Final Report

Impacts of Climate Change on New Jersey Water Resources

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DEP Contract SR-02-082, with amendments SR03-073 and SR04-052

June 1, 2002 – June 30, 2005

$140,000 total funding

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Executive Summary

We have evaluated global climate model simulations of New Jersey climate and determined that the frequency of drought will decrease during the current century along with global warming, but with large variability. We have modified the Regional Atmospheric Modeling System (RAMS) for use in climate simulations. This involved adjustments to the model's convection, turbulence, and land surface schemes, and the discovery that spectral nudging is necessary for simulating high resolution land surface interactions in the correct location. We have attached RAMS to a hydrology model that for the first time simulates water table and stream flow nationally with surface forcing. The project that started with DEP funding is now continuing with funding from the National Science Foundation, and we will soon be able to combine these tools to determine in detail the consequences of future climate change for New Jersey water resources.

Introduction/Problem Statement

The global climate is projected to change significantly in the next century as a result of human pollution of the atmosphere with greenhouse gases and aerosols, and of human modification of the land surface. The Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton et al., 2001), says, "Models project that increasing atmospheric concentrations of greenhouse gases will result in changes in temperature and precipitation, with more hot days, heat waves and heavy precipitation events, leading to more floods and droughts, and adverse impacts on ecological systems, socio-economic sectors and human health." The manifestations of these global changes will be felt in New Jersey, with potentially large impacts on the population through effects on agriculture, water resources, energy supply and demand, air pollution, the coastal region, the urban region, and public health. In the proposed research we will focus on the impacts of future climate change on New Jersey water resources. New Jersey had deficient precipitation for the four years in a row recently. Was this a manifestation of climate change? How often will this happen in the future and what will be the consequences? The current procedure for water resources planning in New Jersey is to plan for the worst drought that has occurred in the past, which was in the 1960s. But as climate changes will droughts like this occur more often or be more severe? The problem to be addressed in the proposed research is to understand the impacts of future climate change on New Jersey, particularly on water resources.

Project Design and Methods

The amount of water available from the Delaware River depends on snowfall and reservoir releases in the northern part of the catchment, and the division between fresh and salt water (the "salt front") in the lower reaches of the river. If sea level rises or flow decreases, the salt front moves up the river, threatening fresh water inlets. Wollock et al. (1993) suggested that the changes in temperature and especially precipitation would affect the frequency of a New York City water crisis more than the frequency of a Philadelphia water crisis if current reservoir-operating procedures were followed in the future. A rise in sea level also would have greater effect on movement of the salt front than on storage in the New York City reservoirs. He concluded that the expected frequencies of water crisis under adverse climate changes could be reduced by modifying the operating procedures used in the Delaware River basin.

To evaluate the impacts of climate change on water resources, we need to produce scenarios of future climate, and then apply these to models that calculate how much water will be available. The most important parameters are precipitation, solar radiation, temperature, and sea level. We evaluated model-generated scenarios from the IPCC Data Distribution Centre and will use the results of the latest global climate model simulations to couple to our own Center for Environmental Prediction (CEP) high-resolution mesoscale climate model. There are many potential impacts of climate change on human activities, and it would be impossible in this project to comprehensively include all the impacts. Rather we focus on a few impacts that are of particular concern to the state of New Jersey, and that reflect the expertise and interests of our team of Rutgers University researchers and the New Jersey Department of Environmental Protection. Here we propose to examine water resources. The main work has been to develop the regional coupled atmosphere-hydrology model.

We are running the Regional Atmospheric Modeling System (RAMS) climate model (Pielke et al., 1992) for a region covering North America, using as boundary conditions the NCEP/NCAR reanalysis (Kalnay et al., 1996). RAMS has been used extensively in many projects around the world. A list of more than 100 papers using RAMS can be found at http://blue.atmos.colostate.edu/ramspublications.shtml and detailed information about RAMS can be found at http://atmet.com/. As RAMS was developed for short-term regional experiments, we have modified it for use in climate simulations. We have also attached it to a detailed hydrology model which explicitly calculates water table and stream flow. Later we will drive this tool at high resolution over New Jersey to examine the effects of climate change, by coupling the new tool, RAMS-Hydro to climate model simulations of future climate, as well as do experiments on the effects of local land cover changes and the urban heat island.

Ayers et al. (1994) presented a comprehensive analysis of the impacts of climate change on the Delaware River Basin water resources, including streamflow and soil moisture. However, they used monthly average output averaged for the entire region, and used statistical techniques to produce the daily output needed for the analysis. We will repeat this experiment, using updated scenarios, with hourly data generated by our model at detailed locations distribute across the entire basin.

Quality Assurance

Not applicable.

Results and Discussion

We evaluated the effects of climate change on frequency of drought in New Jersey by using the output from eight different climate models and looking at their projections for the New Jersey region. We found that in global warming scenarios, the frequency of drought, of different severities and different lengths, will decrease in the future. We made one conference presentation on these results, but the funding did not last long enough to complete a study that was acceptable to a journal.

We have completed two papers which establish the validity of our regional climate model, RAMS, for conducting simulations of precipitation processes and through them, the impacts of changing climate on New Jersey water resources. It is well known that regional climate simulations are sensitive to the size and position of the domain chosen for calculations. In the first paper (Miguez-Macho et al., 2004) we studied the physical mechanisms of this sensitivity. We conducted simulations with the Regional Atmospheric Modeling System (RAMS) for June 2000 over North America at 50 km horizontal resolution using a 7500 km x 5400 km grid and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis as boundary conditions. The position of the domain was displaced in several directions, always maintaining the U.S. in the interior, out of the buffer zone along the lateral boundaries. Circulation biases developed a large scale structure, organized by the Rocky Mountains, resulting from a systematic shifting of the synoptic wave trains that crossed the domain. The distortion of the large-scale circulation was produced by interaction of the modeled flow with the lateral boundaries of the nested domain and varied when the position of the grid was altered. This changed the large-scale environment among the different simulations and translated into diverse conditions for the development of the mesoscale processes that produce most of precipitation for the Great Plains in the summer season. As a consequence, precipitation results varied, sometimes greatly, among the experiments with the different grid positions. To eliminate the dependence of results on the position of the domain, we used spectral nudging of waves longer than 2500 km above the boundary layer. Moisture was not nudged at any level. This constrained the synoptic scales to follow reanalysis while allowing the model to develop the small-scale dynamics responsible for the rainfall. Nudging of the large scales successfully eliminated the variation of precipitation results when the grid was moved. We suggest that this technique is necessary for all downscaling studies with regional models with domain sizes of a few thousand kilometers and larger embedded in global models.

In the second paper (Miguez-Macho et al., 2005) we investigate the reasons for biases in regional climate simulations, trying to discern whether they arise from deficiencies in the model parameterizations or are due to dynamical problems. Using RAMS forced by the NCEP/NCAR reanalysis, we simulated the detailed climate over North America at 50 km resolution for June 2000. First we corrected the RAMS equations to make it applicable to a large region and corrected its turbulence parameterization. Our initial simulations showed large biases in the location of precipitation patterns and surface air temperatures. By implementing higher resolution soil data, soil moisture and soil temperature initialization, and corrections to the Kain-Fritch convective scheme, we were able to remove the temperature biases and precipitation amount errors, but the precipitation location errors remained. We were only able to correct the precipitation location biases by implementing spectral nudging of the large scale (wavelength 2500 km) dynamics in RAMS. This corrected for circulation errors produced by interactions and reflection of the internal domain dynamics with the lateral boundaries where the model was forced by the reanalysis.

RAMS also includes a recently developed land-surface scheme that is fully prognostic in water and energy in vegetation, canopy air, and multiple soil and snow layers (Walko et al. 2000). Each of these component interacts dynamically with the others, and with the atmosphere. Furthermore, each grid cell can be divided into subgrid patches with unique vegetation, soil textural class and moisture, and snow cover. This scheme includes a soil column of user-determined depth and allows soil water to move up and down as driven by gravity drain and capillarity. Until now, RAMS did not include the lateral (within-cell or inter-cell) hydrologic components: surface runoff, groundwater flow, groundwater-stream interactions, and stream flow. This limitation prevents the direct prediction of climate change impacts on regional water resources, and it also prevents the study of the two-way interactions between these various reservoirs of the terrestrial water cycle and the rest of the climate system. Therefore, to overcome this limitation, we have modified it extensively to include the full surface and subsurface hydrologic processes and their full, dynamical interaction with each other and with the atmosphere and soil-vegetation system (Fan et al., 2006; Miguez-Macho et al., 2006). We refer to this new coupled modeling system as “RAMS-Hydrology.”

We have built into RAMS the following new components: a process-based boundary condition (i.e., the water table) for the unsaturated soil column, a mass balance for the saturated storage which governs the water table dynamics, lateral groundwater flow from cell to cell, two-way groundwater-stream interaction within a cell, surface runoff reaching local rivers, and continental river routing to the ocean. Our formulations conserve mass in all reservoirs, are physically based and conceptually simple, and require few parameters. We have completed all the code implementation and have tested the coupled model with a set of preliminary simulations described by Miguez-Macho et al. (2006).

Our approach represents a further step forward toward fully integrating all the reservoirs, atmospheric and land, since we perform this integration in the full, three-dimensional dynamical framework of a state-of-the-art regional climate model. With RAMS-Hydrology, we can now explicitly represent both the vertical and horizontal transports of water in the atmosphere, the land surface, and the subsurface simultaneously. To our knowledge, ours is the first such attempt. This advance allows us, within the context of one internally self-consistent modeling system to (a) simultaneously close the land and atmospheric branches of the terrestrial water cycle while validating simulated regional climate not only with meteorological observations but also with standard hydrologic measurements, (b) predict future changes in quantities such as groundwater levels, river flow, and wetland extent as a result of changes in climate, and (c) explore the co-evolution of these changes with soil moisture, the atmospheric circulation, cloudiness, precipitation, and other aspects of the climate system in a fully coupled, theoretically robust dynamical framework.

We have tested the new RAMS-Hydrology system in preliminary simulations over the North American continent for the period June-September 1997 (Miguez-Macho et al., 2006). These simulations demonstrated the ability of RAMS-Hydrology to successfully capture observed water table depth and river flow in addition to observed meteorological fields such as precipitation. Furthermore, these simulations demonstrated that, even over the course of the relatively short 4-month simulations, the impact of introducing fully coupled surface and subsurface dynamics into the system produced significant impacts (e.g., on the spatial and temporal structure of soil moisture, surface fluxes, and precipitation).

We are now just beginning simulations using RAMS-Hydrology implemented at high resolution over the New Jersey region to investigate how New Jersey water resources will change with future climate. The new Intergovernmental Panel on Climate Change climate model runs have just been completed by all the major climate research centers in the world, and we will use these runs as boundary conditions for our simulations.

We have received a grant from the National Science Foundation (NSF Water Cycle, ATM-0450334, "Coupled Climatic-Hydrologic Change in the Terrestrial Water Cycle of North America in the 20th and 21st Centuries: Natural Variability and Anthropogenic Impacts," March 1, 2005 – February 28, 2010, $786,400) to continue the work started by funding from DEP. We have hired Dr. Richard Anyah as a Postdoctoral Fellow to continue the work. Dr. Gonzalo Miguez-Macho, who was funded for several years by DEP, has returned to a job as a Professor at the University of Santiago de Compostela in Spain, but will continue to collaborate with us at no cost.

Conclusions and Recommendations for Future Research

Global climate change has the potential to have large impacts on precipitation and evaporative demand in New Jersey. Coupled with land use changes and urbanization, the availability of water from surface flow and subsurface extraction may change substantially in the future. Our work will soon quantify these potential influences, and they should be taken into account when planning the future water infrastructure for New Jersey.

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Acknowledgments

I thank Alexander Polissar for his support as program manager and Prof. Georgiy Stenchikov for his collaboration on this work.

List of Publications and Presentations

[Copies of these papers are available at http://climate.envsci.rutgers.edu/robock/robock_imppapers.html]

Publications supported by this grant:

Miguez-Macho, Gonzalo, Georgiy L. Stenchikov, and Alan Robock, 2004: Spectral nudging to eliminate the effects of domain position and geometry in regional climate model simulations, *J. Geophys. Res*., **109**, D13104, doi:10.1029/2003JD004495.

Miguez-Macho, Gonzalo, Georgiy L. Stenchikov, and Alan Robock, 2005: Regional climate simulations over North America: Interaction of local processes with improved large-scale flow. *J. Climate*, **18**, 1227-1246.

The following papers will be completed soon and will all acknowledge support from DEP:

Fan, Y., C. P. Weaver, G. Miguez-Macho, and A. Robock, 2006: Incorporating water table dynamics in a regional climate model: Part I. Observed water table dynamics and scientific questions. To be submitted to *J. Geophys. Res.*

Miguez-Macho, G., Y. Fan, C. P. Weaver, and A. Robock, 2006: Incorporating water table dynamics in a regional climate model: Part II. Implementation of hydrologic processes and parameter estimation. To be submitted to *J. Geophys. Res.*

Anyah, R., G. Miguez-Macho, Y. Fan, A. Robock, and C. P. Weaver, 2006: Incorporating water table dynamics in a regional climate model: Part III. Effects on soil moisture and atmospheric fields at the continental scale. To be submitted to *J. Geophys. Res.*

Anyah, R., Y. Fan, G. Miguez-Macho, A. Robock, and C. P. Weaver, 2006: Incorporating water table dynamics in a regional climate model: Paper IV. Effect on fluxes, boundary layer structure and precipitation. To be submitted to *J. Geophys. Res.*

Presentations on work supported by this grant:

1. Downscaling climate anomalies from a GCM using RAMS (with Gonzalo Miguez-Macho and Georgiy Stenchikov; presented by Gonzalo Miguez-Macho; Fifth RAMS User Workshop, Thera, Greece, September 29 – October 3, 2002)
2. Engineering RAMS to produce improved climate simulations for the mid-Atlantic states of the U.S. (with Gonzalo Miguez-Macho and Georgiy Stenchikov; presented by Gonzalo Miguez-Macho; Fifth RAMS User Workshop, Thera, Greece, September 29 – October 3, 2002)
3. Modeling the present climate and future climate anomalies over North America using RAMS (with Gonzalo Miguez Macho and Georgiy L. Stenchikov; presented by Gonzalo Miguez Macho; AGU Fall Meeting, December 6-10, 2002)
4. Effects of Global Warming on Drought Frequency and Duration in the Northeast United States (with Chaochao Gao; presented by Chaochao Gao; AGU Fall Meeting, December 8-12, 2003)

5. Spectral Nudging to Eliminate the Effects of Domain Position and Geometry in Regional Climate Model Simulations (with G. Miguez-Macho and G. L. Stenchikov; presented by G. Miguez-Macho; AGU Fall Meeting, San Francisco, California, December 13-17, 2004)
6. The impact of water table dynamics on climate (with G. Miguez-Macho, Y. Fan, and C. P. Weaver; presented by G. Miguez-Macho; European Geosciences Union General Assembly, Vienna, Austria, April 24-29, 2005)
7. Global Warming and New Jersey Water Resources (invited presentation; New Jersey Environmental Leaders Meeting, Princeton University, October 12, 2005)