northwest. *International Journal of Climatology*, **27,** 1611-1621.

Salathé, E. P., 2003: Comparison of various precipitation downscaling methods for the simulation of streamflow in a rainshadow river basin. *International Journal of Climatology*, **23,** 887-901.

——, 2005: Downscaling simulations of future global climate with application to hydrologic modeling. *International Journal of Climatology*, **25,** 419-436.

Salathé, E. P., R. Steed, C. F. Mass, and P. Zahn, 2008: A high-resolution climate model for the U.S. Pacific Northwest: Mesoscale feedbacks and local responses to climate change. *Journal of Climate*, **21,** 5708-5726.

Salathé, E. P., Y. Zhang, L. R. Leung, and Y. Qian, 2009: Regional Climate Model Projections for the State of Washington. *Climatic Change,* **in press**.

Widmann, M., C. S. Bretherton, and E. P. Salathé, 2003: Statistical precipitation downscaling over the Northwestern United States using numerically simulated precipitation as a predictor. *Journal of Climate*, **16,** 799-816.

Wood, A. W., L. R. Leung, V. Sridhar, and D. P. Lettenmaier, 2004: Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs. *Climatic Change*, **62,** 189-216.

Zhang, Y., V. Duliere, P. W. Mote, and E. P. Salathé, 2009: Evaluation of WRF and HadRM Mesoscale Climate Simulations over the U.S. Pacific Northwest. *Journal of Climate*, **22,** 5511-5526.

Table 1. Downscaling products used at University of Washington, Climate Impacts Group.

Method	Institutions	Grid Spacing	Time Step	Time Coverage	Scenarios	Data Available
Statistical (BCSD)	UW CIG	1/16-degree (approx 6 km)	Daily	1900-2100	AR4 (CMIP3) AR5 (CMI5) when available	http://www.hydro.washington.edu/2860/
WRF RCM	UW CIG	36 km US West 12 km PNW	3-hourly Some hourly	1970-2070	AR4/AR5 models 4 currently 12+ planned	http://cses.washington.edu/data/pnwrcm (complete data on request)
Regional CPDN	OSU OCCRI UW CIG	25 km US West	Monthly and annual average statistics	1-year time slices current and future	Single model. 1000+ realizations (dependent on volunteers)	Anticipated late 2010 http://climateprediction.net/content/regional-model
NARCCAP	NCAR, Various	50 km North America	3-hourly	1971-2000 2041-2070	AR4 Models 12 Planned	http://www.narccap.ucar.edu/