



Future Climate Sector Midwest Technical Input Report National Climate Assessment

Climate Projections for the Midwest: Availability, Interpretation and Synthesis

WHITE PAPER PREPARED FOR THE U.S. GLOBAL CHANGE RESEARCH PROGRAM
NATIONAL CLIMATE ASSESSMENT
MIDWEST TECHNICAL INPUT REPORT

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At the request of the U.S. Global Change Research Program, the Great Lakes Integrated Sciences and Assessments Center (GLISA) and the National Laboratory for Agriculture and the Environment formed a Midwest regional team to provide technical input to the National Climate Assessment (NCA). In March 2012, the team submitted their report to the NCA Development and Advisory Committee. This white paper is one chapter from the report, focusing on potential impacts, vulnerabilities, and adaptation options to climate variability and change for the future climate sector.



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Summary

Climate projections from multiple sources display close agreement regarding future changes for the Midwest region in annual and seasonal mean temperature, the frequency of temperature thresholds including heat wave occurrences, and the magnitude of temperature indices such as degree day accumulations. Comparison and integration of the downscaled temperature projections also illuminate relatively consistent spatial patterns in projected future temperature change across the Midwest. In contrast, projections of future precipitation change remain highly uncertain for the Midwest. The majority of climate projections are in agreement regarding the sign of the projected change for only the winter season. Precipitation intensity is generally projected to increase by the mid and late century, although error in the downscaled simulations of the frequency distribution of daily and subdaily precipitation for the current climate complicates interpretation of future changes in intensity. Given the importance of extreme hydroclimatic conditions to the region, improved simulation of precipitation is a high priority. Wind climates, particularly wind extremes, represent a major vulnerability to the Midwest. Some wind extremes occur at scales below those captured by global and regional climate models or involve processes that are not well understood, but the current suite of climate projections suggests little change in wind resources or wind extremes to the middle of the current century.

Introduction

Climate change projections, also referred to as climate scenarios, are widely used for assessments of the potential impacts of climate change on natural processes and human activities, including assessments conducted at the local/regional scale such as the scale of the National Climate Assessment Midwest region. A number of different approaches are used to develop climate projections, and the strengths and limitations of each method must be taken into consideration when selecting projections for use in a specific application and when interpreting, comparing, and integrating outcomes from multiple assessment studies and impact analyses.

This whitepaper focuses on climate projections for the National Climate Assessment Midwest region, defined as the states of Minnesota, Iowa, Missouri, Wisconsin, Michigan, Illinois, Indiana and Ohio (National Climate Assessment Factsheet 2012). The goals of the whitepaper are two-fold. First, we briefly review commonly-used approaches to develop local/regional climate projections and highlight strengths and limitations. The intent is to provide readers with a sufficient, although rudimentary, understanding of climate projections for an informed and nuanced interpretation of the substantial literature on potential climate impacts in the Midwest region. Second, we summarize by climate variable potential future changes in the Midwest as synthesized from currently-available peer-reviewed and gray literature. This whitepaper expands upon the document, "Climate of the Midwest U.S.," prepared by Kunkel et al. (2012) for the National Climate Assessment Development and Advisory Committee, in that it is more comprehensive in scope, incorporating the wide range of climate projections available for the region.

Climate Projections

Downscaling Methods

Most often, climate change projections are derived from simulations obtained from global climate models (GCMs). GCMs have a relatively coarse spatial resolution; for example, those used for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) had latitude-longitude spacing that ranged from 4° by 5° to about 1.1° by 1.1°. This motivates the use of "downscaling" methods to infer the high spatial and/or temporal resolution needed for many impact assessments. Downscaling procedures traditionally are classified as either "dynamical" or "statistical".

Common downscaling methods are briefly summarized below and illustrated in Figure 1. Several detailed reviews of downscaling approaches are available (e.g., Mearns et al. 2003; Wilby et al. 2004; Benestad et al. 2008). The summary below is drawn primarily from Winkler et al. (2011a,b), and readers are referred to the original articles for more information including a "checklist" of considerations for evaluating alternative downscaling options (Winkler et al. 2011a).

It is not possible to argue for one downscaling approach as universally "better" than another (Christensen et al. 2007). Rather, the different approaches should be viewed as complementary, and the choice of downscaling approach(s) should be appropriate to the assessment objectives.

Dynamically-downscaled climate projections

Dynamical downscaling employs numerical models, such as regional climate models (RCMs), to simulate fine-resolution climate fields, and can be particularly useful when mesoscale (a few to several hundred kilometers) circulations strongly influence the local/regional climate or when regional-scale influences such as terrain or changing land use are anticipated to have large effects on the future climate of the region (Winkler et al. 2011a). RCMs, like GCMs, are based on the fundamental equations of atmospheric dynamics and thermodynamics. For this reason dynamical downscaling is often a better choice when an assessment requires a suite (e.g., temperature, humidity, wind, and radiation) of physically consistent and spatially and temporally coherent climate variables (Hanssen-Bauer et al. 2005). Typical horizontal resolutions of RCMs for multi-decadal, continental-scale simulations are on the

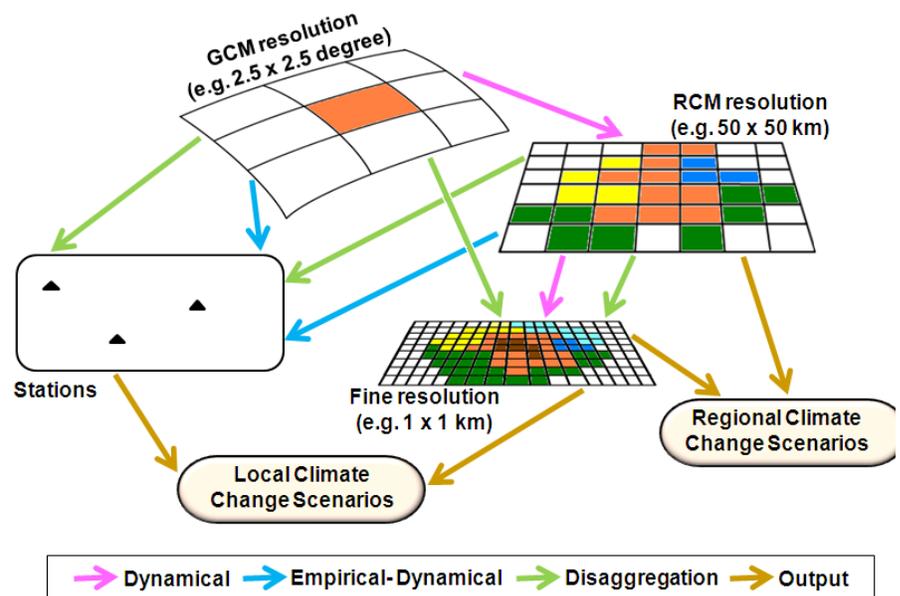


Figure 1. Illustration of the spatial scales of climate projections, as developed using dynamical, empirical-dynamical, and disaggregation downscaling methods applied to GCM simulations. Note that multiple downscaling steps can be applied. SOURCE: Winkler et al., 2011a.

order 25-50 km (Rummukainen 2010). Simulations with resolutions of only a few kilometers are possible using multiple nested RCMs, or when considering shorter periods or smaller domains (e.g., Liang et al. 2004; Hay et al. 2006). For comparison to observations, RCMs are driven by lateral boundary conditions obtained from reanalysis fields, in which a GCM is constrained to follow observations. The reanalysis, which very simply can be thought of as a “blend” of observations and model output, is considered to represent a “perfect” (more correctly, the best possible) GCM and thus allows the errors and biases of the RCM itself to be isolated. RCMs are also driven by coarse-scale simulations from GCMs both for historical and future periods. Comparisons of RCM results when driven by historical reanalyses with corresponding results when driven by a GCM simulation of the corresponding period help to determine errors attributable to using the GCM’s depiction of current climate to force the downscaled results.

Resource constraints often limit RCM simulations to relatively short periods of a few decades in length (e.g. Christensen et al. 2002; Leung et al. 2004; Plummer et al. 2006), especially when a very fine resolution is employed or when simulations are needed over a large spatial domain. Furthermore, simulations with a given RCM typically have been driven by a single GCM or only a small number of GCMs. This limitation arises from several practical considerations: GCMs do not usually store the high time resolution data needed for RCM boundary conditions; the differing output formats for different GCMs require extensive coding or data reformatting so that the data can be read by the input procedures used in the RCMs; and execution of RCMs requires substantial computing time and human resources. Both short simulation periods and limited number of GCMs used in RCM studies have implications for evaluating the uncertainty surrounding projected changes. These constraints may be ameliorated in future RCM simulations that use the CMIP5 GCM results currently being produced. The CMIP5 protocol includes provision for saving output from participating GCMs at sufficient time resolution for use as RCM boundary conditions so that suitable output from more GCMs will be available. The CMIP5 GCMs also use a standard output format which should reduce the effort needed to adapt an RCM to boundary values from different GCMs.

An example of dynamical downscaling is the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009, 2012), which has generated a uniquely detailed suite of regional-scale climate output that is being used extensively in the National Climate Assessment. Under NARCCAP, RCMs have been driven both by reanalysis fields and by GCM results. In the former the lateral boundary conditions are supplied by output from the NCEP-DOE reanalysis (shown as NCEP in Table 1), while in the latter a suite of four GCMs has been used to provide the nesting. Output is

available to all parties and for many variables at a daily or higher temporal resolution.

Statistically-downscaled climate projections

A wide variety of empirical methods are employed in statistical downscaling. Following Winkler et al. (2011a), we categorize statistical downscaling approaches into two broad categories, namely empirical-dynamical downscaling and disaggregation downscaling. The categorization reflects differing underlying philosophies in the downscaling approach. Empirical-dynamical downscaling does not operate directly on the variable of interest as predicted by the global model, typically a surface weather variable such as temperature, precipitation or wind speed. Instead, the variable is inferred from derived relationships to large-scale variables predicted by the model, and selected to represent important dynamical and physical processes in the atmosphere. For example, precipitation can be inferred from a mid-atmospheric circulation property such as vorticity (e.g. Schoof et al. 2010). Underlying this approach is the assumption that GCMs are able to better simulate circulation and “free atmosphere” (i.e. above the boundary layer) variables compared to surface climate variables, as they are less influenced by complex surface fluxes and interactions. Thus, the circulation and free atmosphere variables represent the larger scale environment, and the empirical relationships implicitly capture the effects of local topography, geography and boundary conditions on the surface variables. Another important assumption is that the circulation and/or free atmosphere variables capture the climate change signal. Many empirical-dynamical downscaling approaches are patterned after short-range forecasting techniques such as model output statistics (MOS; Karl et al. 1990) or employ weather typing techniques to link circulation with local or regional climate.

Disaggregation methods attempt to infer fine-scale values from coarse-scale spatial or temporal fields of a particular variable, such as precipitation, although additional variables, including circulation and free atmosphere variables, may be included in the downscaling function to

Table 1: Available NARCCAP simulations.

Regional Climate Models (RCMs)	Global Climate Models (GCMs)				
	GFDL	CGCM3	HADCM3	CCSM	NCEP
CRCM		X		X	X
ECP2	X		X		X
HRM3	X		X		X
MM5I			X	X	X
RCM3	X	X			X
WRFG		X		X	X
Time Slices	X			X	
ECPC					X
WRFP					X

SOURCE: <http://www.narccap.ucar.edu/>

improve the relationship. Often the large-scale values are first adjusted for bias (error) in the GCM simulated values. To date, disaggregation downscaling has been the most common approach for developing local/regional climate projections. The relatively fewer resources needed for disaggregation downscaling methods compared to either dynamical or empirical-dynamical downscaling likely has contributed to their popularity. In particular, the “delta method” was one of the first downscaling methods employed in climate impact assessments. For this popular approach, coarse-scale GCM simulations of monthly means and accumulations of climate variables (e.g., surface temperature and precipitation) are spatially interpolated to a finer resolution grid or to station locations, the difference or ratio between the GCM projected value for a future period and for a control (historical) period is calculated, and the differences (for temperature) or ratios (for precipitation) are applied to gridded or station specific historical observed time series. One limitation of the delta method is that it does not capture future changes in variability. Temporal disaggregation is also commonly used. For example, stochastic weather generators (e.g. Wilks 1992; Katz 1996; Semenov and Barrow 1997; Dubrovsky et al. 2004, Qian et al. 2008; Semenov 2008) are often used to obtain finer temporal resolution from monthly projections. Typically, weather generators use Markov processes to simulate wet/dry days and then estimate wet day amounts, temperature and solar radiation conditional on precipitation occurrence (Wilby et al. 2004; Wilks 2010). Recent developments in weather generators include preserving the spatial and temporal correlations of the climate variables among locations (e.g., Baigorria and Jones 2010).

An assumption of both empirical-dynamical and disaggregation downscaling is that the statistical relations are stationary in time; i.e., relationships observed for the current climate will be applicable in the future. In contrast to dynamical downscaling, statistical downscaling is not as resource intensive, making it easier to build a larger ensemble (i.e., suite) of projections based on a number of GCMs and also to include multiple future time slices.

Available Climate Change Projections for the National Climate Assessment Midwest Region

In the support documents provided by Kunkel et al. (2012), four sets of climate projections are utilized. These include: 1) coarse-scale simulations from fifteen GCMs obtained as part of the Climate Model and Intercomparison Project Phase 3 (CMIP3; Meehl et al., 2007), 2) time series of monthly temperature and precipitation at a 1/8° latitude/longitude resolution obtained by applying a combined bias correction and spatial disaggregation downscaling procedure known as the “BCSD method”

(Maurer et al. 2002) to the CMIP3 GCM simulations, 3) daily time series of temperature and precipitation obtained from temporal disaggregation of the BCSD spatially downscaled monthly and temperature values by adjusting randomly-selected observed daily time series by the projected differences in the monthly values (i.e., the delta method), and 4) nine RCM simulations obtained from the North American Regional Climate Change Assessment Project (NARCCAP). Thus, the guidance provided to the National Climate Assessment includes one set of non-downscaled climate projections, two sets of projections downscaled using disaggregation approaches but with different temporal resolutions, and a set of dynamically-downscaled projections.

Considerable additional resources are available for climate change assessments for the Midwest region. A number of fine-resolution climate projections with global coverage have been developed by research groups worldwide that may be relevant for assessment activities in the Midwest depending on the assessment goals. Additionally, climate change projections have been developed specifically for the Midwest. Available climate projections are summarized in Appendix 1. As can be seen from the table, these projections differ in terms of downscaling procedure, resolution, time slices, the number of GCMs from which projections are derived, and the underlying greenhouse gas emissions scenarios.

Considerations when Using and/or Interpreting Climate Projections

As noted above, climate projections are important components of climate impact studies; however, they must be interpreted carefully, keeping in mind the underlying assumptions and limitations and possible sources of uncertainty. Below we highlight three issues of particular significance when interpreting and using climate projections.

Influence of regional topography or circulation on climate

Unique characteristics of a region need to be taken into consideration when interpreting local/regional climate projections. An example for the Midwest of topographic influences is the Great Lakes and the surrounding lake-modified climates. The Great Lakes are crudely represented in GCMs; for example, in the HadCM3 model used in IPCC AR4, the lakes appear as a single water body (Figure 2). Consequently, simple spatial interpolation of GCM output to a finer-resolution grid or a location will result in climate projections that inadequately (if at all) capture the influence of the Great Lakes on the local climate. Furthermore, dynamical downscaling using RCMs may not fully capture the effect of the lakes, as many RCMs do not

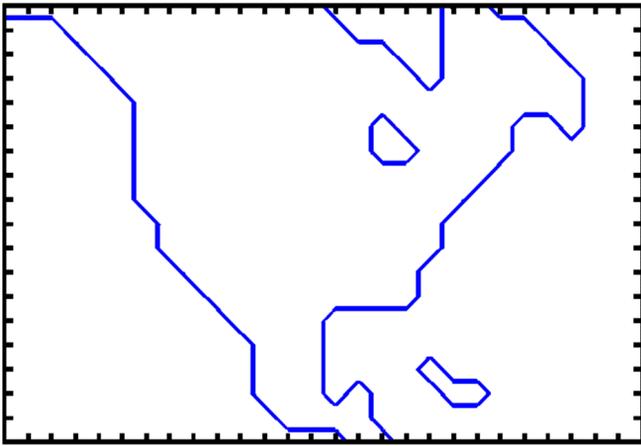


Figure 2. Land-sea mask for North America in the HadCM3 global climate model, one of the models used in the IPCC AR4.

include a lake module, and lake temperature is crudely estimated in some RCMs as the average of nearshore Atlantic and Pacific temperatures.

The impacts of regionally-specific atmospheric circulation must also be considered when interpreting and using climate projections. As an example, the western portion of the Midwest region frequently experiences a southerly low-level wind maximum known as the "low-level jet," especially at night during the warm season (Walters et al. 2008). These jets contribute to the transport of moisture into the region, and downstream convergence can act to initiate or sustain convective precipitation systems that propagate across the region. The low-level jet is poorly represented in some GCMs and RCMs, introducing uncertainty into warm season precipitation projections. Furthermore, the propagating mesoscale convective precipitation systems induced by the jet are poorly represented at typical RCM grid spacings (Anderson et al. 2007) and are absent in GCMs executed at typical climate scales.

Ensembles and multi-model means

One of the most robust conclusions from climate model evaluation studies is that there is no single best model for all locations, periods, or variables of interest (Pierce et al. 2009). Therefore, most climate change assessments employ an ensemble (i.e., suite) of climate projections. As pointed out by Winkler et al. (2011b), ensembles provide an estimation of what Jones (2000) refers to as the "calibrated range of uncertainty", and what Stainforth et al. (2007) refer to as the "lower bound on the maximum range of uncertainty". Ensembles usually include projections derived from a number of different GCMs and projections obtained from GCM simulations driven with different greenhouse gas emissions scenarios. More recently, projections developed from multiple simulations from the same GCM, but where selected physical parameterizations are perturbed or where initial conditions have been slightly modified to evaluate variability, are included in an ensemble (e.g., Murphy et al.

2007). Less frequently, an ensemble includes projections derived using multiple downscaling methods. A schematic illustrating the potential components of an ensemble of climate projections is shown in Figure 3.

Multi-model means, or in other words the average of the individual members, are frequently used to summarize an ensemble of climate projections, and indeed this is the approach used by Kunkel et al. (2012) in the National Climate Assessment support documents. The motivation for this usage comes from medium range weather forecasting, where the ensemble mean has been shown on average to be a better prediction than the prediction of an individual member (Christensen et al. 2010). The most common method for producing the ensemble mean is to take the simple arithmetic average of all participating models. Alternative methods have been proposed in which the participating models are unequally weighted (e.g., Giorgi and Mearns 2003). However, recent research concluded "we do not find compelling evidence of an improved description of mean climate states using performance-based weights in comparison to the use of equal weights" (Christensen et al. 2010). Transferring this concept to climate projections is hindered by the interdependence among the ensemble members, as GCMs and RCMs employ similar numerical schemes and parameterizations (Tebaldi and Knutti 2007). Because of this interdependence, consensus among projections should not be confused with skill or reliability (Maraun et al. 2010). Another situation where a multimodel mean may be misleading is when some members of an ensemble project a positive change in a climate variable while others project a negative change. In this case, the multimodel mean of the projected change can approach zero even though all of the ensemble members project a substantial change but of opposite sign. The near-zero ensemble mean may be interpreted as "no change" when an arguably more informative interpretation is that the nature of the change is uncertain. Precipitation projections tend to highly uncertain and often of opposite sign; thus, simple multimodel means may not be very informative in considering future changes in precipitation.

"Shelf life" of climate projections

The National Climate Assessment organizers have requested that any new analyses for the assessment utilize climate projections developed from IPCC AR4 era GCMs. On the other hand, the available peer-reviewed literature for a particular sector or region employs climate projections from older versions of GCMs in addition to more recent simulations. In fact, there is often a substantial lag between the release of new GCM simulations and the development of downscaled climate projections, and a further lag associated with the evaluation of the downscaled projections and their use in applications. Thus, much of the literature reviewed for the National Climate Assessment will have employed simulations from earlier versions of GCMs. As pointed out by Winkler et al. (2011b), the common assumption is that once a newer version of a GCM

is available scenarios based on older versions are obsolete. Against this view it can be argued that older model runs have an advantage in that they often have been extensively compared to observations. Thus, the characteristics and limitations of older model runs are better understood than are those of newer models that have not been as thoroughly evaluated. Additionally, recent guidance from the IPCC (Knutti et al. 2010) suggests that it may be appropriate to combine GCM simulations from different “eras” in an ensemble. Concomitantly, it is appropriate to integrate outcomes from assessment studies that used climate projections developed from older versions of GCMs with those that employed scenarios developed from more recent GCM simulations.

Evaluation of Climate Projections

Evaluation is the responsibility of both the suppliers and the users of climate projections. Here we summarize recent attempts for the Midwest region to evaluate GCM projections and RCM simulations available from NARCCAP. These examples were selected to illustrate evaluation techniques and strengths and weaknesses of climate projections. Although evaluation examples are provided for only one downscaling method (i.e., dynamical downscaling),

evaluation is also a necessary step for statistical downscaling. An important consideration is that the evaluation needs to be conducted in light of the potential application, and the climate variables included in an evaluation should reflect the key concerns of the application. As an example, a recent evaluation of an empirical-dynamical downscaling procedure employed a large suite of precipitation metrics selected to represent future changes in precipitation thresholds and extremes including, among others, wet day probability, mean dry spell length, wet day precipitation intensity, and the 90th percentile of wet day precipitation (Schoof et al. 2010).

GCM simulations

Several studies have provided information on GCM performance relevant to the Midwest region. Ruiz-Barradas and Nigam (2010) examined precipitation over North America in four GCMs (CCSM3, GFDL CM2.1, HadCM3, and ECHAM5). They noted seasonal differences in regional precipitation biases, with the western U.S. generally being too wet in spring and the central U.S. generally being too wet in summer (except for CCSM3). They found that interannual variability of precipitation in the Great Plains region (which includes the western part of the Midwest region that is our focus) was generally similar to observed values, though the performance of each model was not necessarily consistent

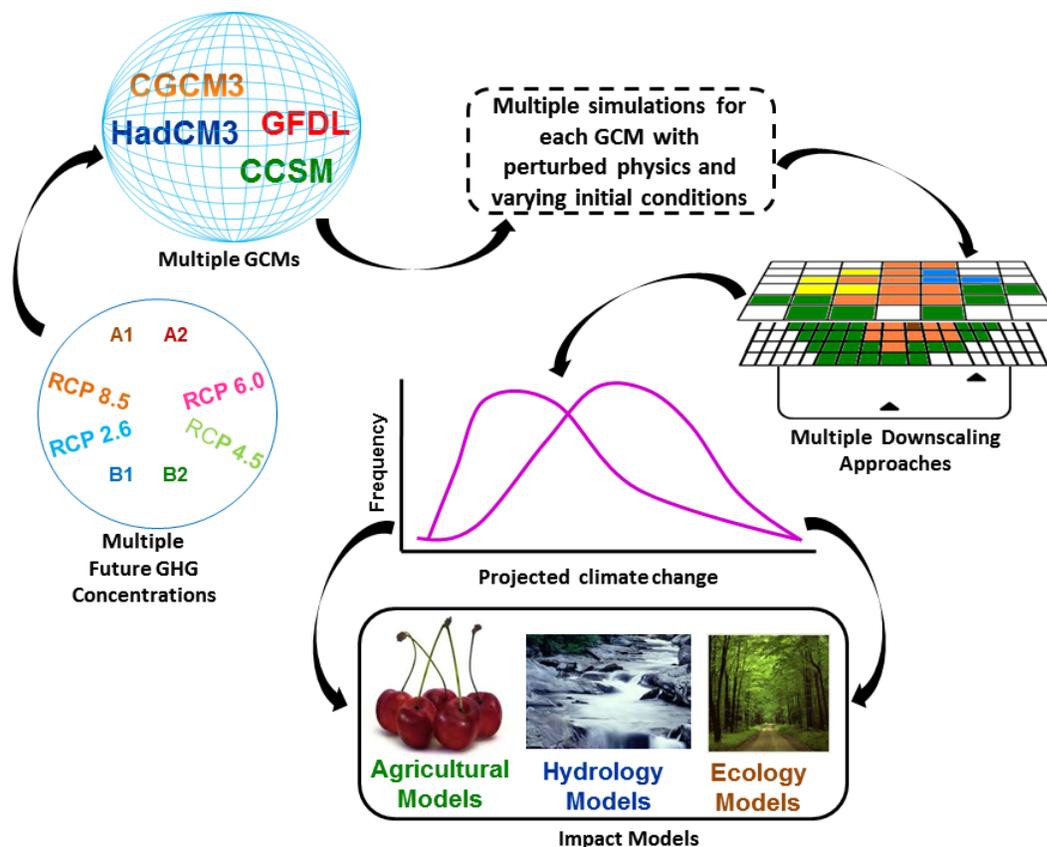


Figure 3. Development of an ensemble of climate projections. The dashed line indicates uncertainty sources that are infrequently considered. SOURCE: Winkler et al. 2011b.

across seasons. The models varied in their ability to capture remote influences of sea-surface temperature on Great Plains precipitation, with CCSM3 failing to reflect the observed correlation with central Pacific sea-surface temperature. McCrary and Randall (2010) examined 20th century drought over the Great Plains in three GCMs (CCSM3, GFDL 2.0, and HadCM3). They found that all of the models produced excessive precipitation over the Great Plains. Simulated drought for the region was comparable to observations but the models differed in the nature of their drought forcing. While drought in GFDL CM2.0 and HadCM3 corresponded with low-frequency variations in sea-surface temperature, CCSM3 showed no significant correlation between precipitation and tropical Pacific sea-surface temperature (which is broadly consistent with the findings of Ruiz-Barradas and Nigam 2010). They suggest that drought persistence in CCSM3 may be related to local feedbacks arising from that model's tight land-atmosphere coupling.

In a more comprehensive study, Wehner et al. (2011) evaluated 19 models from CMIP3 focusing on their ability to reproduce observed temperature, precipitation, and drought incidence over North America as measured by the Palmer Drought Severity Index (PDSI). Results for the North American domain as a whole showed that all models underpredicted the areal extent of drought. Although Wehner et al. (2011) did not focus specifically on the Midwest, their computations of ensemble means across all models show that over most of the Midwest temperature bias is slightly negative while precipitation bias is small. As noted elsewhere ensemble means can hide substantial inter-model variability and the authors noted substantial variations in performance amongst the models. Diagnoses of PDSI from projections through the 21st century following the A1B emissions scenario showed that all models produced increases in the frequency and severity of drought. An interesting finding from their study is that much of the variability amongst the model projections, which often has been taken as a measure of uncertainty, results from differences in climate sensitivities amongst the models (i.e., projected temperature change for a given change in greenhouse gas concentrations). Variations in model projections for drought were lower when the models were referenced to a given temperature change rather than a given time period.

NARCCAP simulations

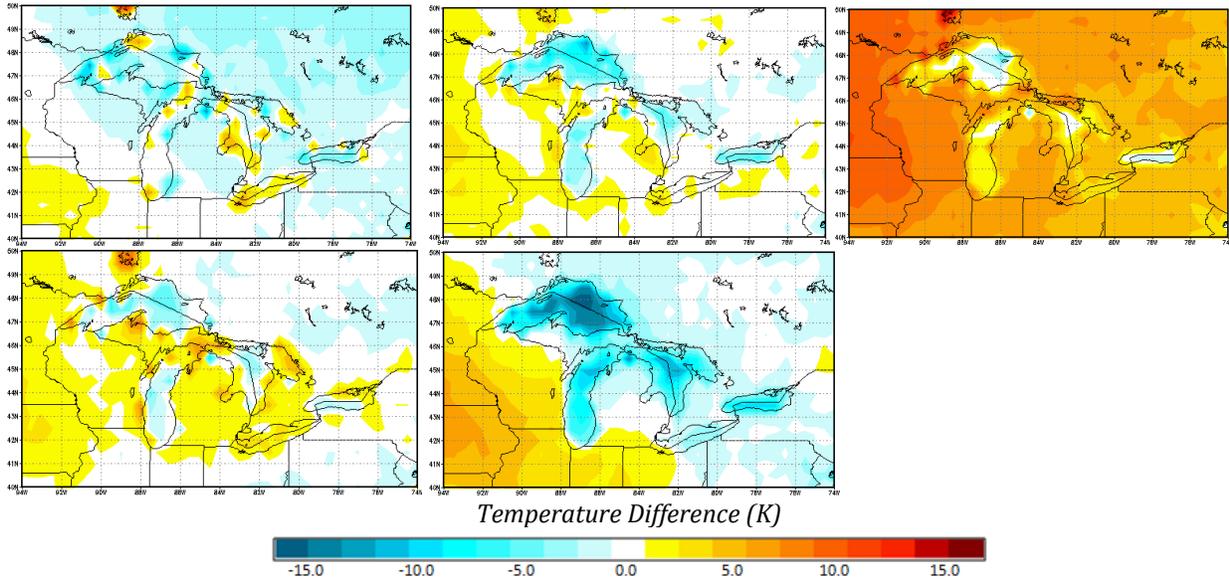
Evaluation of downscaled near-surface variables for a historical period can be used to assess the skill of the downscaling. Mearns et al. (2012) examined a variety of skill metrics for NARCCAP simulations of precipitation and temperature in current climate (1980-2004) using reanalysis fields as boundary conditions. Consistent with other studies they found there was no single best model across all metrics. There were suggestions of an advantage for regional climate models that use spectral nudging, in which the largest spatial scales of the boundary data are

used to constrain the interior of the model domain as well as the boundaries.

Evaluations using the NARCCAP suite to simulate multiple descriptors of wind climates over the contiguous U.S. (Pryor and Barthelmie 2011, Pryor and Barthelmie 2012a, Pryor et al. 2012d) suggest that application of the RCMs improves the simulation of wind climates during 1979-2000 relative to the driving reanalysis and that the RCMs exhibit some skill in depicting historical wind regimes. Furthermore, evaluation of 50-year return period wind speed derived from the NARCCAP output for the historical period (1979-2000) relative to extreme wind speed estimates computed from station observed daily maximum fastest mile speeds at 35 stations across the contiguous U.S. revealed that the RCMs exhibit some skill in capturing the macro-scale variability of extreme wind speeds. Simulations of intense and extreme wind speeds by the RCMs were found, at least to some degree, to be independent of the lateral boundary conditions, instead exhibiting greater dependence on the RCM architecture. Although not employing NARCCAP simulations, a recent analysis of dynamically-downscaled wind speeds for a nominal height of 10 m with the lowest model level (approx. 70 m a.g.l.) from the Rossby Center RCM (RCA3) run at four resolutions (ranging from 50 × 50 km to 6 × 6 km) found that model resolution had the largest impact on wind extremes compared to central tendency (Pryor et al. 2012e).

An understanding of the spatial differences in the performance of downscaled projections, such as the dynamically-downscaled NARCCAP simulations, is critical when interpreting projected future changes. Cinderich (2012) recently completed a comparison for the Great Lakes region of the NCEP-driven simulations for five of the RCMs in the NARCCAP suite to 32-km resolution temperature and precipitation values from the North American Regional Reanalysis (NARR; Mesinger et al. 2006) for 1981-2000. Large inter-model differences in performance are evident (Figure 4). January mean temperatures from the HRM3 simulation are considerably warmer than NARR temperatures across the entire Great Lakes domain, whereas for the other RCMs the January mean temperatures are warmer than NARR only in the southwestern and/or western portion of the domain. In contrast, the simulated July mean temperatures are cooler than the NARR values across much of the domain for the ECP2, MM5I and WRFG simulations. The CCRM and NARR July mean temperatures are comparable across most of the U.S. portion of the Great Lake region, whereas the HRM3 mean July temperatures are warmer than NARR in the western portion of the domain. For both months, large deviations in air temperature are seen over the Great Lakes. These differences likely reflect error in both the RCM and NARR temperature fields. In January, the RCMs, particularly ECP2, tend to overestimate mean daily precipitation compared to NARR in the northern portion of the Great Lakes region, whereas in July precipitation is

January



July

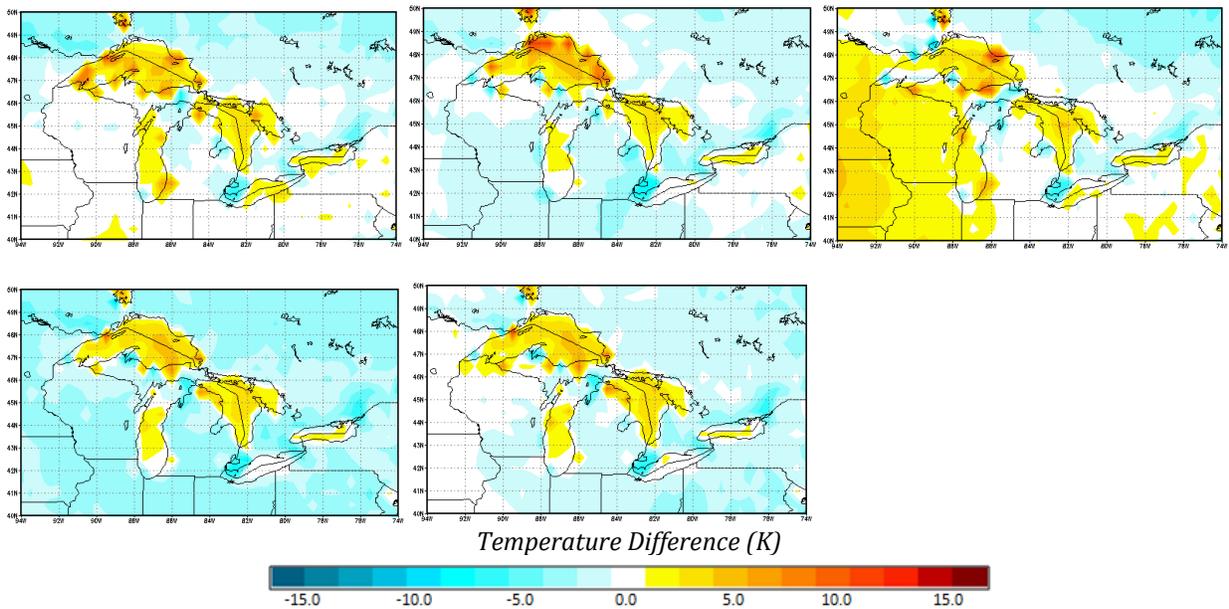


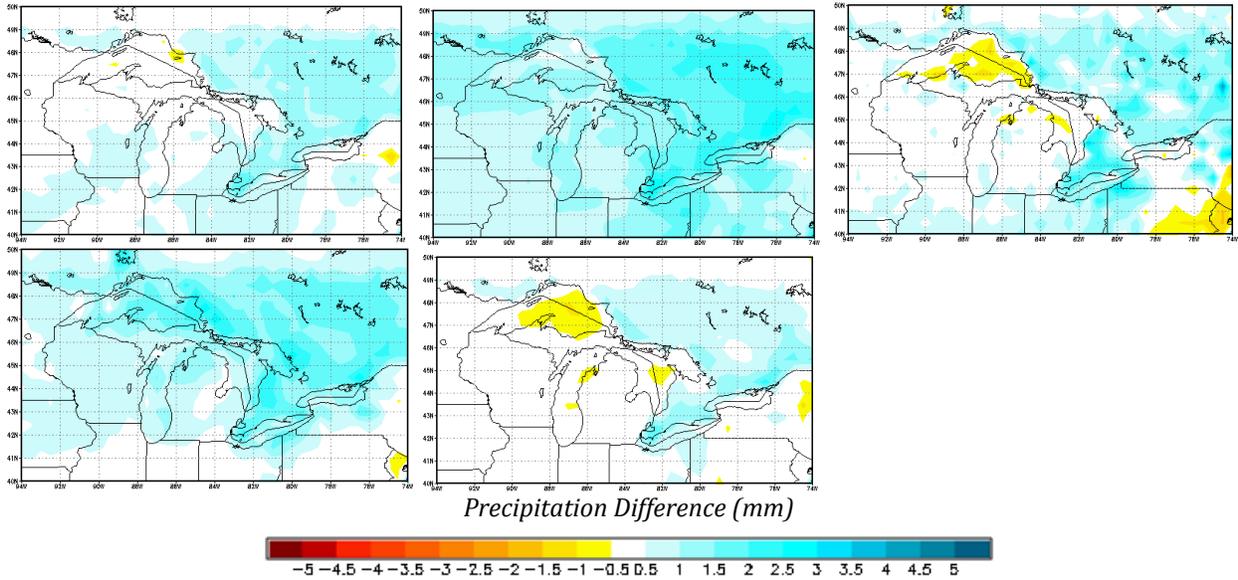
Figure 4. Mean surface-air temperature differences between NARR and five NARCCAP simulations for January and July. The top row (from left to right) shows the differences for the CRCM, ECP2, and HRM3 simulations and the bottom row the differences for the MMSI and WRFG simulations. SOURCE: Cinderich (2012)

underestimated in the southwestern and/or western portions of the domain (Figure 5).

A final example of the evaluation of NARCCAP simulations for the Midwest focuses on the differences in the distribution of daily maximum and minimum temperatures between the observations at individual stations along the

eastern shore of Lake Michigan and the NCEP-driven RCM-simulated temperature at the nearest land grid point (Figure 6; Abraham et al., personal communication). Additionally, GCM-driven RCM simulations for a historical period are compared to observed values and the simulated values from the NCEP-driven run. For brevity, histograms are shown for only one location (Eau Claire, Michigan) and

January



July

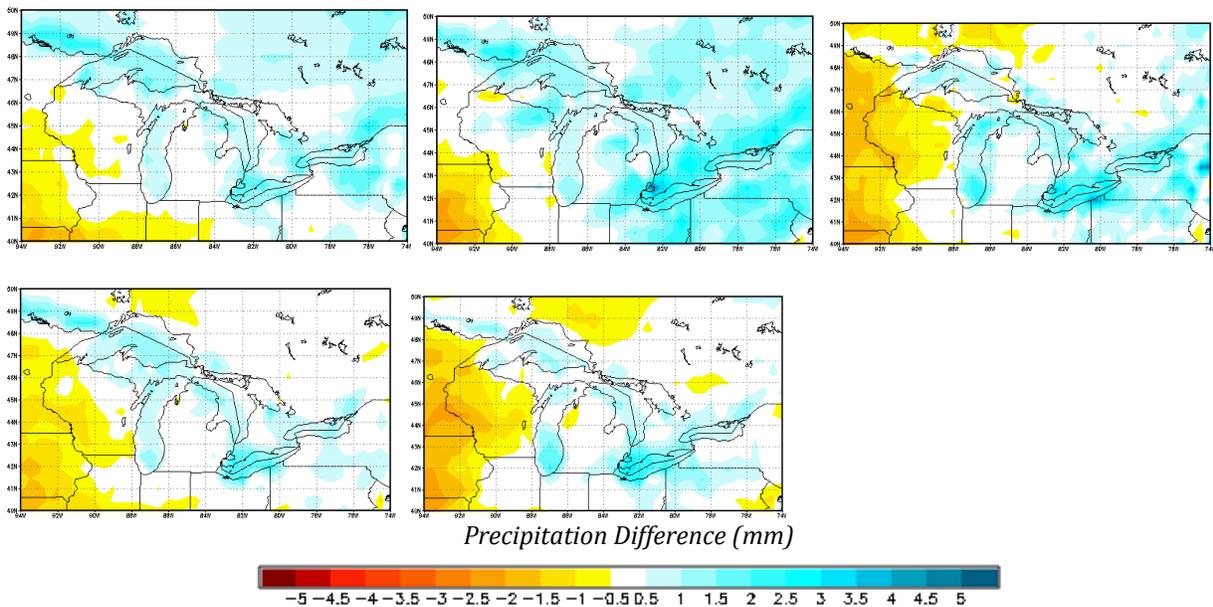


Figure 5. Differences in mean daily precipitation between NARR and five NARCCAP simulations for January and July. The top row (from left to right) shows the differences for the CRCM, ECP2, and HRM3 simulations and the bottom row the differences for the MM5I and WRFG simulations. SOURCE: Cinderich (2012)

one RCM (WRFG). When the annual distribution of daily maximum and minimum temperature is considered (top two histograms in Figure 6), the frequency distribution obtained from the NCEP-driven WRFG simulation follows

closely the observed distribution. However, when the observed distributions are compared to the frequency distributions for the historical simulations driven by the GCMs, larger deviations are observed, particularly a substantial cold bias for the CCSM-driven simulation.

Comparison by season suggests that this cold bias is particularly large during winter. These comparisons indicate that, at least for some assessment studies, the application of bias correction procedures to the NARCCAP simulations should be considered.

Projected Future Climate Change for the Midwest Region

The discussion below describes potential future change for three primary surface climate variables, namely precipitation, temperature and wind. For each variable, we attempt to summarize and integrate the numerous climate projections available for the Midwest region, highlighting the consistency, when present, and the uncertainty surrounding the projections. As already noted available climate projections were developed from a range of GCMs and utilizing a wide variety of downscaling methods.

Precipitation

The majority of previous research on future precipitation change in the Midwest has focused on projected changes in annual and seasonal precipitation totals and on precipitation intensity.

Annual and seasonal precipitation

The large degree of uncertainty surrounding precipitation projections for the Midwest region has been evident since the initial United States National Climate Assessment completed in 2000 which employed simulations from only two IPCC Second Assessment era GCMs (i.e., CGCM1 and HadCM2). Whereas the CGCM1 scenario suggested much drier future conditions in the northwestern portion of the Midwest and annual increases of 20-40% elsewhere by the end of the century, the HadCM2 scenario projected increases in annual precipitation ranging from 20 to 70 percent across the Midwest by 2100 (Sousounis and Albercock 2000). In support of the IPCC AR4, 21 GCMs were utilized to simulate future conditions for 2080-2099 under the SRES A1B greenhouse gas emissions scenario (Christensen et al. 2007). The ensemble mean suggests an increase in annual and winter (December, January February) precipitation for most of the Midwest region but little change or even a small decrease in summer (June, July, August) precipitation (Figure 7). The number of GCMs projecting an increase versus decrease in precipitation provides one measure of the ensemble spread. For the Lower Peninsula of Michigan and northern Ohio, Indiana, and Illinois, over 90 percent of the 21 GCMs projected an increase in annual and wintertime precipitation by 2080-2099, and at least 67 percent of the models suggest increased precipitation

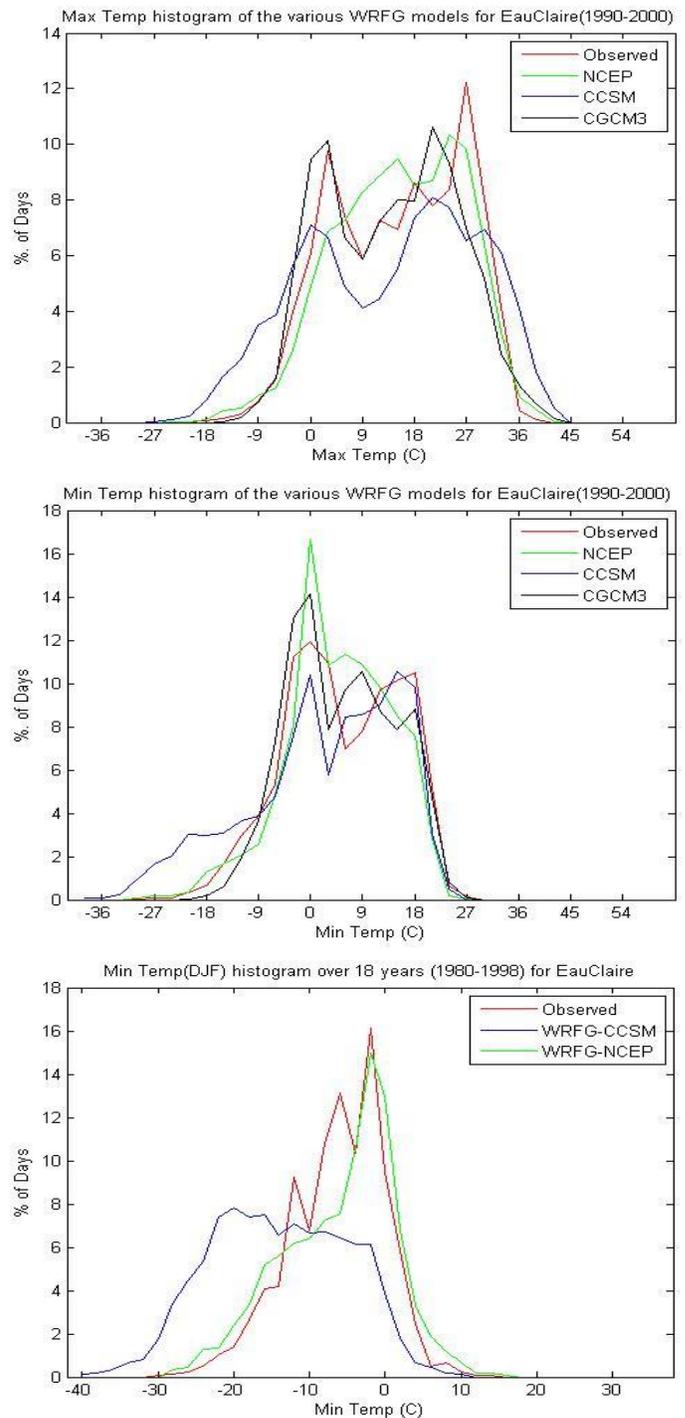


Figure 6. Top row: Histograms of the annual distribution of daily maximum and minimum temperature for 1980-2000 a) observed at Eau Claire Michigan (red line), b) simulated by WRFG driven by NCEP reanalysis (green line), c) simulated by WRFG driven by the CCSM GCM (blue line), and d) simulated by WRFG driven by the CGCM3 GCM (black line). Bottom row: Observed and simulated values of minimum temperature for winter (December, January, February). SOURCE: Z. Abraham, P.-T. Tan, Ferdinan, J. Winkler, and S. Zhong, Michigan State University, personal communication.

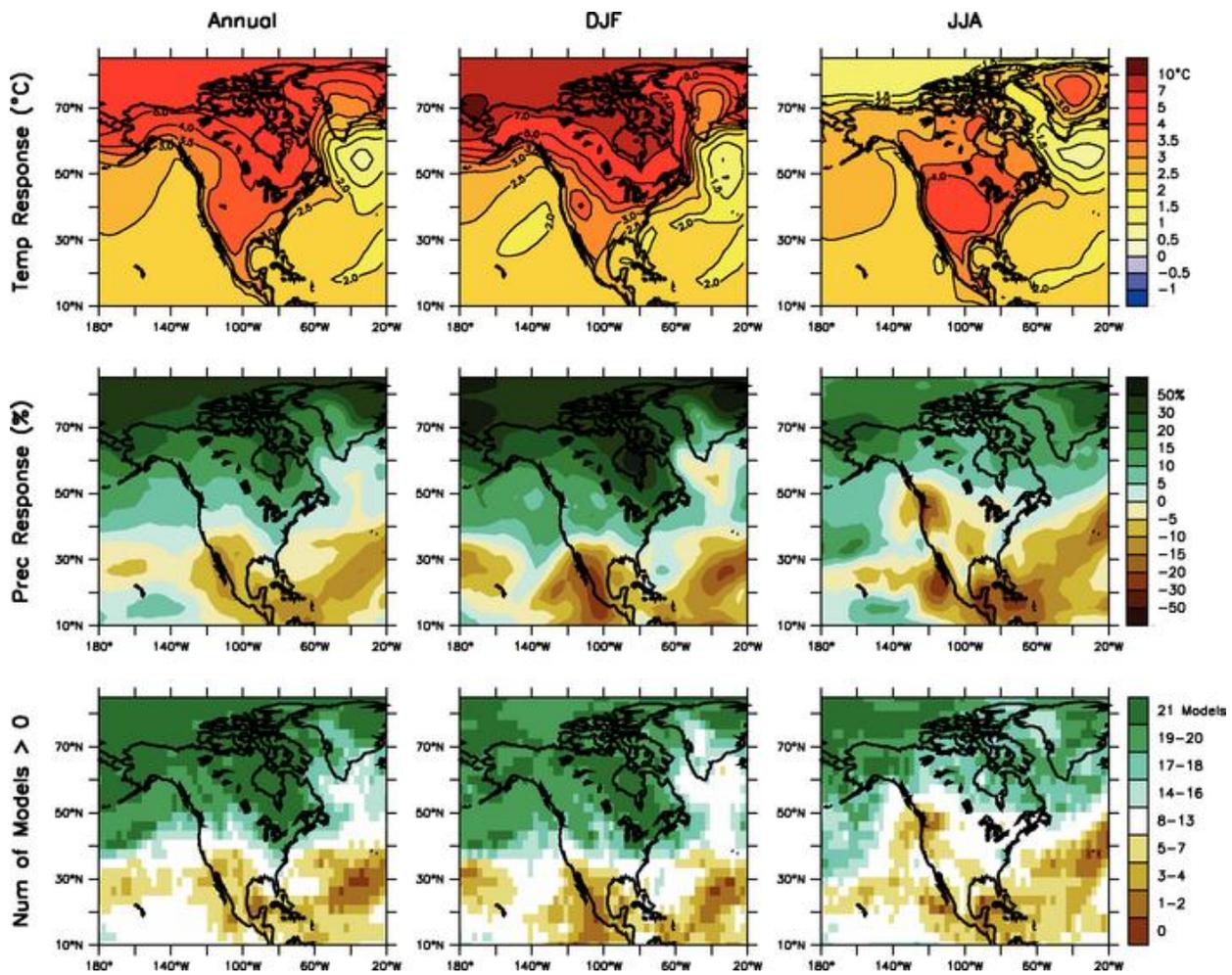


Figure 7. Temperature and precipitation changes over North America from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation. SOURCE: Christensen et al. 2007.

elsewhere in the Midwest region. In contrast, approximately half of the 21 GCMs projected an increase in summer precipitation in the Midwest by the end of the 21st century, with the other half suggesting a decrease or little change, again pointing out that a near-zero ensemble mean does not necessarily reflect a consensus of no change. Using the same set of GCMs, Hayhoe et al. (2010a) calculated region-wide estimates of precipitation change for the U.S. Great Lakes region under three different greenhouse gas emissions scenarios (A1FI, A2, B1). Projected changes in annual precipitation ranged from -2 to +10 percent for the mid-21st century, and by the end of the century only two of the 21 models projected a decrease in annual precipitation with the remaining models suggesting higher annual precipitation for the U.S. Great Lakes region.

As expected, the uncertainty surrounding the GCM-projected precipitation is also evident for the projections downscaled from the GCMs. One example is the precipitation projections for Wisconsin developed by the Wisconsin Initiative for Climate Changes Impacts (WICCI).

These scenarios were statistically downscaled from 14 GCMs from the CMIP3 archive (Kucharik et al. 2010; WICCI 2011). Ensemble averages suggest an approximately 25% increase in wintertime precipitation by the middle of the 21st century across the state, with more precipitation occurring as rain or freezing rain than currently. Similarly, ensemble averages suggest an increase in mean precipitation during early spring (i.e., March), although not in mid or late spring, with an approximately 50 percent increase by mid-century in the amount of March precipitation falling as rain rather than snow. There is little agreement among the different climate scenarios regarding the sign of the projected change in summertime precipitation in Wisconsin. This is in contrast to the downscaled precipitation scenarios developed as part of the Pileus Project (Pileus Project 2007; Winkler et al. 2012b) for neighboring Michigan from four IPCC Third Assessment era GCMs (CGCM2, HadCM3, ECHAM4, CCSM). These scenarios suggest drier conditions during summer (Andresen et al. 2007). The sign of the projected change for autumn precipitation in Wisconsin also varies among the

WICCI climate projections, although the ensemble mean suggests an increase in precipitation especially for northern Wisconsin. Hayhoe et al. (2010) also found considerable seasonal differences in the sign of the projected precipitation change for the U.S. Great Lakes region based on projections from three GCM simulations from the CMIP3 archive that were statistically downscaled to a 1/8 degree resolution. The scenarios developed by Hayhoe et al. (2010) suggest an increase in regional precipitation in winter and spring, but not for summer and fall. Larger projected changes in winter and spring precipitation were found under higher greenhouse gas emissions, and the projected increases were greatest in the southern portion of the Great Lakes region (i.e., Illinois, Indiana, Ohio).

The projections of precipitation occurrence (the number of wet days) and precipitation intensity (the amount of precipitation on wet days) prepared by Schoof et al. (2010) for a large number of stations across the United States provide some additional insights on potential future changes in precipitation. These statistically-downscaled projections, developed from 10 IPCC AR4-era (CMIP3) GCMs, exhibit a high degree of variability, but results for the Midwest suggest several general tendencies: 1) a decrease in wet day probability during the cold season of around -5% and -8% for 2046-2065 and 2081-2100, respectively; 2) increased cool season (November-March) precipitation by mid and late century for over two-thirds of stations within the Midwest region, with the exception of the northwestern portion where ensemble averages suggested that cool season precipitation would decrease; 3) a decrease in the number of wet days by the end of the 21st century for summer (June, July, August) but with some inconsistencies between GCMs and stations; and 4) an almost equal number of stations within the Midwest region with projected increases and decreases in warm season precipitation in the 2046-2065 period, with the exception of the southwestern portion of the region where most stations displayed declining warm season precipitation.

The projections of future precipitation change obtained from the coarse-scale output from 15 GCMs from the CMIP3 archive and nine RCM simulations from the NARCCAP archive as described in the climate guidance document prepared for the National Climate Assessment (Kunkel et al. 2012) are generally consistent with the projections described above. The CMIP3 models projected both increases and decreases in precipitation for mid and late-century time periods, as did the NARCCAP dynamically-downscaled projections. The ensemble means of annual precipitation for the nine NARCCAP simulations are largest (10-15% increase) in the Great Lakes region, particularly northern Wisconsin and the Upper Peninsula of Michigan, areas where earlier studies (e.g., Christensen et al. 2007) indicate greater consistency in the sign of the projected change. Consistent with the earlier results of Schoof et al. (2010), the ensemble mean changes were smallest for the southwestern corner of the Midwest region, an area for which GCM projections display considerable uncertainty in the sign of the projected change (Figure 7). A similar but stronger southwest to northeast gradient is seen for the multi-model

mean of precipitation change for the 15 CMIP3 models, with average projected changes for the end of the century ranging from approximately a 5% decrease in the southwestern portion of the Midwest region to close to a 10% increase in the northern portion.

The National Climate Assessment guidance document also highlights seasonal differences in projected future changes in precipitation. The NARCCAP projections for summer differ from those described above in that a substantial decrease in precipitation is suggested by the ensemble mean in the extreme southwestern portion of the study area. Ensemble mean values are close to zero across the remainder of the Midwest region, very likely reflecting inconsistent signs in the projected summertime precipitation among the nine NARCCAP RCM simulations. The largest projected changes, as indicated by the ensemble means, occur in winter; the multi-model average suggests a precipitation increase of greater than 10% over much of the Midwest. The spatial distribution of the NARCCAP multi-model mean change for spring and fall suggests a northwest to southeast gradient with projected changes in fall and spring precipitation of over 10% increase in the northwestern portion of the Midwest and little change (again likely a reflection of inconsistent sign of the projection change) in the eastern and southeastern portions of the Midwest. This spatial pattern had not previously been seen in downscaled projections of spring and fall precipitation change.

Precipitation intensity

Assuming warmer temperatures and consequent higher evaporation, available atmospheric moisture is likely to increase in the future, and one would expect precipitation intensity to increase as well. However, projecting future precipitation intensity is challenging as the probability density function of daily precipitation rates needs to be well simulated in order to have confidence in the projected changes. This is not typically the case (see earlier discussion of evaluation of climate projections). A further complication is that the choice of probability density function for evaluating future changes may influence the interpretation. For example, Gutowski et al. (2007) note that while a gamma distribution can provide a useful general description of precipitation intensity and its change under future climates, other approaches may be more appropriate when considering precipitation extremes. Nevertheless, a small number of analyses have explicitly attempted to evaluate how precipitation intensity may change in the Midwest.

The aforementioned WICCI scenarios suggest that two to three additional heavy precipitation events, defined as daily precipitation rate of two or more inches, can be expected per decade in Wisconsin by the mid-21st century. This would correspond to a 25 percent increase in the frequency of heavy precipitation. Kunkel et al. (2012) reported that the multi-model mean change in the number of days with precipitation greater than one inch from the nine NARCCAP simulations varies from little or no change in the southeastern and eastern portion of the Midwest region to

an over 30% increase in the northern portion of the region by mid century. The percentage increases in frequency are projected to be larger for more extreme precipitation events (e.g., precipitation rates greater than one inch, two inches, three inches, and four inches). More generally, Schoof et al. (2010) found that, based on downscaled climate projections from ten GCMs, intense precipitation events in the Midwest are likely to either continue at their current frequency or increase in frequency, regardless of the sign of the change in total precipitation. Furthermore, the magnitude of the 90th percentile precipitation rate is projected to increase by mid and late century. They interpreted this finding as indicative of a positive shift in the central tendency and widening of the probability distribution for wet day precipitation intensities. The projected increase in frequency of heavy precipitation is broadly consistent with observed trends in the late 20th century as described by Groisman et al. (2012). They suggest that both global climate change and intensification of agricultural land use may have influenced this trend, and recommend experiments using regional climate models to quantify the relative roles of these influences.

Temperature

Below we highlight projected changes in annual and seasonal mean temperatures, commonly employed temperature indices (e.g., growing degree days), and temperature thresholds and extremes.

Annual and seasonal temperature

Although climate projections are in general agreement that annual and seasonal temperatures will increase by mid century and later, the degree of warming can differ substantially. Starting with the ensemble means from the 21 GCM simulations reported in the IPCC AR4 (Christensen et al. 2007), annual mean temperatures over the Midwest are expected to increase by approximately 5.5°F (3°C) by 2080-2099 under the A1B emissions scenario (Figure 7). The ensemble means suggest a larger increase in summer (June, July, August), ranging from approximately 8°F (4.5°C) over the western portion of the Midwest and 7°F (4.0°C) over the eastern, and in winter (December, January, February) a generally southwest to northeast gradient is observed with a mean increase of more than 6°F (approximately 3.5°C) in the southwestern portion of the Midwest and over 9°F (5°C) in the northeast. Based on the direct (not downscaled) analysis of the output from 21 CMIP3 GCMs, Hayhoe et al. (2010) report an average increase in mean annual temperature by mid century of approximately 3.5°F (2°C) under lower emissions and approximately 5.5°F (3°C) under high emissions, and an increase by the end of the century of 5.5°F (3°C) under lower greenhouse emissions and 9°F (5°C) under higher emission. Kunkel et al. (2012) employed the same suite of 21 CMIP3 models, and found multi-model mean projected changes in annual mean temperature by the end of the 21st century ranging from approximately 9.5°F (5.3°C) in

northwestern portion of the Midwest region to 7.5°F (4.2°C) in the southeastern portion for the A2 emissions scenario by the end of the century. A distinct northwest to southeast gradient in the multi-model mean projections of the change in annual mean temperature is also observed under the B1 emissions scenario and for a mid century time slice.

Downscaled climate projections in general project somewhat higher changes in annual and seasonal mean temperature than the global model output. The WICCI climate scenarios, downscaled from IPCC AR4 era GCM simulations under the A1B emissions scenario and averaged across all ensemble members, suggest increases in annual mean temperature of 4-9°F in Wisconsin by the middle of the century. The WICCI scenarios also project the largest warming to occur in northern Wisconsin and the least warming along Lake Michigan. Seasonal differences in the rate of warming are also seen from this set of climate projections. Projected warming is least in summer, ranging from 3-8°F (1.7-4.4°C) with larger changes projected for northern Wisconsin. In winter mean temperatures are projected to warm 5-11°F (2.8-6.1°C) by mid 21st century with the largest increases found in northwestern Wisconsin. Spring and autumn mean temperatures in Wisconsin are projected to increase at mid century by 3-9°F (1.7-5.0°C) and 4-10°F (2.2-5.6°C), respectively, with the largest increases in northern Wisconsin.

Compared to the WICCI projections, the downscaled projections developed by Hayhoe et al. (2010a) for the U.S. Great Lakes region from three CMIP3 models suggest greater complexity in the seasonal variations in projected changes. For an early period defined as 2010-2039, Hayhoe et al. report larger projected changes in winter compared to spring and summer, but by mid century they found that the seasonality reversed with larger changes projected in summer compared to winter and spring. In terms of spatial variation, the Hayhoe et al. downscaled scenarios suggest larger increases in summer mean temperature in the southern portion of the region (e.g., Indiana, Illinois), whereas projected changes in mean winter temperature are largest in the northern portion (e.g., Wisconsin and Minnesota). Kunkel et al. (2012) found a similar spatial pattern in the distribution of projected temperature change by mid century in winter versus summer from the NARCCAP dynamically-downscaled projections for the Midwest. Additionally, the NARCCAP projections suggest relatively uniform projected changes in spring and autumn mean temperature across the Midwest by mid century.

Temperature thresholds and indices

Although the terms are sometimes used interchangeably, we make a distinction between a temperature “threshold” and a temperature “extreme”. A temperature threshold refers to the exceedance of a specified temperature value, selected for its relevance to a natural or human activity or process. In contrast, a temperature extreme is defined in reference of the frequency distribution of temperature and

refers to the magnitude of the temperature values at specified probability levels (e.g., the 95th percentile). We confine the discussion below to temperature thresholds, as they have been the focus of most analyses of climate projections for the Midwest. We also discuss in this subsection commonly-used temperature indices, such as degree days which are a measure of heat accumulation from a specified base value.

Not surprisingly, the frequency of freezing ($\leq 32^{\circ}\text{F}$, $\leq 0^{\circ}\text{C}$) temperatures is expected to decrease in the future. The Pileus Project projections for 15 locations in Michigan and surrounding states, when averaged across all ensemble members, suggest that by mid century approximately 15 fewer days will experience minimum temperatures below freezing, whereas by the end of the century a decrease of more than 30 days is projected (Pileus Project 2007). Ensemble means for the NARCCAP simulations, when averaged over the entire Midwest region, suggest that by mid century 22 fewer days per year will report minimum temperatures below $\leq 32^{\circ}\text{F}$ ($\leq 0^{\circ}\text{C}$) (Kunkel et al. 2012), although spatial and inter-model variations are apparent.

Changes in the frequency of heat waves are of particular concern due to potential impacts on human health and mortality. The Pileus Project scenarios suggest for Michigan and surrounding areas that the number of days with temperatures $\geq 95^{\circ}\text{F}$ ($\geq 35^{\circ}\text{C}$), averaged across the ensemble members, will increase by 5 days by mid century and 19 days by the end of the 21st century (Pileus Project 2007). For the neighboring state of Wisconsin, the WICCI scenarios project an average increase by mid century in the frequency of maximum temperatures greater than 90°F (32°C) from approximately 26 days in the southern portion of the state to 12 days in the northern portion (see web slide show of projected changes available at <http://www.wicci.wisc.edu/climate-change.php>). Multi-model means from the NARCCAP simulation suite point to considerable spatial variability across the Midwest region, with an approximately 25 day average increase in the frequency of maximum temperatures $\geq 95^{\circ}\text{F}$ ($\geq 35^{\circ}\text{C}$) in the southern portion of the Midwest region and fewer than 5 days in the northern portion by mid century (Kunkel et al. 2012). The NARCCAP projection (5 days) for the northern Midwest is in good agreement with the mean projected value from the Pileus Project scenarios for the mid century time frame (Pileus Project 2007). Additional analysis of the NARCCAP simulations points to a potential increase in the length of heat waves in some parts of the Midwest. The multi-model means suggest that the annual maximum number of consecutive days per year with maximum temperature $\geq 95^{\circ}\text{F}$ ($\geq 35^{\circ}\text{C}$) will increase by 15 days in the extreme southern portion of the Midwest region, although little change is expected across a broad swath of the northern Midwest. The downscaled scenarios developed by Hayhoe et al. (2010a,b) from three GCM simulations also suggest an increased risk of extreme heat waves. By the end of the century, the frequency of heat waves similar to the 1995 heat wave event responsible for nearly 800 deaths

in Chicago (Kunkel et al. 1996) is projected to range from every other year (low greenhouse gas emissions) to three times per year (high greenhouse gas emissions). Furthermore, heat waves similar to the devastating European heat wave of 2003 could occur in the Chicago metropolitan area, with at least one such event projected before mid century and 5 to 25 events projected to occur by the end of the century, depending on the greenhouse gas emissions scenario (Hayhoe et al. 2010b).

In terms of temperature indices, the ensemble mean of the Pileus Project scenarios suggests that the median date of last spring freeze in Michigan could occur approximately a week earlier than present by mid century and two weeks earlier by late century, with similar changes, although toward a later date, in the median time of occurrence of first fall freeze (Pileus Project 2007). These changes in freeze dates should lead to an increase in the length of the frost-free season. The multi-model means of the NARCCAP simulations suggest a fairly uniform increase across the Midwest of approximately 20-25 days in the length of the frost-free season by mid century (Kunkel et al. 2012). The projected changes based on the Pileus Project scenarios are somewhat smaller with an increase for Michigan of approximately 15 days projected for mid century and 29 days for late century, although substantial differences are evident between the ensemble members.

Warmer temperatures can be expected to reduce heating requirements but increase cooling requirements, and the climate projections available for the Midwest region support this interpretation. The NARCCAP multi-model means, when averaged across the region, suggest a 15% decrease in heating degree days (Kunkel et al. 2012). When viewed spatially, greater reductions are seen in the northern portion of the region although the north-south gradient is relatively weak. The magnitudes of the projected changes in cooling degree days are anticipated to be larger than the absolute changes in heating degree days. The NARCCAP multi-model means suggest a 66% increase in cooling degree days, when averaged across the Midwest region. However, a strong south to north gradient is projected with considerably larger increases in cooling degree days in the southern portion of the region. The Pileus Project scenarios (Pileus Project 2007) suggest a somewhat smaller increase of cooling degree days compared to the NARCCAP simulations. The ensemble mean for the Pileus Project scenarios is an approximate increase of 200 cooling degree days in the Lower Peninsula of Michigan compared to an increase of 400 CDDs in the same region projected by the NARCCAP simulations.

Finally, growing degree day (GDD) accumulations in the Midwest are projected to increase. The areally-averaged NARCCAP multi-model means suggest a 32% increase for the Midwest in base 50°F (10°C) GDDs by mid century (Kunkel et al. 2012), whereas the Pileus Project scenarios project an average increase for Michigan of 14% for base 41°F (5°C) GDDs and 19% for base 50°F (10°C) GDDs by

mid-century (Pileus Project 2007). Larger average increases of 33% and 45% are anticipated in Michigan for base 41°F (5°C) GDDs and base 50°F (10°C) GDDs, respectively, by the end of the century.

Freeze Risk

One cannot assume that warmer temperatures will bring more favorable conditions for plants such as perennials that currently are vulnerable to springtime freeze damage. Early spring warm-ups may result in greater freeze risk if plants are at a more advanced stage of development at the time of last spring freeze. On the other hand, if the date of last spring freeze advances to a much earlier date in synchrony with plant development, spring freeze risk may not change or even decrease. Considerable uncertainty exists regarding the future susceptibility of perennial plants in the Midwest to below freezing temperatures when preceding crop development is considered. Winkler et al. (2012a), using a suite of climate projections for 15 locations in Michigan and surrounding states that were developed by applying several empirical-dynamical downscaling methods to four IPCC Third Assessment era GCMs, found that approximately half of the scenarios project for the mid and late century little change in growing degree day accumulation (a measure of plant development) at the time of last spring freeze whereas the other half project greater crop development at the time of freezing temperatures. Similarly, an approximately equal number of scenarios suggest an increase versus a decrease in the median GDD accumulation outside the frost free period (i.e., the growing season).

Apparent temperature

In the Midwest, high summer temperatures are often accompanied by elevated near-surface humidity, which enhances human heat stress through reduction of evaporative cooling from the skin. The combined effect of temperature and humidity on human heat stress is often quantified using “apparent temperature”. While historical tendencies in air temperature over the Midwest have been of comparatively modest magnitude, apparent temperatures have exhibited marked increases, driven in large part by increases in atmospheric moisture (Rogers et al. 2009). Projections for future apparent temperature regimes across the Midwest derived using disaggregation downscaling of 10 GCMs under three greenhouse gas emissions scenarios all

suggest an increase in the magnitude of apparent temperature, with a substantial fraction of the increase deriving from increased humidity (Schoof 2012). Thus the probability of heat stress events is projected to increase across the Midwest in the coming decades relative to the historical period. This interpretation is complicated, however, by the few attempts to downscale coarse-scale humidity projections for the Midwest region.

Wind

Recent analyses of RCM output from the NARCCAP suite has focused on possible climate change signals across a range of wind climate descriptors including the mean, 50th percentile, 90th percentile, 95th percentile, 20 and 50 year return period wind speeds and wind energy density (i.e., wind resource) (Pryor and Barthelmie 2011, Pryor et al. 2012d). Some of these analyses assessed whether there was consistency in the change of the different parameters in the middle of the current century versus the end of the twentieth century. The results generally display only a weak consistency on the climate change signal in any of the descriptors. However, approximately 22% of grid cells show a lower 90th percentile wind speed in all of the RCM simulations. In keeping with results of analyses that

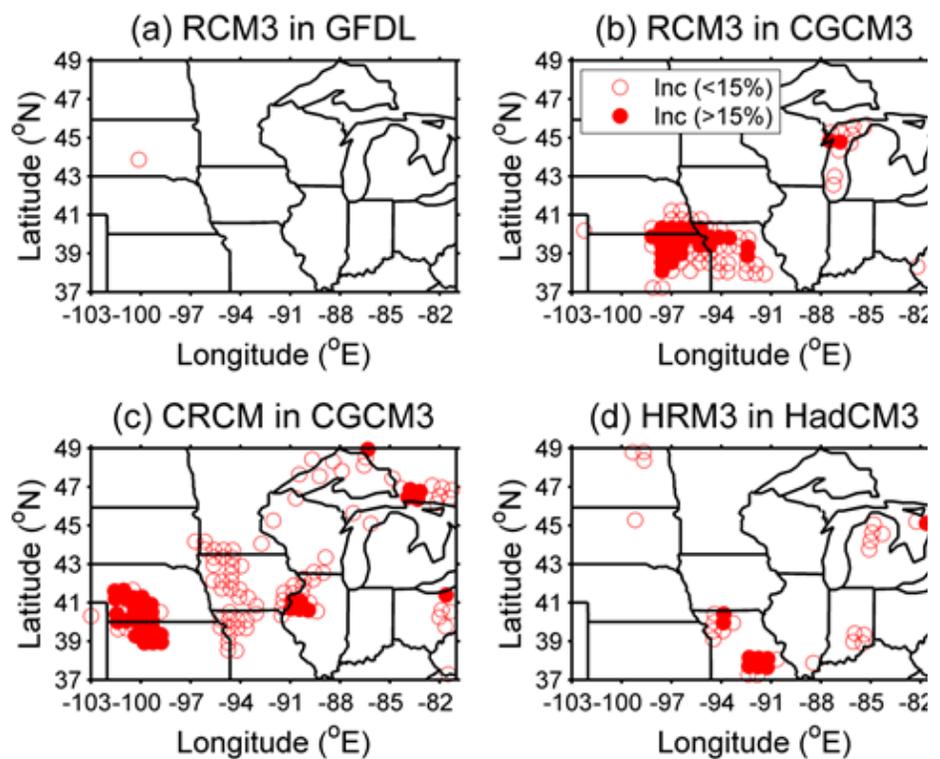


Figure 8. Difference in the fifty-year return period sustained wind speed (U_{50yr}) over the Midwestern US for 2041-2062 vs. 1979-2000. The frames show the different AOGCM-RCM combinations. The magnitude of change is only shown for grid cells where the value for the future period lies beyond the 95% confidence intervals on the control period. Note; none of the grid cells behind the legend in frame (b) exhibited significant changes. SOURCE: Pryor and Barthelmie (2012b).

indicate the RCMs generally develop extreme wind climates that are to some degree independent of the lateral boundary conditions, extreme wind speeds are generally not characterized by a consistent change on the basis of the eight sets of simulations considered. Only 1% of grid cells over the contiguous USA indicate a consistent signal of either higher or lower values for the 20- or 50-year return period wind speed in the future. Changes in 50-year return period wind speeds over the Midwest from four of the NARCCAP simulations are shown in Figure 8. As for the entire NARCCAP domain, relatively few grid cells within any of the GCM-RCM combinations exhibit substantially higher or lower values for the extreme wind speed in the future. However, it is important to note that the wind climate exhibits large inherent variability at a range of time scales from minutes to decades. Analyses of a single future period of only 22 years duration precludes general inferences regarding trends in any aspect of the wind climate. Earlier research over Europe has shown that in the near-term, inter-annual and inter-decadal variability dominates over any temporal trend and that, based on results of dynamical downscaling, intense and extreme winds are unlikely to evolve out of the historical envelope of variability until the end of the current century (Pryor et al. 2012c).

Level of Confidence

We are in agreement that the following statements reflect the level of confidence that can be placed on future climate projections for the Midwest region:

- There is no single best climate model or downscaling approach.
- There is greater confidence in projected temperature change than precipitation change.
- In spite of confidence in future warmer temperatures, change in freeze risk remains uncertain.
- The degree of uncertainty surrounding precipitation change remains high, although annual precipitation and precipitation during the cool season are expected to increase, particularly for the eastern portion of the Midwest region.
- There is little confidence in the sign (positive or negative) of change in mean precipitation for the warm season. There is somewhat greater confidence in projections of increases in the frequency and intensity of extreme warm season precipitation events.
- The use of a multimodel mean of a projected change may be misleading, particularly for projected changes in precipitation.
- Wind climates, including high impact wind events, remain challenging to simulate with the validity necessary to make assertions regarding the likelihood of change.

Concluding Remarks

In this whitepaper we introduced readers to key considerations when using and interpreting climate projections with a specific focus on the U.S. Midwest region. Climate models and climate downscaling techniques are evolving, and model skill with respect to representing features of the current and historical climate is improving. Nevertheless, as documented herein, uncertainties remain, particularly with respect to the ability to project changes in high impact, low probability events, and confidence in future projections is generally higher for thermal regimes than for hydroclimates or wind climates.

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Appendix 1: Available climate change projections for the National Climate Assessment Midwest region

Name/ Reference	Coverage/Resolution/ Variables/Period	Ensemble Size	Downscaling Procedures	Availability
CMIP3 GCM archive (Meehl et al. 2007)	<ul style="list-style-type: none"> • Global • Spatial resolution varies by GCM • Archived at monthly time step, but finer time steps available for most models 	<ul style="list-style-type: none"> • Over 20 GCMs (AR4 era) • 3 emissions scenarios (SRES A2, A1B, B1) 	Not downscaled	<ul style="list-style-type: none"> • Graphical summaries available in IPCC AR4 Working Group I report. • Time series of monthly precipitation and mean temperature available from the Program for Climate Model Diagnosis and Interpretation (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)
Bias Corrected and Downscaled WCRP CMIP3 Climate Projections (Maurer et al. 2007)	<ul style="list-style-type: none"> • Global • 1/8° lat/lon resolution • Mid century and late century time slices 	<ul style="list-style-type: none"> • 16 GCMs (IPCC AR4 era) • 3 emissions scenarios (SRES A2, A1B, B1) 	Disaggregation (BCSD) method. Gridded temperature and precipitations observations were upscaled to a 2° resolution and GCM projections were regridded to this resolution. Quantile mapping was used to calculate change factors which were then downscaled using a simple inverse distance approach and applied to the original finely gridded observed dataset.	Monthly time series available through Climate Wizard http://www.climatewizard.org and at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections
TYN SC 2.0 (Mitchell et al. 2004)	<ul style="list-style-type: none"> • Global • 0.5° lat x 0.5° lon • Mean monthly cloud cover, diurnal temperature range, precipitation, temperature, vapor pressure • 2001-2100 	<ul style="list-style-type: none"> • 5 GCMs (IPCC TAR era). • 4 emission scenarios (SRES A1FI, A2, B2, B1) 	Disaggregation downscaling. Spatial interpolation using thin plate spline scheme.	Available at http://www.cru.uea.ac.uk/cru/data/hrg
WorldCLIM	<ul style="list-style-type: none"> • Global coverage • ~1km resolution • Climatological (30 year) mean monthly temperature and precipitation • 7 overlapping 30-year periods in 21st century 	<ul style="list-style-type: none"> • 3 GCMs (IPCC TAR era) • 2 SRES emissions scenarios 	Disaggregation downscaling (spatial interpolation)	Available at http://worldclim.org
International Centre for Tropical Agriculture (CIAT)	<ul style="list-style-type: none"> • Global • 4 spatial resolutions (30 arc-seconds, 2.5 arc-minutes, 5 arc-minutes and 10 arc-minutes). • Climatological (30 year) mean monthly 	<ul style="list-style-type: none"> • 24 IPCC AR4 models 	Disaggregation downscaling (spatial interpolation)	Available at http://www.ccafs-climate.org

	temperature and precipitation			
10' Future Climate Grids (Tabor and Williams 2010)	<ul style="list-style-type: none"> • Global • 10' resolution • Climatological (20 year) mean monthly temperature and precipitation • Two time slices, 2041-2060 and 2081-210 	<ul style="list-style-type: none"> • 24 GCMs (IPCC AR4 era) • 3 emissions scenarios (SRES A1b, A2, B1) 	Disaggregation downscaling. GCM simulations are debiased with respect to their mean differences from 20th-century observations. The differences are downscaled to 10' resolution with a spline interpolation and added to mean 20th century climatologies from the CRU CL2.0 dataset.	Available at http://ccr.aos.wisc.edu/resources/data_scripts/ipcc/index.html
NARCCAP (Mearns et al. 2012)	<ul style="list-style-type: none"> • North America • ~50 km • 3-hourly time step • Multiple climate variables including temperature, precipitation, humidity and wind • Two time slices, 1960-1990 and 2040-2070 	<ul style="list-style-type: none"> • 9 simulations developed from combinations of 4 GCMs (IPCC AR4 era) and 6 RCMs • SRES A2 emissions scenario 	Dynamical downscaling (RCM models)	http://www.narccap.ucar.edu
Schoof et al. 2010	<ul style="list-style-type: none"> • 963 stations in United States • Daily precipitation • 3 time slices (1961-2000, 2046-2065, 2081-2100) 	<ul style="list-style-type: none"> • 10 GCMs (IPCC AR4 era) • A2 emissions scenario 	Disaggregation downscaling. Statistical parameters of gamma distribution were downscaled using first-order Markov chain.	Contact author.
Schoof 2009	<ul style="list-style-type: none"> • 53 stations in the Midwest • Daily temperature • 3 time slices (1961-2000, 2046-2065, 2081-2100) 	<ul style="list-style-type: none"> • 8 GCMs (IPCC AR4 era) • A2 emissions scenario 	Empirical-dynamical downscaling. Transfer functions were developed separately for each location that related large-scale values of mid-tropospheric temperature and humidity to surface temperature (perfect prog method).	Contact author.
Kunkel et al. 2012	<ul style="list-style-type: none"> • Midwest • Multi-model averages of projected changes in annual and seasonal mean temperature and precipitation and for extremes and thresholds 	<ul style="list-style-type: none"> • CMIP3 GCM and NARCCAP RCM simulations • A2 and B1 emissions scenarios for CMIP3 models; A2 emissions scenario for NARCCAP simulations 	Dynamical downscaling	Guidance document prepared for the authors of the NCA report and members of the regional and sectoral technical input teams. Available from NCA.
Hayhoe et al 2010	<ul style="list-style-type: none"> • US Great Lakes region • 1/8 degree grid and individual weather stations • Monthly and daily temperature and precipitation 	<ul style="list-style-type: none"> • 3 GCMs from CMIP3 archive • SRES A1FI, B1 emissions scenarios 	Disaggregation downscaling using 1) the Maurer et al. 2007 approach to downscale monthly temperature and precipitation to a regular grid, and 2) asynchronous quantile regression for downscaling to individual stations and daily resolution	Contact author. [NOTE: an updated dataset for the entire US will soon be released and available via the USGS climate projection port]
Pileus Project (Winkler et al., 2012)	<ul style="list-style-type: none"> • 15 locations in the Great Lakes region of North 	<ul style="list-style-type: none"> • 4 GCMs (IPCC AR4 era) 	Empirical-dynamical downscaling. Regressions equations were developed	User tool to view summary graphics for temperature scenarios available at

	<p>America</p> <ul style="list-style-type: none"> • Daily temperature and precipitation • 2000-2099 	<ul style="list-style-type: none"> • 2 emissions scenarios (A2, B2) • 8 empirical-dynamic downscaling variants based on “perfect prog” approach 	<p>for each location that related large-scale circulation (the predictors) to surface climate variables (the predictands).</p>	<p>www.pileus.msu.edu Precipitation scenarios available from author</p>
<p>WICCI Kucharik et al. 2010; Notaro et al. 2011; WICCI 2011</p>	<ul style="list-style-type: none"> • Wisconsin • 0.1° lat x 0.1° lon • Daily temperature and precipitation • 1960-1999, 2045-2064, 2081-2100 	<ul style="list-style-type: none"> • 14 GCMs from CMIP3 archive • SRES A2,A1B, and B1 emissions scenarios 	<p>Disaggregation downscaling. Statistical relationships were developed between GCM fields and parameters of the probability density function for a local climate variable . The parameters were interpolated to fine grid, and a random number generator was used to obtain daily values.</p>	<p>Maps of multi-model means available at http://www.wicci.wisc.edu and http://ccr.aos.wisc.edu/climate_modeling/wisconsin_climate</p>