In press for the journal Mitigation and Adaptation Strategies for Global Change, as part of the special issue entitled:
“Northeast United States Climate Impact Assessment”
guest edited by:
Dr. Cameron P. Wake, University of New Hampshire; Dr. Peter Frumhoff, Union of Concerned Scientists; Dr. James McCarthy, Harvard University; Dr. Jerry Melillo, Marine Biological Laboratory; Dr. Susanne Moser, National Center for Atmospheric Research; and Dr. Don Wuebbles, University of Illinois.
July 2007

Regional Climate Change Projections for the Northeast U.S.

Katharine Hayhoe[1,2], Cameron Wake[3], Bruce Anderson[4], Xin-Zhong Liang[5], Edwin Maurer[6], Jinhong Zhu[5], James Bradbury[7], Art DeGaetano[8], Anne Hertel[9], and Donald Wuebbles[9]

[1] Corresponding author: Dept. of Geosciences, Texas Tech University, P.O. Box 41053, Lubbock, TX. Phone: (806) 742-0015, Fax: (806) 741-0100, Email: katharine.hayhoe@ttu.edu
[2] ATMOS Research & Consulting, Lubbock, TX
[3] Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH
[4] Dept. of Geography and Environment, Boston University, Boston, MA
[5] Illinois State Water Survey, Champaign, IL
[6] Dept. of Civil Engineering, Santa Clara University, Santa Clara, CA
[7] Climate System Research Center, Dept. of Geosciences, University of Massachusetts, Amherst, MA
[8] Northeast Regional Climate Center, Dept. of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY
[9] Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL

Running Head: Climate Projections for the Northeast U.S.

Abstract

Climate projections at relevant temporal and spatial scales are essential to assess potential future climate change impacts on climatologically diverse regions such as the northeast United States. Here, we show how both statistical and dynamical downscaling methods applied to relatively coarse-scale atmosphere-ocean general circulation model output are able to improve simulation of spatial and temporal variability in temperature and precipitation across the region. We then develop high-resolution projections of future climate change across the northeast U.S., using IPCC emission scenarios combined with these downscaling methods. The projections show increases in temperature that are larger at higher latitudes and inland, as well as the potential for changing precipitation patterns, particularly along the coast. While the absolute magnitude of change expected over the coming century depends on the sensitivity of the climate system to human forcing, significantly higher increases in temperature and in winter precipitation are expected under a higher as compared to lower scenario of future emissions from human activities.

Keywords: Climate change, downscaling, general circulation model, greenhouse gas emission scenarios, Northeast United States

1. Introduction

One of the greatest concerns of future climate change is the potential impact at the local to regional scale. Global changes in the climate system will interact with the distinctive geographic characteristics of individual regions to produce a climate change signal unique to that region. These changes in regional climate have the potential to affect many aspects of our lives and our communities, including our health and welfare, agriculture and natural ecosystems, water and air quality, and our economy. Climate changes therefore need to be evaluated at regional and seasonal scales to make the projections relevant on a human scale. The spatial scale of the information used as a base to investigate the impact of changing climate on various sectors in our society can also affect the magnitude and sometimes even the sign of the potential change and corresponding impacts (e.g., Mearns et al. 2001; Doherty et al. 2003; Tsvetsinskaya et al. 2003; Kueppers et al. 2005).

To study the potential effects of climate change, we rely primarily on climate projections from coupled atmosphere-ocean general circulation models (AOGCMs), driven by a range of plausible scenarios describing how population, technology, and energy use might develop in the future. Model analyses and inter-comparisons have shown that the latest generation of AOGCMs provides a reasonable representation of observed climate change at the global scale over the last century (Solomon et al. 2007). However, it is not certain which (if any) of these models accurately recreate observed trends in climate at the regional scale, or if they correctly represent the processes responsible for climate variability at the regional level (Kunkel et al. 2006). This uncertainty has important implications for the validity of the conclusions drawn in regional climate impact assessments. These conclusions generally rely on the relatively coarse spatial pattern of changes in temperature, precipitation, and other climate features produced by AOGCMs to drive estimates of projected impacts (e.g., NAST 2000).

To assess the potential for dynamical and statistical downscaling to enhance global-scale climate projections by incorporating regional-scale information, we focus on the Northeast U.S. (NE). This region covers the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Pennsylvania. Although relatively small from a geographical perspective, the climatic gradient across the NE is one of the steepest in the country (Ludlum 1976; Zielinski and Keim 2003).

2. Observational Data and Model Simulations

To validate model output, AOGCM climate and downscaled historical climate are compared with observational temperature and precipitation records, based on a subset of the United States Historical Climatology Network (USHCN) (Karl et al. 1990; Easterling et al. 1999; Williams et al. 2005). The USHCN station data represents the best available data source for investigating changes in temperature and precipitation since 1900. The stations are selected based on length and quality of data, which includes limiting the number of station changes and correcting for known biases (Karl et al. 1986; Quayle et al. 1991; Karl and Williams 1987; Karl et al. 1988).

To assess potential future changes in temperature precipitation, we relied on projections from three of the latest Intergovernmental Panel on Climate Change (IPCC) AR4 coupled AOGCMs: U.S. National Oceanographic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory CM2.1 (Delworth et al. 2005), United Kingdom Meteorological Office HadCM3 (Pope et al. 2000), and U.S. Department of Energy/National Center for Atmospheric Research Paralled Climate Model (PCM) (Washington et al. 2000). Climate sensitivity for these models ranges from 1.3ºC to 3.3^{o}C, covering the lower part of the IPCC 1.5ºC-4.5^{o}C uncertainty range (Solomon et al. 2007).

Historical AOGCM simulations (for the period 1960 to 1999) correspond to the Coupled Model Intercomparison Project "20th Century Climate in Coupled Models" or 20C3M scenarios

(Covey et al. 2004). These represent each modeling group's best efforts to represent observed climate over the past century and generally include forcing from anthropogenic emissions of greenhouse gases, aerosols, and reactive species; changes in solar output; particulate emissions from volcanic eruptions; changes in tropospheric and stratospheric ozone; and other influences required to provide a complete picture of climate over the last century.

Future simulations were forced by the IPCC Special Report on Emission Scenarios (SRES; Nakienovi et al. 2000) higher (A1fi) and lower (B1) emissions scenarios. These scenarios describe internally consistent pathways of future societal development and corresponding greenhouse gas emissions. Although neither of these scenarios include climate-related emission reduction policies, the broad range of projected atmospheric carbon dioxide (CO_2) concentrations in 2100 represented by these scenarios (970 ppm under A1fi, 550 ppm under B1) mean that these scenarios can be used as proxies to estimate changes likely to occur under a continuation of present-day economic growth rates (A1fi) as compared with a scenario aimed at stabilizing CO_2 concentrations near 550 ppm (B1) (Van Vuuren and O'Neill 2006).

Monthly AOGCM temperature and precipitation fields for all three models and two future scenarios were statistically downscaled for regions with a resolution of 1/8° (Wood et al. 2002). Downscaling used an empirical statistical technique that maps the probability density functions for modeled monthly precipitation and temperature for the climatological period (1961–1990) onto those of gridded historical observed data, so the mean and variability of monthly observations are reproduced by the climate model data. The bias correction and spatial disaggregation technique is one originally developed for adjusting AOGCM output for long-range streamflow forecasting (Wood et al. 2002). It was later adapted for use in studies examining the hydrologic impacts of climate change (VanRheenan et al. 2004) and compares favorably to different statistical and dynamic downscaling techniques (Wood et al. 2004). At each grid-cell, the observed values for a randomly selected month were then rescaled to match the downscaled, bias-corrected monthly temperature and precipitation values, with the same month used throughout the domain to preserve spatial correlation structures. Daily humidity values consistent with the daily precipitation and temperature were estimated using the iterative technique described by Thornton et al. (2000) and implemented in the Variable Infiltration Capacity (VIC) hydrology model. Thus, the approach is designed to be driven by projections of the AOGCM at the monthly scale, with historically plausible daily sequences within any month.

This method compares favorably to other statistical and dynamic downscaling techniques (Wood et al. 2004). It also carries the additional benefit of being able to generate the daily climate inputs for models and scenarios that did not save their output at daily resolution. However, there are also some disadvantages to this approach. First, statistical generation of daily values from monthly temperature and precipitation do not necessarily reflect possible changes in atmospheric circulation as simulated by the global models on scales of days to weeks, except so far as these are reflected by the global models' monthly means. Furthermore, this approach assumes that the shapes (although not the mean) of the monthly historical temperature and precipitation distributions used to generate the daily values for each month remain unchanged over time. This assumption may not be valid for many regions of the globe, where model-simulated increases in daily extremes are often not directly proportional to what would be projected based on shifts in the mean value alone.

Regional model simulations were conducted using PCM simulations only as boundary conditions for the 1990s, 2020s, 2050s and 2090s under the SRES A1fi and B1 scenarios. The CMM5 is a climate extension of the fifth-generation Pennsylvania State University-National

Center for Atmospheric Prediction Research (PSU-NCAR) Mesoscale Model (MM5) version 3.3 (Dudhia et al. 2000) developed by Liang et al. (2001). Important modifications include incorporation of more realistic surface boundary conditions and cloud cover prediction. It has been demonstrated that the CMM5 has pronounced skill in downscaling precipitation (Liang et al. 2004a, 2004b) and soil moisture and temperature (Zhu et al. 2005).

3. Comparison of Regional Model-Based and Statistically Downscaled Temperature and Precipitation Fields with Observations

To compare model simulations with observations, we examine the potential for AOGCM output to be translated into the higher-resolution spatial and temporal distributions required for assessing regional-scale climate change impacts. For detailed comparisons between high-resolution regional model simulations and AOGCM output, comparisons between statistical and dynamical downscaling methods, and comparisons between different types of statistical methods, we refer the reader to a number of publications already available in the literature (e.g., Deque et al. 2005; Wood et al. 2004; Mearns et al. 2003; Wilby et al. 1998, 2000; Wilby and Wigley 1997; Hewitson and Crane 1996). In addition, a detailed analysis of how well historical model simulations from nine AOGCMs are able reproduce past trends in surface climate, hydrology, biometeoroloigcal indicators, and regional circulation patters in the Northeast US is provided by Hayhoe et al. (2007, in review). Here, our focus is on illustrating the potential for such methods to remove some of the known biases in AOGCM data for use in regional impact assessments.

Recognizing the limitations of global models and respecting the purpose for which they are currently designed (those being the simulation of global and large-scale climate features and processes), we do not attempt inappropriate comparisons of their performance against either the absolute values of surface temperature, precipitation, etc., nor against higher-resolution temporal or spatial distributions of surface climate across the NE. However, as changes in fine-scale temporal and spatial climate characteristics are valuable for estimating potential impacts on human health (e.g., extreme heat days), infrastructure (e.g., heavy rainfall events), ecosystems, and agriculture (e.g., identifying shifting optimal growth zones), we assess the ability of a representative dynamical (regional modeling) and a statistical (correlation-based) downscaling method to translate global model simulations into absolute values and distributions of surface climate. The successes and failures of these downscaling approaches can be taken as a proxy of their ability to simulate and/or account for the small-scale processes that affect the distributions of temperature and precipitation across the domain.

First, we compare 1990s mean summertime daily maximum temperatures from the USHCN station data with the mean daily maximum temperatures from the regional climate model (RCM), statistical downscaling (SD), and PCM output (Figure 1, a through d). Although the coarser-scale PCM data cannot capture the fine-scale variations, particularly those in upstate New York and across the New Hampshire/Vermont border, the RCM and SD methods do capture these variations. In general, both methods compare well with the observations, although the RCM data appears slightly too warm along the coastal regions over the northern portion of the domain. This may result from inadequate representation of land surface processes related to soil moisture, vegetation cover, and/or the use of static versus dynamic surface albedo in this region. Model-simulated sea surface temperatures in the Gulf of Maine are, on average, anomalously high and could also be contributing to the observed RCM coastal bias.

Figure 1 (e through h) compares total summertime precipitation from the USHCN station observations to those from the RCM, SD, and PCM simulations. It appears that the RCM and

PCM have too little precipitation, particularly over the southern portion of the domain. This may be due to the general failure of the Grell cumulus scheme to adequately represent convection over coastal regions. The Grell scheme realistically simulates the nocturnal precipitation maxima and their associated eastward propagation of convective systems over the Great Plains, where the diurnal timing of convection is controlled by the large-scale tropospheric forcing. (The Kain-Fritsch scheme is more accurate for the late afternoon peaks in the southeast U.S. where moist convection is governed by the near-surface forcing [Liang et al. 2004a].) In comparison, the SD has too much precipitation, particularly through the central portion of the domain. Towards the north of our domain of interest, part of this could be attributed to the fact that the 140 km^2 resolution fails to reproduce variations due to mountainous terrain; however, as the SD simulations are trained on the 1961-1990 period and apply projected changes to base period values (so that precipitation anomalies are applied proportionately to where base period precipitation fell), this would seem to indicate that the spatial relationship between large- and small-scale precipitation in this region has shifted slightly in the RCM but not in the SD method because distributions are fixed to match historical observations.

To assess the ability of model simulations to reproduce the extremes of daily maximum temperatures and daily precipitation rates, we also calculated the 10% exceedence threshold (not shown) for the USHCN, RCM, SD, and PCM data, defined as the daily maximum temperature (or daily precipitation rate) which is only exceeded 10% of the time. The RCM appears to capture the structure and magnitude of the observed extreme temperatures. Statistical downscaling simulations show values which are slightly too low in the northern portion of the domain and PCM values which are too low across the entire domain.

The overall agreement in daily extreme temperature statistics between SD and RCM, but greater differences in daily precipitation statistics, illustrates how extreme precipitation projections can be expected to benefit from dynamical modeling or more sophisticated statistical treatment. Observed distributions of daily May-August maximum temperatures are nearly perfectly reproduced by both RCM and SD, although both slightly under-estimate the peak frequencies between 25^{o}C-30^{o}C. For daily rainfall rates, both the PCM and SD exhibit a tendency to drizzle, having too many light-rainfall days with precipitation rates < 10 mm/day. For days with rainfall rates > 10 mm/day, both SD and RCM are close to observed, but PCM has markedly too few. Overall, the RCM distribution appears to better capture both the amount of light-rainfall days as well as the number of heavy- to extreme-rainfall days. However, the convection scheme used in the RCM clearly influences the distribution, with Liang et al. (2006), showing that in the Southeast Gulf States and North American monsoon regions, the Kain-Fritsch scheme produces more frequent intermediate rainfall days than the Grell scheme, in better agreement with observations.

Given the relationship between day-to-day surface climate variability and the frequency of seasonal circulation patterns, this suggests that the RCM and, to a lesser degree, the SD approach, is able to successfully convert AOGCM boundary conditions into seasonal weather pattern frequencies that result in distributions of surface climate that are reasonably close to observed. This success is most likely related to the enhanced resolution of the fine-scale topography in both of these estimates. Coupled with the RCM and SD's ability to reproduce the spatial distributions of mean summer temperature and precipitation and temperature extremes, these results suggest that the application of downscaling techniques, whether dynamic or statistical, to generate high-resolution climate simulations for use in impact assessments is reasonably justified in terms of their ability to simulate present-day climate. However, it is clear that simulation of fine-scale heavy precipitation, which often depends strongly on small-scale topographical and dynamical features, still involves some significant uncertainties regardless of the downscaling method used.

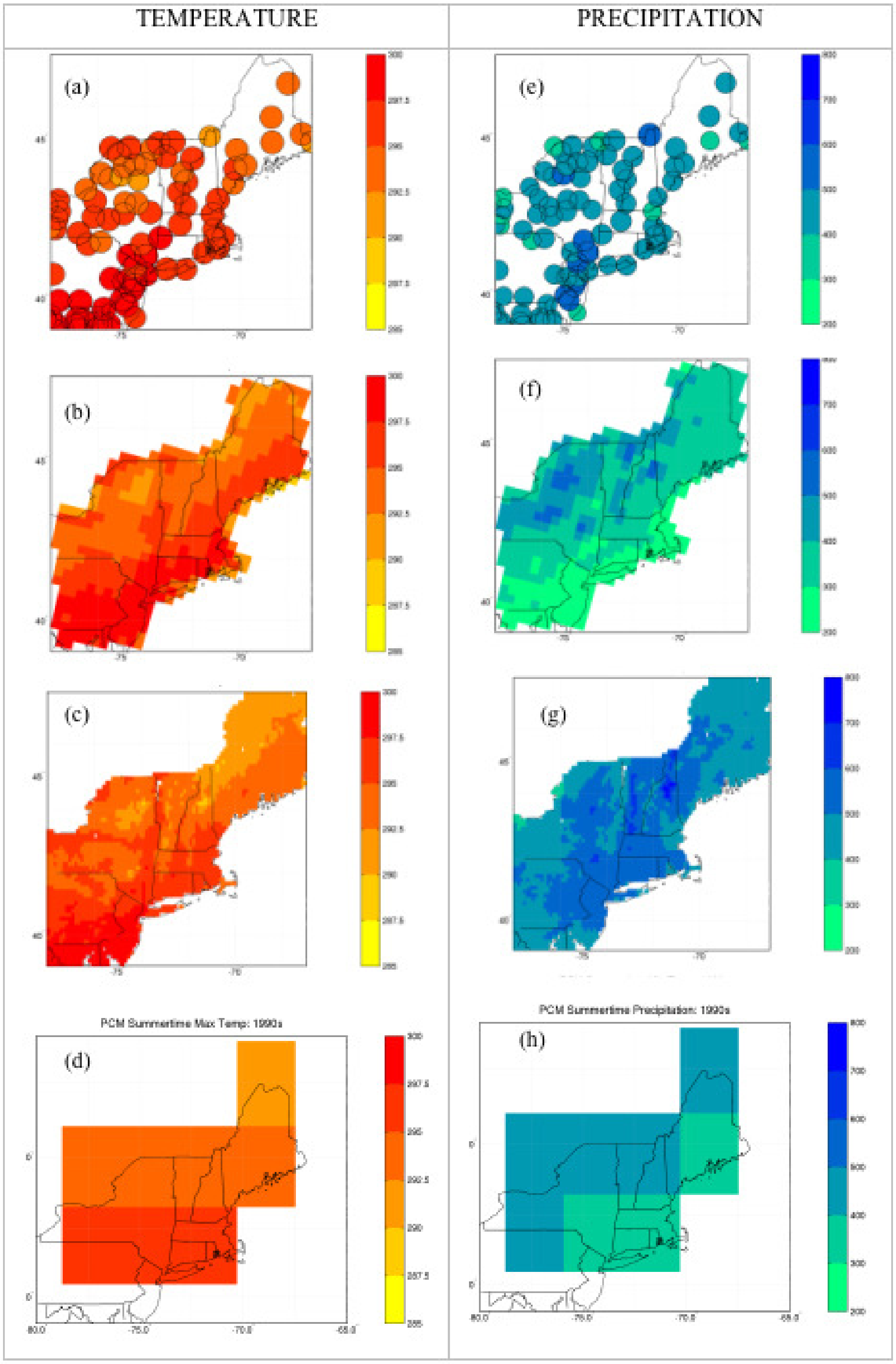

Figure 1. Comparison of 1990s (a,e) observed, (b,f) regional model-simulated, (c,g) statistically-downscaled, and (d,h) PCM-generated seasonal-mean summertime maximum daily temperatures (K), and total precipitation (mm).

4. Future Projections

Over the coming century, temperatures across the NE are projected to continue to rise, with larger increases under higher emissions scenarios relative to lower emissions scenarios, and significantly greater increases in summer as compared to winter temperatures. Changes in annual and seasonal precipitation also show significant seasonal dependence. By the end of the century, winter precipitation is projected to increase an average of 20% under B1 and 30% under A1fi, but shows small decreases (on the order of a few percent) in summer.

In terms of spatial distributions, the largest temperature increases by end-of-century (2070-2099) appear towards the northern part of the domain in both the SD and RCM simulations. However, as shown in Figure 2, there are also some significant differences. The SD approach merely translates projected PCM-based temperature increases onto historical temperature patterns, with changes increasing uniformly from south to north. The RCM, however, shows a "hot spot" centered on coastal southern Maine, with lesser temperature increases radiating out from that location.

For precipitation, there were also some significant differences in spatial distribution between the two approaches. The SD projections show decreases across the whole northern part of the domain and increases across the south, while RCM projections show a smaller area of decrease (over only southern Maine/eastern New Hampshire) and increase (restricted to the south coast). Mean summertime rainfall difference (the difference between the accumulated summertime precipitation from the 2090s minus the 1990s) shows some spatial differentiation, suggesting that northern New England could dry out (by upwards of 50-100mm over 10 years) while southern New England appears to receive more rainfall.

In terms of temperature extremes, both the SD and RCM produce very similar shifts in the summer, with the SD data indicating an approximately 10% larger increase in days between 30-35°C than the RCM (Figure 3a). Both the SD and RCM approaches indicate ~20-40 more days per year above the 1990 90th percentile temperature threshold by the 2090s (which represents an effective doubling of the number of days that exceed the 1990 threshold), with the largest increases occurring throughout the south-central part of the domain. Projected changes in both mean and extreme temperatures are expected to have significant impacts on climate across the NE, including effects on biological and hydrological indicators (Hayhoe et al. 2007).

Changes in the daily precipitation probability distribution function for SD projections (Figure 3b) indicate a decrease in low-rainfall (<10mm/day) events whereas the RCM data indicates an increase. For higher precipitation amounts, both methods produce very similar results. The standard deviation of daily rainfall from RCM and SD simulations for days that had daily rainfall amounts greater than 1 cm shows that "average" daily rainfall events in the 2090s will be about 5 mm larger than in the 1990s. While both PCM and SD data show a decrease in intensity over the northern portion of the domain and a slight increase over the southern portion, the RCM indicates a significant intensification of rainfall rates over the coastal regions and a slight decrease inland. Differences in daily precipitation statistics between the RCM and SD approaches illustrate the much greater impact of daily distribution of monthly precipitation anomalies as compared to temperature; thus, extreme precipitation projections will benefit from dynamical modeling or a more sophisticated statistical treatment.

At least in the summer, the geographic variations in SD temperature and precipitation are consistent with the projected changes in regional atmospheric circulation patters as defined by the position of the East Coast Trough (Bradbury et al., 2002) and the Polar Front Jet (Hayhoe et al., in review). As mentioned, the northward shift in the summertime Polar Front Jet is expected to result in warmer summertime temperatures, particularly in the north, as seen in the downscaled data. The eastward shift in the position of the East Coast Trough would tend to produce drier conditions over New England, consistent with the temperature changes in the SD data.

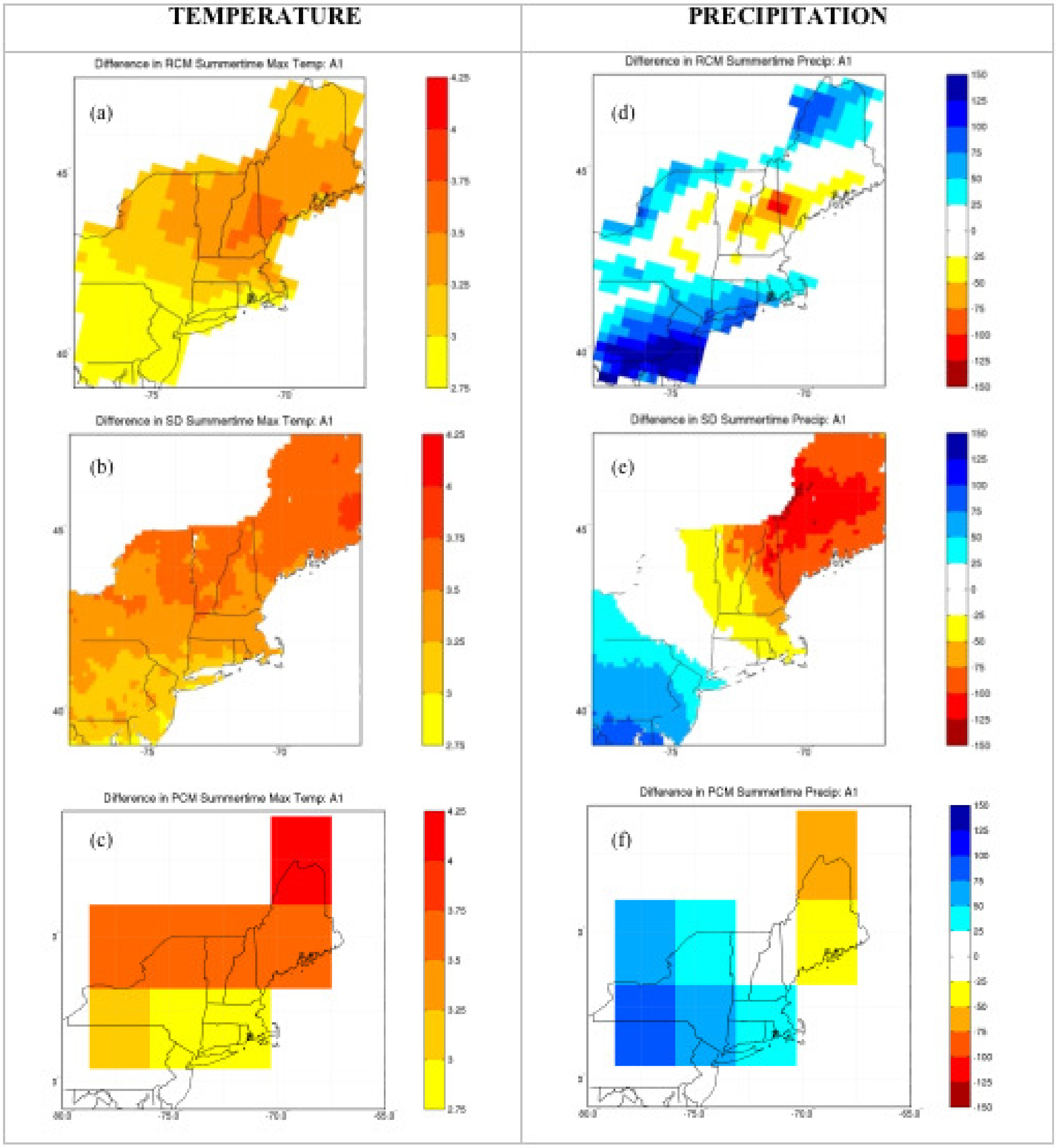

Figure 2. Projected changes in daily maximum temperatures (K) and total precipitation (mm) as simulated by (a) MM5-based regional modeling, (b) statistical downscaling and (c) PCM for the 2090s relative to 1990s.

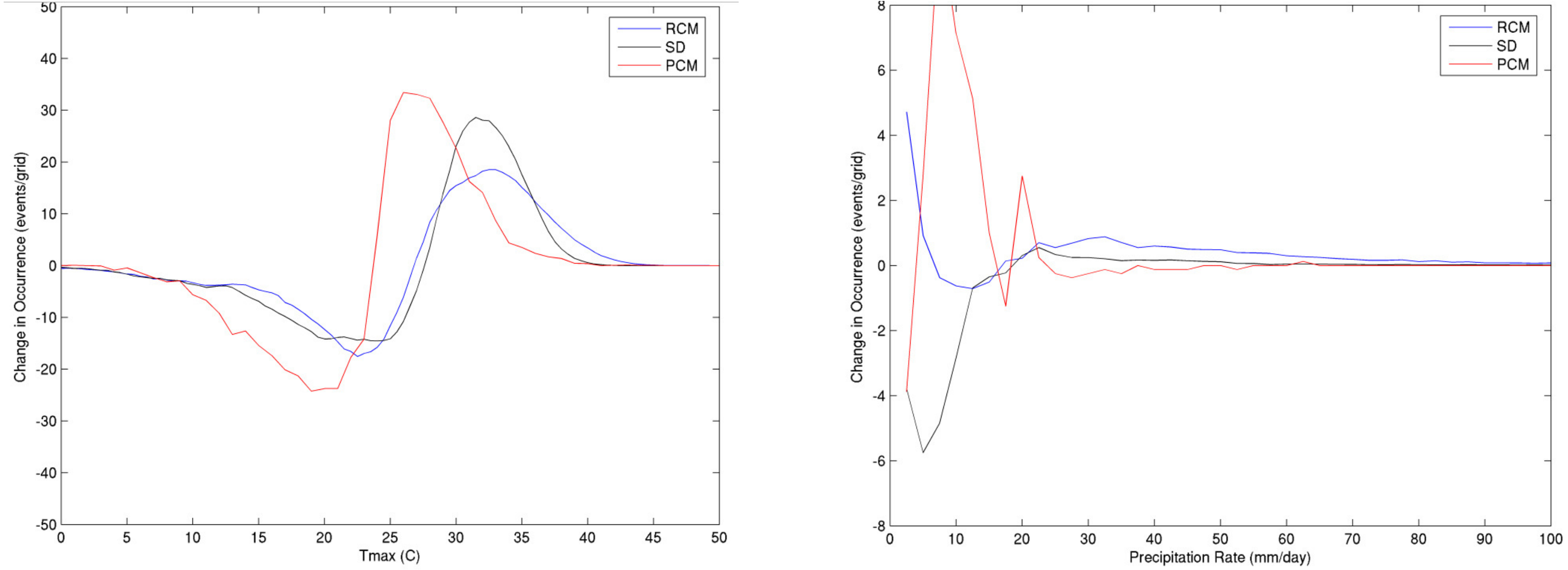

Figure 3. Difference in the probability distribution functions of (a) summer maximum daily temperatures (^{o}C) and (b) daily precipitation (mm/day) between 2090-99 and 1990-99 as projected by the MM5-based regional climate model simulations, statistical downscaling, and directly from the PCM model under the A1fi emissions scenario.

5. Conclusions

Global model simulations of future climate are the foundation for assessments of future regional climate impacts (e.g., Giorgi et al. 2001; Hayhoe et al., 2007). Although the AOGCMs contain significant biases and lack the spatial resolution required for many impact assessments, downscaling approaches appear to exhibit significant skill in taking AOGCM simulations and producing both spatial and temporal distributions in the northeast US that are relatively close to observed climatology for the 1990s. In terms of temperature, the statistical and dynamical approaches are relatively close in terms of both past and future simulations. However, for precipitation, and especially daily precipitation statistics, the RCM approach is clearly superior as the SD as applied here cannot project changes in extreme precipitation, nor can it resolve projected changes in dynamics, seen here particularly along the coast, that are likely to result in shifting spatial patterns of precipitation across the region.

Acknowledgements

We acknowledge NOAA/FSL and NCSA/UIUC for their supercomputing support. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model output, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model output analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy. The research was partially supported by the United States Environmental Protection Agency under award number EPA RD-83096301-0 and by the National Oceanographic and Atmospheric Administration under award number NA05OAR4601080. The views expressed are those of the authors and do not necessarily reflect those of the sponsoring agencies or the Illinois State Water Survey.

REFERENCES

Bradbury JA, Keim BD, and Wake CP (2002) U.S. East Coast trough indices at 500-hPa and New England winter climate variability. J Climate 15:3509-3517

Covey C, AchutaRao KM, Cubasch U et al (2003) An Overview of Results from the Coupled Model Intercomparison Project (CMIP). Global and Planetary Change 37:103-133

Delworth TL, Broccoli AJ, Rosati A, et al (2006) GFDL's CM2 global coupled climate models – Part 1 – Formulation and simulation characteristics. J Climate 19:643-674

Deque, M et al, 2005: Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from PRUDENCE results. Clim Dynamics 25:653-670

Doherty, RM, Mearns LO, Reddy KR et al (2003) Spatial scale effects of climate scenarios on simulated cotton production in the southeastern USA. Climatic Change 60 99-129

Dudhia, J, Gill D, Guo YR et al (2000) PSU/NCAR Mesoscale modeling system tutorial class notes and user's guide: MM5 modeling system version 3. Available at http://www.mmm.ucar.edu/mm5/documents/tutorial-v3-notes.html. Cited 9 May 2007

Easterling DR, Karl TR, Lawrimore JH et al (1999) United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data for 1871-1997 ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html. Cited 9 May 2007

Giorgi F, et al (2001) Regional climate information: Evaluation and projections. In: Houghton JT et al (eds) Climate Change 2001: The Scientific Basis. Cambridge University Press, 583–638

Hayhoe K, Wake CP, Anderson B et al (in review) Quantifying the Regional Impacts of Global Climate Change: Evaluating AOGCM Simulations of Past and Future Trends in Temperature, Precipitation, and Atmospheric Circulation in the Northeast US. Bulletin of the American Meteorological Society

Hayhoe K, Wake CP, Huntington TG et al (2007) Past and future changes in climate and hydrological indicators in the U.S. Northeast. Climate Dynamics 28: 381-407. DOI 10.1007/s00382-006-0187-8

Hewitson, BC, Crane RG (1996) Climate downscaling: techniques and application. Clim Research, 7, 85-95

Karl TR, et al (1986) A model to estimate the time of observation bias with monthly mean maximum, minimum, and mean temperatures for the United States. J. Clim Appl Meteorol 25: 145– 160

Karl TR, Williams CW Jr (1987) An approach to adjusting climatological time series for discontinuous inhomogeneities. J Clim Appl Meteorol 26:1744–1763

Karl TR, Diaz HF, and Kukla G (1988) Urbanization: its detection and effect in the United States climate record, J Climate 1:1099–1123

Karl TR, Williams, CN Jr, Quinlan FT, and TA Boden (1990) United States Historical Climatology Network (HCN) Serial Temperature and Precipitation Data. Environmental Science Division, Publication No. 3404, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 389 pp

Kueppers, LM, Snyder MA, Sloan LC et al (2005) Modeled regional climate change and California endemic oak ranges, Proc Nat Ac Sci 102:16281-16286

Kunkel, KE, Liang X-Z, J Zhu J, and Lin Y (2006) Can CGCMs simulate the 20th century "warming hole" in the central United States? J Climate,19:4137-4153

Liang, X-Z, Kunkel KE, and Samel AN (2001) Development of a regional climate model for U.S. Midwest applications. Part I: Sensitivity to buffer zone treatment. J Climate 14:4363-4378

Liang, X-Z, Li L, Dai A, and Kunkel KE (2004a) Regional climate model simulation of summer precipitation diurnal cycle over the United States. Geophys Res Lett, 31, L24208, 10.1029/2004GL021054

Liang, X-Z, Li L, Kunkel KE et al (2004b) Regional climate model simulation of US precipitation during 1982-2002. Part 1: annual cycle. J Climate 17:3510-3528

Liang, X-Z, Pan J, Zhu J et al (2006) Regional climate model downscaling of the US. summer climate and future change. J Geophys Res 111, D10108, DOI 10.1029/2005JD006685

Ludlum, DM 1976: The Country Journal: Northeast Weather Book. Houghton Mifflin, Boston.

Mearns, LO, Giorgi F, McDaniel L, C Shields (2003) Climate scenarios for the southeastern US based on GCM and regional model simulations. Climatic Change 60:7-35

Mearns, LO, Easterling W, Hays C, Marx D (2001) Comparison of agricultural impacts of climate change calculated from high and low resolution climate change scenarios: Part I. The uncertainty due to spatial scale. Climatic Change 51:131-172

Nakienovi N, Alcamo J, Davis G et al (2000) Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. Cambridge, UK and New York, NY

National Assessment Synthesis Team (NAST) (2000) Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. US Global Change Research Program, Washington, DC. Available at http://www.usgcrp.gov/usgcrp/Library/nationalassessment/overview.htm. Cited 9 May 2007

Pope, VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parameterizations in the Hadley Centre climate model—HadCM3 Clim Dynamics 16:123-146

Quayle RG, Easterling DR, Karl TR, Hughes PY (1991) Effects of recent thermometer changes in the cooperative station network. Bull Am Met Soc 72:1718– 1724

Solomon S, Qin D, Manning M (2007) The Physical Basis of Climate Change: IPCC Working Group I. Available at http://www.ipcc.ch/. Cited 9 May 2007.

Thornton, PE, Hasenhauer H, White MA (2000) Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria. Agricultural and Forest Meteorology 104:255-271

Tsvetsinskaya, EA, Mearns LO, Mavromatis T et al (2003) The effect of spatial scale of climatic change scenarios on simulated maize, winter wheat, and rice production in the southeastern United States. Climatic Change 60:37-71

Van Vuuren, DP and O'Neill BC (2006) The consistency of IPCC's SRES scenarios to recent literature and recent projections. Climatic Change, DOI: 10.1007/s10584-005-9031-0

VanRheenan, NT, Wood AW, Palmer RN Lettenmaier DP (2004) Potential implications of PCM climate change scenarios for Sacramento-San Joaquin River Basin hydrology and water resources. Climatic Change 62:257-281.

Washington WM et al (2000) Parallel Climate Model (PCM) Control and Transient Simulations Clim Dynamics 16:755-774

Wilby RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. Prog Phys Geog,21:530-548

Wilby, RL, Wigley TML, Conway D et al (1998) Statistical downscaling of general circulation model output: A comparison of methods. Water Resource Res 34:2995-3008

Wilby, RL, Hay L, Gutowski W et al (2000) Hydrological responses to dynamically and statistically downscaled climate model output. Geophys Res Lett 27:1199-1202

Williams, CN Jr, Menne MJ, Vose RS, and Easterling DR (2005) United States Historical Climatology Network Monthly Temperature and Precipitation Data.ORNL/CDIAC-118, NDP-019. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. Available at http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html. Cited 9 May 2007

Wood A, Leung LR, Sridhar V, Lettenmaier D (2004) Hydrologic implications of dynamical and statistical approaches to downscaling climate model surface temperature and precipitation fields Climatic Change 62: 189-216

Wood AW, Maurer EP, Kumar A, Lettenmaier D (2002) Long-range experimental hydrologic forecasting for the eastern United States. J Geophys Res 107: 4429, DOI 10.1029/2001JD000659

Zhu, J, Liang X-Z (2005) Regional climate model simulation of U.S. soil temperature and moisture during 1982-2002. J Geophys Res 110, D24110. DOI10.1029/2005JD006472

Zielinski G A, Keim BD (2003) Northeast Weather, Northeast Climate. University Press of Northeast, Lebanon, NH.