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Climate Change in Wisconsin

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Project Overview

Wisconsin’s geographical setting gives rise to a rich set of climatic conditions that help shape our state’s environmental, social and economic resources. In the coming decades, we can anticipate that these influences on state resources will be affected in both expected and unexpected ways as our climate changes. Understanding and assessing these climate changes requires *(i)* expertise in previous climate changes, *(ii)* understanding of global climate projections – including their uncertainty, and *(iii)* understanding how these global projections relate to regional scale variables that are relevant for policy analysts and policy makers. A first step in assessing the influence of climate change on Wisconsin’s environment and economy involves *developing projections of climatic variables that are relevant to specific impacts in Wisconsin*. Unfortunately, the global climate models (GCMs) that produce projections of future climate have poor spatial resolution (the entire State of Wisconsin could be represented by as little as two grid points), and suffer major deficiencies in their ability to simulate non-standard climatic variables [such as extreme precipitation (hydrology, flooding, human health), snow fall and duration (wildlife management, tourism), freezing rain (energy infrastructure, forestry), etc.]. The disconnect between the information produced by GCMs and the information that is needed in specific impacts assessments is a major stumbling block for making climate change assessments relevant for policy analysts and policy makers.

Motivated by the needs of the impacts and policy communities for obtaining relevant climatic information for assessing climate changes in Wisconsin, the funded proposal included three major objectives:

1. Develop regional-scale, daily precipitation, and minimum and maximum temperature projections for Wisconsin for the 21st century
2. Calculate a set of non-standard climate variables needed by impacts and policy communities, using model output variables (including daily data from objective 1) and observations
3. Design a web-based repository for present-day climatic conditions and future climate projections that will be utilized by impacts scientists, policy analysts and makers, and the citizens of Wisconsin

Through the duration of the proposed work, the climate scientists worked closely with impact scientists, policy analysts, and policy makers through their involvement with the Wisconsin Initiative on Climate Change Impacts (WICCI).

Project Team

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Project Report

Funding from the FY 2008-2009 Focus on Energy Environmental and Economic Research and Development Program was provided to the Wisconsin Initiative on Climate Change Impacts (WICCI) Climate Working Group (CWG) to develop and disseminate projections of climate change over Wisconsin (primary tasks outlined below). Data were to be produced at a temporal and spatial scale that would be relevant for climate impact assessment in Wisconsin. In particular, the major objectives of the present proposal are:

1. Develop regional-scale, daily precipitation, and minimum and maximum temperature projections for Wisconsin for the 21st century
2. Calculate a set of non-standard climate variables needed by impacts and policy communities, using model output variables (including daily data from objective 1) and observations
3. Design a web-based repository for present-day climatic conditions and future climate projections that will be utilized by impacts scientists, policy analysts and makers, and the citizens of Wisconsin

The funded project succeeded in accomplishing and in many ways surpassing these three objectives.

The major objectives of this research are described below. More description of the project can be found in the individual progress reports (submitted seperately), the Schedule of Work, the description of the downscaling methodology (Lorenz et al. 2011a), a user guide to the downscaled data (Lorenz et al. 2011b), and the description of historical and anticipated climate change in Wisconsin (Vimont et al. 2011; this document is included as a Supplementary Document).

I. Develop regional-scale, daily precipitation, and minimum and maximum temperature projections for Wisconsin for the 21st Century

The primary objective of this project was to develop a set of regional-scale projections of daily temperature and minimum and maximum temperature that could be used in climate impact assessments throughout the state. In producing these projections, a series of conversations between climate scientists (those associated with the project) and other scientists and stakeholders took place during Summer 2007 – Summer 2008 (and continued through the course of the project) to identify priorities for user data needs. The following needs were identified:

1. Data should be at a fine spatial scale (about 10km by 10km) to allow resolution of regional scale variations.
2. Data should be produced at a daily time scale.
3. Extreme events (e.g. intense precipitation events, exceptionally warm or cold days) should be well represented in the data.
4. Uncertainty should be characterized in the analysis.
5. The following variables are needed for this project: precipitation, maximum temperature, minimum temperature, daily mean temperature, snowfall and snow depth, potential evapotranspiration.

The downscaled data that were developed under this project accounted for these needs.

The original proposed work outlined a methodology for producing downscaled daily temperature and precipitation at a fine-scale resolution for Wisconsin. The proposed methodology had been used by other researchers to successfully downscale monthly temperature and precipitation. However, upon initiation of the project, the team quickly realized that the proposed methodology would not adequately represent extreme events. As such, the original proposed methodology was scrapped, and a new methodology was developed "from scratch". The new methodology is outlined in Lorenz et al. (2011a), and in Notaro et al. (2010).

Based on requirements for daily, fine spatial scale data with realistic representation of extreme events, a new downscaling methodology was developed during the first six months of the project. This methodology was developed by David Lorenz. The methodology is novel in that instead of downscaling a particular variable to a given location, the methodology downscales the probability distribution that a variable should follow, given information about the large-scale flow. The methodology is described below.

The statistical downscaling consists of two stages. First, the statistical relationship between the large-scale atmospheric state and local temperature / precipitation at weather stations is determined for each calendar month from the observational record (1950-2007). Second, this established statistical relationship is applied to predict the local temperature / precipitation given a climate model's large-scale atmospheric state. The relationship between the large-scale atmospheric state and the weather stations is cross validated for all variables and seasons by alternately leaving out three years of data, fitting the remaining years and testing the fit on the left out data. The cross validation suggests that all statistical relationships found are robust.

Typically, statistical downscaling is used to relate the large-scale atmospheric state to one specific value of the temperature / precipitation at a point. With this approach, however, the downscaled variability and extremes at the point will be too small unless the relationship between the large-scale and the point is artificially inflated (von Storch 1999), which then artificially exaggerates the climate change resulting from changes in the large-scale. Therefore, in order to both simulate the variability and extremes *and* to properly account for the effect of the large-scale on the weather at a point, we relate the large-scale atmospheric state to the Probability Density Function (PDF) of temperature / precipitation at a point instead of a single value of temperature / precipitation. This approach takes into account that the large-scale atmospheric state does not completely specify the evolution of the atmosphere at small scales, instead the large-scale specifies the range and likelihood of particular outcomes at a point. To create a specific downscaled time series of temperature / precipitation at a point, we draw random numbers from the particular PDF for each individual day in the record. Obviously, there are an infinite number of possible time series given the large-scale atmospheric evolution. We call these possible outcomes *realizations*.

For maximum and minimum temperature, we use linear regression to relate large-scale maximum / minimum temperature to local maximum / minimum temperature. In classical linear regression, the errors in the linear 'fit' between the predictand and the predictor are assumed to be a Gaussian distribution with variance equal to the error variance. This Gaussian distribution with mean given by the linear 'fit' and constant error variance is the PDF of local temperature given the large-scale. Note that linear regression only assumes that the *errors* from the linear fit are Gaussian. Although the temperature in certain seasons can be strongly skewed, we find that the large-scale temperature is also strongly skewed so that linear regression actually works quite well.

For precipitation, we use two separate statistical models: one for the occurrence of precipitation (is the day wet or dry?) and the other for the amount of precipitation if the day is wet. Because the distributions of both precipitation occurrence and precipitation amount are highly nonnormal, we use more flexible statistical models including Generalized Linear Models (GLM) (Nelder and Wedderburn, 1972). For precipitation occurrence, we use the GLM also known as logistic regression. For precipitation amount we find that GLMs are not general enough so we fit the precipitation amount to the generalized gamma distribution (Stacy, 1962) with the scale parameter and one of the shape parameters dependent on the large-scale atmospheric state. Both of these precipitation models are fit using maximum likelihood.

We use the NCEP Reanalysis (Kalnay et al., 1996) for the large scale and the National Weather Service's Cooperative Observer Program's (COOP) for the point observations. The COOP stations within 42.1-47.1°N, 93.4-86.6°W that report at least 83.3% of months during January 1950 to December 2007, and do not exhibit blatant observer biases in precipitation occurrence / weak precipitation (Daly et al., 2007), are included, consisting of a well-distributed network of 170 stations for daily maximum and minimum temperature and 164 stations for daily precipitation. Before applying the fitted relationship between the Reanalysis and the COOP stations to the climate models, we quantile adjust the climate models' PDFs of the large-scale predictors to remove climate model biases (e.g. Wood et al., 2004).

For this project we have generated three realizations of gridded daily precipitation and maximum and minimum temperature. Instead of interpolating the raw atmospheric variables from the stations to the grid, the parameters of the PDFs are first interpolated to a 0.1 ° x 0.1° grid and then random realizations are generated using the gridded PDFs. This basically eliminates the reduction in variance and extremes that typically occurs when one interpolates the raw data.

Results for expected climate change in Wisconsin are constructed from available daily output from the CMIP3 archive. Changes are expressed as the expected average climate change by mid 21st century (2046-2065) and by late 21st century (2081-2100) relative to average conditions over the late 20th century (1961-2000). Results in this analysis are presented for three different future scenarios for greenhouse gas emissions from the Special Report on Emissions Scenarios (SRES; see Nakicenovic et al. 2000): the B2 scenario (low emissions), the A1 scenario (high emissions) and the A1B scenario (moderate to high emissions). Although observed emissions since 1990 have exceeded even the highest of these three scenarios (Raupach et al. 2007), these three scenarios still represent reasonable guesses for expected climate change over the 21st century in the absence of aggressive global mitigation.

The resulting data set includes the following:

- Three first order variables: precipitation, maximum temperature, and minimum temperature
- 0.1° by 0.1° spatial resolution (about 10km by 10km)

- Downscaled projections are produced for each of fourteen different large-scale climate model projections (some scenarios have fewer than fourteen models)
- Data are downscaled for the "Climate of the 20th Century Simulation" (20C3M; 1961-2000), and the three different emissions scenarios described above (B1, A2, A1B; 2046-2065 conditions, and 2081-2100 conditions). Further work (requested by forestry scientists) extended the time periods to a continuous record from 1960-2100.
- For each model, each emissions scenario, and each time period, three different realizations of the downscaled data were produced (to better include extreme events in the downscaled data).

To our knowledge, this data set represents one of the most comprehensive sets of downscaled data available for a given region. In all, the first order data (only these three variables) amounts to ~200Gb of information.

Additional information about the methodology, and a tutorial on how one can use the data, is provided in Lorenz et al. (2011a, 2011b).

II. Calculate a set of non-standard climate variables needed by impacts and policy communities, using model output variables (including daily data from objective 1) and observations

The second set of objectives involved constructing additional, "second order" variables for describing climate change in Wisconsin. These variables use the downscaled precipitation and maximum and minimum temperature data that were developed under Objective I, and as such are not directly downscaled. We produced estimates of snow (snowfall, coverage, depth, duration), potential evapotranspiration, and plant hardiness zones. Specific methodologies for snow variables and potential evapotranspiration are included in Notaro et al. (2010) and in Vimont et al. (2011).

To produce projections of snow cover changes, the WICCI downscaled temperature and precipitation data, for the late 20th century (20C3M) and both mid- and late 21st century (A2, A1B, and B1 emission scenarios), were used to force the National Weather Service conceptual snow accumulation and ablation model, SNOW-17 (Anderson, 1973, 2002, 2006). For each of 11-15 global climate models and all emission scenarios, three realizations of climate data are used to drive the snow model. Changes in Wisconsin-averaged snowfall, snow depth, and snow cover fraction are presented in Notaro *et al*. (2010).

Potential evapotranspiration represents the amount of water that could be evaporated from land, water, and plant surfaces if soil water was unlimited, or the maximum water loss to the atmosphere. It is largely driven by temperature and solar radiation. Potential evapotranspiration calculations used the widely-accepted Priestley-Taylor (1972) method to estimate daily potential evapotranspiration using the WICCI downscaled climate data. Based on this method, an increase in temperature results in an increase in evapotranspiration, while an increase in atmospheric moisture or cloud cover (evident by a lower diurnal temperature range) results in reduced solar input to the Earth's surface and thus reduced evapotranspiration. Using the downscaled temperature data for Wisconsin, daily potential evapotranspiration was estimated for the late 20th century (20C3M) and mid- and late 21st century (A2, A1B, and B1 emission scenarios) for three realizations of 11-15 global climate models. Given that only maximum temperature, minimum temperature, and precipitation are available in the WICCI downscaled dataset, several approximations are applied in computing potential evapotranspiration, such as relating the difference between the daily maximum and minimum temperature to the amount of solar radiation attenuated by atmospheric moisture and clouds.

Projected shifts in the plant hardiness zones and the impact on gardening of perennial plants in Wisconsin are explored in Notaro *et al*. (2010a). Based on downscaled average annual minimum temperature from the WICCI downscaled climate data, maps of the USDA plant hardiness zones for Wisconsin are produced for the recent historical period (1980-1999), mid-21st century (2046-2065), and late 21st century (2081-2100) using both A2 and B1 emission scenarios. Presently, zones 3b-5b are found in Wisconsin, with Washburn County as a location representative of zone 3b and Milwaukee County representative of zone 5b.

III. Design a web-based repository for present-day climatic conditions and future climate projections that will be utilized by impacts scientists, policy analysts and makers, and the citizens of Wisconsin

The underlying goal of this objective was to provide a means for disseminating the downscaled climate data to other researchers and to the public. We accomplished this goal through two methods: individual interactions with other researchers, and a more general interface for viewing the major results of the analysis.

Instead of serving the entire data set over the web, we dealt with data requests on an individual basis. As mentioned earlier, the precipitation and maximum and minimum temperature data amount to over 200Gb of data (snow and potential evapotranspiration projections nearly doubled the amount of data) in NetCDF format (which is not always standard). Addressing requests on a case-by-case basis required more time, but in the long run was more productive as we could tailor the data to the specific needs of the particular research group. Some examples of data that were provided include: maps of model mean changes in variables provided in either NetCDF or ArcGIS format, time sequences of probability distribution parameters for point locations (for hydrological applications), spatio-temporal downscaled data, rescaled historical time series (used for assessing hydrological impacts in Milwaukee), and spatial maps of various variables.

In tandem with the completion of Objective I above, we produced plots of historical and projected climate change in Wisconsin. These plots were posted on an interactive website at: http://ccr.aos.wisc.edu/cwg, and provide a resource for public dissemination of the data, as well as a source for researchers with minimal data needs. The release of the website coincided with a media release and information campaign about WICCI to ensure that researchers and individuals in the state were made aware of the projections.

Finally, this project helped to fund the Wisconsin Initiative on Climate Change Impacts First Assessment Report, which will be released on Feb. 8, 2011. Much of the analysis in that assessment report would not have occurred without the downscaled data that were produced under this project. The Assessment Report is an excellent example of the outreach and public dissemination that were deemed an important part of the present project.

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Lorenz, D. and the Wisconsin Initiative on Climate Change Impacts Climate Working Group 2011b: Downscaling Temperature and Precipitation for Wisconsin – A summary of the Data for CCR. *In Progress.*

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Publications Resulting from this Grant

I. Peer Reviewed Publications

Kucharik, C. J., S. P. Serbin, E. J. Hopkins, S. Vavrus, and M. M. Motew, 2010: Patterns of climate change across Wisconsin from 1950 to 2006. *Physical Geography*, **31**, 1-28. Notaro, M., D. Lorenz, and D. Vimont, 2010: 21st century Wisconsin gardening – Transformed by climate change. *Wisconsin Natural Resources*, August 2010, 17-19. https://mywebspace.wisc.edu/mnotaro/web/garden_wisconsin.pdf

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Wisconsin Initiative on Climate Change Impacts, 2011: Wisconsin's Changing Climate: Impacts and Adaptation. 2011. Wisconsin Initiative on Climate Change Impacts. Nelson Institute for Environmental Studies, University of Wisconsin-Madison and the Wisconsin Department of Natural Resources, Madison, Wisconsin. *Available from:* http://www.wicci.wisc.edu/publications.php

II. Publications in Preparation for Peer Review

Holman, K. and S. Vavrus, 2011: Understanding extreme precipitation events in climate simulations of the twentieth and twenty-first centuries. *In Preparation for J. Hydrometeorology.*

III. Other Publications

Holman, K. 2010: Understanding extreme precipitation events in climate simulations of the twentieth and twenty-first centuries. Masters Thesis, University of Wisconsin – Madison Department of Atmospheric and Oceanic Sciences. 48pp.

Lorenz, D. and the Wisconsin Initiative on Climate Change Impacts Climate Working Group 2011a: Downscaling Temperature and Precipitation for Wisconsin. *In Progress. Available via email to the author.*

Lorenz, D. and the Wisconsin Initiative on Climate Change Impacts Climate Working Group 2011b: Downscaling Temperature and Precipitation for Wisconsin – A summary of the Data for CCR. *In Progress. Available via email to the author.*

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Appendix A: Findings from the Climate Working Group

A copy of Vimont et al. (2011), the WICCI CWG contribution to the WICCI First Assessment Report, is provided as a separate, supplementary document, which outlines the major findings from the downscaled data.