Use of General Circulation Model Simulations in Regional Hydrological Climate Change Impact Studies

Thomas E. Croley II
Research Hydrologist
Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan

Introduction

Climatic change impacts many aspects of the hydrologic cycle, with interrelated consequences for mankind that often are difficult to discern. Specific regional climate change associated with global warming is highly uncertain. However, it is important to understand the implications to assess the seriousness of the greenhouse effect and to make timely decisions on projects in whose lifetime there may be significant changes. Considerations of situations that may occur (scenarios) help identify possible effects and bound future conditions. Researchers have used general circulation models (GCMs) of the earth's atmosphere to simulate many years of climatic conditions under current conditions and for a doubling of global carbon dioxide levels. They used a larger-than-regional scale for many internally consistent daily meteorological variables. Regional hydrological models can be linked to GCM outputs to assess changes associated with climate change scenarios. The impacts of climate change on regional water supplies have been the focus of several recent studies.

The U.S. Environmental Protection Agency (USEPA, 1984) and Rind (personal communication, 1988) used the hydrologic components of general circulation models to assess changes in water availability in several large regions throughout North America. Rind used only four regions for the entire continent and indicated the need for smaller region assessments. Because the Laurentian Great Lakes possess tremendous water and heat storage capacities coupled with constricted lake outlets, they respond slowly to

state and transient changes in Great Lakes hydrology consequent with these scenarios (Croley, 1990; Hartmann, 1990; and USEPA, 1989).

The present paper presents the methodology of linkage between the hydrology models and the GCMs as used by GLERL for the USEPA study. It then examines the implications of these linkages in hydrological impact assessments.

Component Process Models

The Great Lakes Environmental Research Laboratory developed conceptual model-based techniques and a master computer procedure that integrates the six processes outlined below:

1. GLERL's Large Basin Runoff Model provides rainfall-runoff relationships for simulating moisture storages and runoff from the watersheds draining into the Great Lakes.
2. Overland meteorological data reduction provides estimates of overlake precipitation on each of the lakes.
3. Point thermodynamic models permit the calculation of the heat storages and evaporation from each of the lakes.
4. The Lake Superior regulation plan allows outflow decisions into the St. Marys River.
5. The Hydrologic Response Model routes flows through the connecting channel network between the lakes.
6. The Lake Ontario regulation plan permits decisions of outflows to the St. Lawrence River.

Together, these six processes provide a model of the entire Great Lakes system. GLERL developed the model specifically to look at climate change impacts by doing simulations with historical meteorology (representing an unchanged climate) and simulated meteorology (representing a changed climate) and by comparing the simulations. The model requires

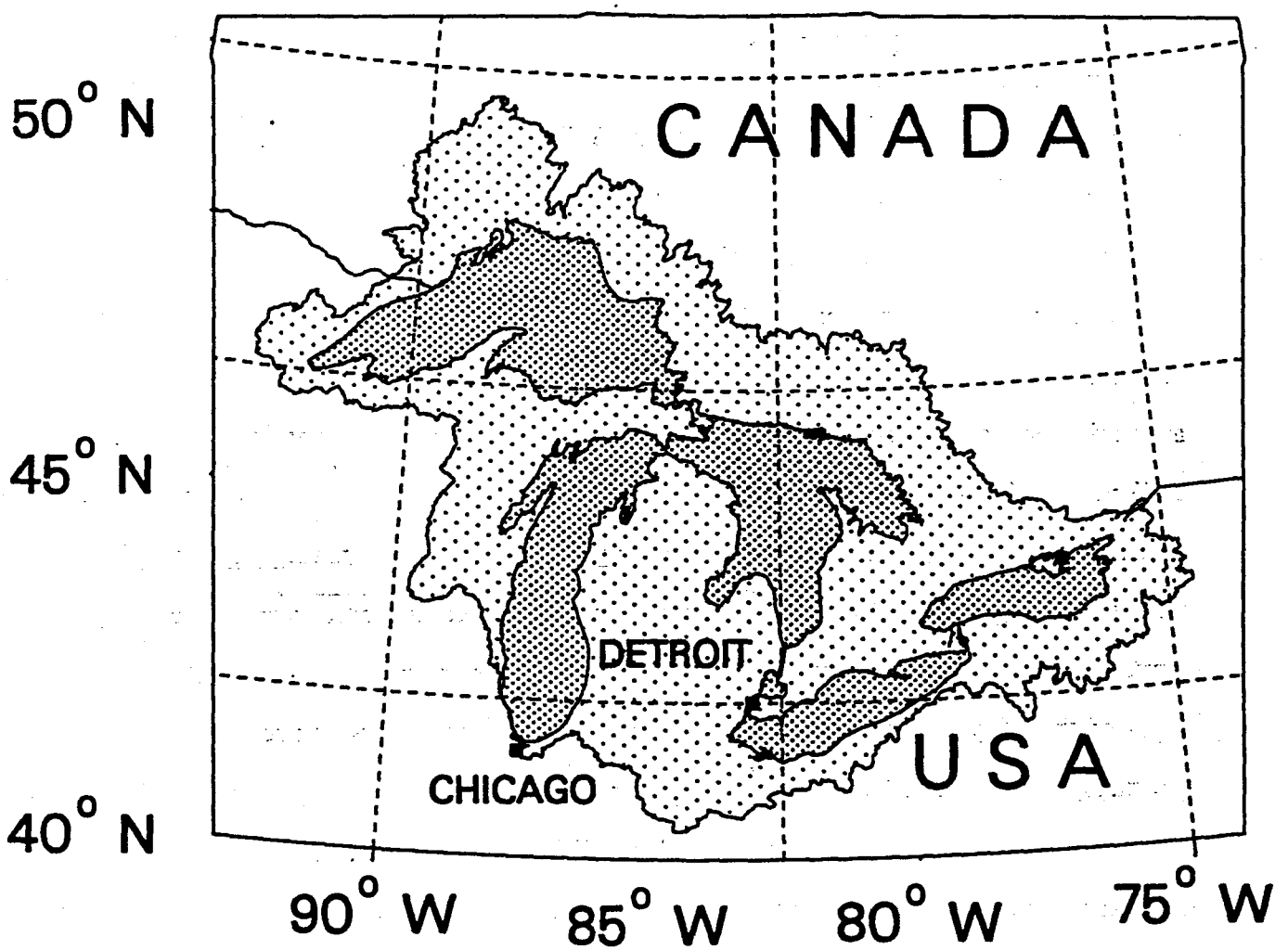

Figure 7

GFDL GCM gridpoints for the Great Lakes Basin

spaced 7.83 degrees latitude by 10 degrees longitude (GISS), 4.44 by 7.5 (GFDL), and 4 by 5 (OSU). Figure 7 illustrates the GFDL grid and Tables 4, 5, and 6 show $1xCO_2$ mean monthly January air temperature over the United States, $2xCO_2$ air temperatures, and their ratio, respectively, from the GISS model. These values define averaged GCM output over the grid. Each value in Tables 4-6 represents an average over a grid square centered on the given location, and applying halfway to the neighboring locations in the table. The ratios in Table 6 resulted by converting the temperatures in Tables 4 and 5 to absolute temperatures and by dividing $2xCO_2$ values (Table 5) by respective $1xCO_2$ values (Table 1). (To convert to absolute temperatures in Kelvin degrees from Celsius degrees, add 273.16 degrees.) The average monthly ratios at each grid location of precipitation, specific humidity, and cloud cover were computed directly from the $1xCO_2$ and $2xCO_2$ GCM results. Since the GCMs did not produce wind speeds directly, they came indirectly from momentum terms, resulting in monthly averages that poorly reflect instantaneous values. Also, since they were vector, instead of scalar, averages that tend to be low, they resulted in unrepresentative ratios. GLERL used differences instead.

GLERL applied these monthly ratios and differences to daily historical data sets to estimate 30-year sequences of atmospheric conditions associated with a changed climate, referred to as the "$2xCO_2$" scenarios. Each of the 770,000 square kilometers within the Great Lakes basin was inspected to see which of the GISS, GFDL, or OSU model grid points were closest. Then they applied the monthly adjustment at that grid point to data representing that square kilometer. By combining these values for all square kilometers representing a watershed or a lake surface they derived areally-averaged monthly scenario adjustments. They applied these adjustments to their areally-averaged daily data sets for the watershed or lake surface, respectively. GLERL multiplied (or added) the adjustment ratio (or difference) to the historical data to derive the $2xCO_2$ "data" (they used each monthly adjustment for all days of that month). For example, they multiplied the ratio of absolute air temperature in

Table 4. GISS Model January Composite Surface Air Temperature: Control Run ($1xCO_2$), degrees Celsius.

Latitude (Degrees)	Longitude (Degrees)						
	-130.00	-120.00	-110.00	-100.00	-90.00	-80.00	-70.00
58.70	-14.03	-19.66	-20.24	-21.48	-22.29	-19.58	-19.12
50.87	3.98	-7.26	-9.67	-9.25	-8.34	-11.44	-12.39
43.04	9.84	-0.45	-8.16	-6.21	-3.32	-4.27	-0.02
35.22	14.40	9.37	-2.65	0.62	0.83	7.01	16.68
27.39	19.05	16.70	12.45	10.70	17.00	19.66	22.48

Table 5. GISS Model January Composite Surface Air Temperature: Climate Change Run ($2xCO_2$), degrees Celsius.

Latitude (Degrees)	Longitude (Degrees)						
	-130.00	-120.00	-110.00	-100.00	-90.00	-80.00	-70.00
58.70	-7.25	-11.00	-10.92	-11.86	-7.52	-3.88	-5.97
50.87	7.67	-0.64	-3.40	-3.75	-3.28	-3.33	-4.18
43.04	13.74	6.14	-0.85	0.29	2.88	1.86	4.97
35.22	17.92	14.18	4.46	5.67	5.57	10.61	19.11
27.39	22.00	21.67	17.37	14.91	19.41	22.16	25.30

Table 6. GISS Model January Composite Surface Air Temperature Ratio, ($2xCO_2/1xCO_2$).

Latitude (Degrees)	Longitude (Degrees)						
	-130.00	-120.00	-110.00	-100.00	-90.00	-80.00	-70.00
58.70	1.0262	1.0342	1.0369	1.0382	1.0589	1.0619	1.0518
50.87	1.0133	1.0249	1.0238	1.0208	1.0191	1.0310	1.0315
43.04	1.0138	1.0242	1.0276	1.0244	1.0230	1.0228	1.0182
35.22	1.0122	1.0170	1.0263	1.0184	1.0173	1.0128	1.0084
27.39	1.0101	1.0172	1.0172	1.0148	1.0083	1.0086	1.0095

There were serious difficulties in analyzing transient impacts of climate change with short historical data sets. In simulating 80 years (1981-2060) by using 30 years of historical data (1951-80) repeated three times, the variations contained in the historical record repeat of course. As GLERL made adjustments to the historical data to reflect the transient GISS climate changes, they found that the repeating fluctuations of the historical record completely dominated the superimposed climate changes. This obscured the effect of climate change. They could have used 30-year averages to filter historical variations for presentation of the results. However, the simulations contained only two complete 30-year periods and a 30-year average filters some of the climatic change as well. GLERL discerned the $2xCO_2$ signal from the historical variations in the adjusted data sets by comparing values 30 years apart, thus eliminating the (repetitive) historical variations. They used the following approach to give a very general idea of transient behavior. They compared the GCM $2xCO_2$ and base cases transient simulation changes for decades 1, 4, and 7 (1981-90, 2011-20, and 2041-50, each based on the same 1951-60 data period). Similarly, they compared changes for decades 2, 5, and 8 (1991-00, 2021-30, and 2051-60), each based on the same 1961-70 data period. Finally, they compared changes for decades 3 and 6 (2001-10 and 2031-40), each based on the same 1971-80 data period. This allowed them to eliminate the effect of the repetitive natural variations since the same underlying historical data segments were used in each grouping and climate change trends could be identified.

Implications

The hydrological study results should be received with caution, since they are, of course, dependent on the GCM outputs with inherent large uncertainties in the components, assumptions, and data. Transfer of information between the GCMs and the hydrologic models in the manner described involves several more assumptions. First, as previously mentioned, spatial and temporal variabilities of the $1xCO_2$ and $2xCO_2$ data sets are the

each other. Of secondary importance, the spatial averaging of meteorological values over a GCM grid box filters all variability that exists in the GCM output over that grid box. If researchers could use GCM outputs at the grid box corners and interpolate between these point values, then they might preserve at least some of the spatial variability. Of course, we know little about the validity of spatial linear interpolation and, for highly variable spatial data, it may be inappropriate. However, the same is true for the spatial averaging used to supply GCM results.

The present average spatial resolution of GLERL's models is about 1000-5000 km^2. Spatial resolutions finer than this are unnecessary, and GLERL could do much in assessing changes at resolutions of 100,000-1,000,000 km^2 with lumped versions of their hydrology models. The coarse spatial resolution of these models is still much finer than the present GCM grids. Since GLERL has daily models derived for other purposes, they used a daily resolution of data with the models even though weekly or monthly data are adequate for this spatial scale. (They did not address short-term fluctuations associated with storm movement in the study.)

There are some specific insensitivities and uncertainties in the hydrology models that are useful to note in conjunction with designing linkages with GCM output data sets. One such insensitivity is with respect to wintertime precipitation. Without temperatures below freezing, the snowpack is insensitive to precipitation. Although the GISS, GFDL, and OSU scenarios show conflicting estimates of possible precipitation changes, each shows increases in air temperatures that significantly reduce snowpack storage, especially in the southern Great Lakes basin. Thus, even if precipitation increases are larger than any suggested by the GCMs, warmer winters will greatly reduce snowpack. Similarly, regardless of actual changes in precipitation, the Great Lakes basin will experience reductions in soil moisture storage and runoff. Soil moisture and runoff both peak shortly after snowmelt and then drop throughout the summer and fall due to high

However, this also illustrates the potential for uncertainty in changes in estimated net supplies (and lake levels).

In using GCM simulations as inputs to regional impact models, it must be remembered that there are several inherent problems with this general approach to evaluating climate change impacts. The linkage between GCM and hydrology models is poor; no feedback exists between these independent models. While the GCMs have crude hydrologic process models, they represent inappropriately large scales and use very simplified conceptualizations. The regional hydrologic impact models may do a much better job of representing the hydrology of an area than the GCMs. However, their use with GCM outputs does not allow the GCM to use these refined processes. The feedback from the land surface (and lake surface) hydrometeorological properties cannot exist without incorporating the regional hydrology models into the atmospheric models. The best potential for this incorporation exists in the newly emerging area of mesoscale atmospheric and hydrologic modeling. Here, mesoscale (regional) atmospheric models merge with regional hydrology models to incorporate process feedbacks between the models both ways. Given that a GCM regional hydrology model simulation, similar to that described in this paper is attempted, then problems will complicate the interpretations of the impacts. The problems include questions of scale matching, spatial and temporal structure similarities between $1xCO_2$ and $2xCO_2$ simulations, and the other information transfer problems enumerated above.

References

Allsopp, T. R., and S. J. Cohen 1986. CO_2-Induced Climate Change and Its Potential Impact on the Province of Ontario, in Preprint Volume: Conference on Climate and Water Management - A Critical Era, Boston, Massachusetts, American Meteorological Society, pp. 285-290.

Cohen, S. J. 1986. Impacts of CO_2-induced climatic change on water resources in the Great Lakes basin, Climatic Change, 8:135-153.

Proceedings
of
A Symposium on Climate Scenarios

University of Waterloo

June 12, 1991

Editor: M. Sanderson, Director
The Water Network