5.0 PHYSICAL/CLIMATE SYSTEMS

5.1 ISSUE PAPER

Great Lakes Climate Scenarios and Physical Response *

By
Thomas E. Croley II
Great Lakes Environmental Research Laboratory
National Oceanic and Atmospheric Administration

Abstract: Climate change impacts on the Great Lakes may be understood by considering atmospheric scenarios with hydrologic models. Scenarios are traditionally generated as general circulation model (GCM) simulations of the earth's atmosphere. Typically, researchers change historical meteorology to match mean changes observed in the atmospheric scenarios, observe changed process model outputs, and compare to model results from unchanged data. This method keeps spatial and temporal variability the same in the adjusted data sets as in the historical base period. Changes are made independently to each historical meteorological variable, ignoring their interdependencies. GCM simulations are over grids that are coarse compared to the scale of interest of the Great Lakes. Recently, scenarios were taken from other climes and transposed to the Great Lakes to preserve reasonable spatial and temporal variations and to avoid the other problems. In all methods, the linkage between the atmospheric scenarios and the hydrology models allows no feedback between the surface and the atmosphere in scenario development and hydrologic impact estimation. Now, mesoscale atmospheric models are embedded within GCMs and coupled to relevant surface hydrology models. This allows more relevant scales for regional impact estimation and dynamic linkages between the atmosphere and the surface. We must link atmospheric models to existing large-scale irregular-area surface models to adequately portray the hydrology and lake thermodynamics of the Great Lakes. Only as sufficiently fine grids become available for surface hydrology models in the next few years will hydrological impacts be directly estimable from purely gridded models.

Introduction

Climatic change will impact on many aspects of the hydrologic cycle in the Laurentian Great Lakes, with interrelated consequences. The impacts on Great Lakes water supply components and both basin and lake storages and fluxes of water and heat must be understood before these consequences can be assessed. Considerations of situations that may occur (scenarios) help identify possible effects and bound future conditions. Preliminary impact estimates considered simple constant changes in air temperature or precipitation. *Quinn and Croley* (1983) estimated net basin supply to Lakes Superior and Erie. *Cohen* (1986) estimated net basin supply to all Great Lakes. *Quinn* (1988) estimated lower water levels due to decreases in net basin supplies on

Lakes Michigan-Huron, St. Clair, and Erie.2

Researchers have run general circulation models (GCMs) of the earth's atmosphere to simulate climates for current conditions and for a doubling of global carbon dioxide levels ($2xCO_2$). They used a larger-than-regional scale for many internally-consistent daily meteorological variables. The U.S. Environmental Protection Agency (*USEPA*, 1984) and *Rind* (personal communication, 1988) used the hydrologic components of general circulation models. They assessed changes in water availability in several regions throughout North America, but the regions were very large. Rind used only four regions for the entire continent and indicated needs for smaller region assessments. Regional hydrological models can link to GCM outputs to assess changes associated with climate change scenarios. *Allsopp and Cohen* (1986) used Goddard Institute of Space Sciences (GISS) $2xCO_2$ climate scenarios with net basin supply estimates.

Other efforts that linked hydrological models to GCM outputs originated in studies commissioned by the U. S. Environmental Protection Agency (EPA). EPA, at the direction of the U.S. Congress, coordinated several regional studies of the potential effects of a $2xCO_2$ atmosphere. The studies addressed various aspects of society, including agriculture, forestry, and water resources (*USEPA*, 1989). They directed others to consider alternate climate scenarios by changing historical meteorology similar to the changes observed in GCM simulations of $2xCO_2$, observing changed process model outputs, and comparing to model results from unchanged data. *Cohen* (1990, 1991) discusses other studies that use this type of linkage methodology and also discusses his concerns for comparability between studies using different types.

As part of the EPA study, the Great Lakes Environmental Research Laboratory (GLERL) assessed steady-state and transient changes in Great Lakes hydrology consequent with simulated $2xCO_2$ atmospheric scenarios from three GCMs (*Croley*, 1990; *Hartmann*, 1990; *USEPA*, 1989). Those studies, in part, and the high water levels of the late 1980s prompted the International Joint Commission (IJC) to reassess climate change impacts on Great Lakes hydrology and lake thermal structure. GLERL adapted the EPA study methodology for the IJC studies (*Croley*, 1992b) to consider $2xCO_2$ GCM scenarios supplied by the Canadian Climate Centre (CCC).

This paper outlines GLERL's physical process models, presents the methodology of linkage between regional hydrological models and GCMs, interprets problems with the methodology, and outlines directions for future climate change assessment methodologies.

Great Lakes Physical Process Models

GLERL developed, calibrated, and verified conceptual model-based techniques for simulating hydrological processes in the Laurentian Great Lakes (including Georgian Bay and Lake St.Clair, both as separate entities). These include models for rainfall-runoff [121 daily watershed models (*Croley*, 1983a,b; *Croley and Hartmann*, 1984)], over-lake precipitation (a daily estimation model), one-dimensional (depth) lake thermodynamics [7 daily models for lake surface flux, thermal structure, and heat storage (*Croley*, 1989, 1992a; *Croley and Assel*, 1993)], channel routing [4 daily

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models for connecting channel flow and level, outlet works, and lake levels (*Hartmann*, 1987, 1988; *Quinn*, 1978)], lake regulation [a monthly plan balancing Lakes Superior, Michigan, and Huron (*International Lake Superior Board of Control*, 1981, 1982) and a quarter-monthly plan regulating Lake Ontario and the St. Lawrence Seaway outflows (*International St. Lawrence River Board of Control*, 1963)], and diversions and consumptions (*International Great Lakes Diversions and Consumptive Uses Study Board*, 1981).

The GLERL Large basin Runoff Model uses daily precipitation, minimum and maximum air temperature, and insolation to determine daily moisture storages, evapotranspiration, and basin runoff for each of the 121 watersheds contributing runoff to the Great Lakes. The model uses meteorological data from over 1800 stations about and in the watersheds, combined through Thiessen weighting. The GLERL Lake Evaporation and Thermodynamics Model of lake heat storage and surface fluxes uses daily air temperature, dewpoint temperature, wind speed, and cloud cover to determine lake heat fluxes and storage, surface temperature, and evaporation. It uses daily meteorological over-land data from 5 to 10 near-shore stations about each Great Lake, assembled and averaged by way of Thiessen weights, for correction to over-lake data. GLERL assembled daily historical data as areal averages for all 121 watersheds (precipitation and minimum and maximum air temperatures) for all periods used in their climate change studies. They also assembled daily historical data as areal averages for all seven lakes (precipitation, air temperature, dewpoint temperature, wind speed, and cloud cover) for the same periods.

EPA Methodology

GLERL integrated the models into a system to estimate lake levels, whole-lake heat storage, and water and energy balances for forecasts and for assessment of impacts associated with climate change (*Croley*, 1990, 1992b; *Croley and Hartmann*, 1987; *Croley and Lee*, 1993). GLERL developed the system specifically to look at the impact of changed climate by doing simulations with changed meteorology (that represent scenarios of changed climate) and comparing with simulations based on historical meteorology (representing an unchanged climate).

Steady-State Climate Change Assessments. EPA required that GLERL first simulate 30 years of "present" Great Lakes hydrology by using historical daily average, maximum, and minimum air temperatures, precipitation, wind speed, dewpoint temperature, and cloud cover data for the period 1 January 1951 through 31 December 1980 with present diversions and channel conditions. They called this the "base case" scenario. GLERL arbitrarily set the initial conditions but used an initialization simulation period of 1 January 1948 through 31 December 1950. This allowed the models to converge to conditions (basin moisture storages, lake heat storages, water surface temperatures, and lake levels) initial to the period of 1 January 1951 through 31 December 1980. GLERL repeated this 30-year simulation, with initial conditions set equal to their averages over the simulation period, until these averages were unchanging. This facilitated investigation of "steady-state" conditions. The next step was to conduct simulations with adjusted data sets.

EPA obtained output from atmospheric GCM simulations, representing both

"present" and $2xCO_2$ steady-state conditions, from GISS, the Geophysical Fluid Dynamics Laboratory (GFDL), and the Oregon State University (OSU). They then supplied ratios of $2xCO_2$ to present monthly absolute air temperature, specific humidity, cloud cover, and precipitation, and differences of $2xCO_2$ and present wind speed to GLERL every 7.83° latitude by 10° longitude (GISS), 4.44° by 7.5° (GFDL), and 4° by 5° (OSU). GLERL applied these monthly adjustments to their daily historical data sets to estimate 33-year sequences of atmospheric conditions associated with the $2xCO_2$ scenarios. They inspected each of the 770,000 square kilometers within the Great Lakes basin to see which of the GCM grid points were closest for each GCM (GISS, GFDL, and OSU). Then they applied the monthly adjustment at that grid point to the square kilometer. By combining these values for all square kilometers representing a watershed or a lake surface, they derived areally-averaged monthly scenario adjustments which they applied to their areally-averaged daily historical data sets for the watershed or lake surface, respectively, to derive the $2xCO_2$ meteorology scenario (they used each monthly adjustment for all days of the month). This method keeps spatial and temporal (inter-annual, seasonal, and daily) variability the same in the adjusted data sets as in the historical base period.

GLERL then used the $2xCO_2$ scenario in hydrology impact model simulations similar to those for the base case scenario. As for the base case scenario, they repeated the simulation until long-term averages, also used as initial conditions, were unchanging in an attempt to address steady-state conditions. They interpreted differences between the $2xCO_2$ scenario and the base case scenario as resulting from the changed climate.

Transient-Case Climate Change Assessments. EPA obtained several more GCM simulations to represent the interim from the present to future $2xCO_2$ conditions. As instructed by EPA, GLERL first simulated 80 years of "present" lake levels and component processes over the period 1981-2060 by using historical daily data for the 1951-80 period, repeated three times. The first simulation used initial conditions observed 1 January 1981. The second used the end-of-run conditions from the first simulation as initial conditions and the third used end-of-run conditions from the second. After completing this "base case" scenario, they conducted simulations with adjusted data sets.

EPA supplied 9 sets of monthly $2xCO_2$ adjustments, one set for each decade from 1970-79 through 2050-59. GLERL interpolated between decadal averages to obtain adjustments for each month of each year of the period 1981-2059. They applied them in three simulations as for the base case. They made the 1981-2010 adjustments to the 1951-80 data for the 1981-2010 period simulation. They made the 2011-40 adjustments to the 1951-80 data for the 2011-40 simulation. They made the 2041-59 adjustments to the 1951-1969 data for the 2041-59 simulation. They took the 2060 adjustment the same as the 2059 adjustment, since the GISS scenario ended in 2059, and applied it to 1970 data for the 2060 simulation. GLERL again combined adjustments for each month from the nearest atmospheric model grid point for all square kilometers representing a watershed or a lake surface to derive an areally-averaged adjustment for each watershed or lake surface. They then used the transient scenario segments in simulations as they did with the original historical data. They combined them to represent the entire period of interest and then interpreted

differences between the $2xCO_2$ transient scenario and the base case scenario as resulting from the changing climate.

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. GLERL found that the repeating fluctuations of the historical record completely dominated the superimposed climate changes, obscuring climate change effects. GLERL discerned the $2xCO_2$ signal from the historical variations by comparing values 30 years apart, thus eliminating the (repetitive) historical variations. They compared $2xCO_2$ and base case simulation changes for decades 1, 4, and 7 (1981-90, 2011-20, and 2041-50, each based on the same 1951-60 data period). Likewise, 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).

IJC Methodology

GLERL's general procedure for the investigation of steady-state behavior under a changed climate for the IJC is similar to that used for the EPA, as detailed above and elsewhere (*Croley*, 1992b) except that the period 1948-88 was used for the simulations. GLERL also modified their procedure to estimate "steady-state" conditions, which formerly was to repeat the simulation with initial conditions set equal to their averages over the simulation period, until they were unchanging. This procedure required many iterations for a few subbasins with very slow groundwater storages and suggested very different initial groundwater storages than were used in calibrations. Actually, the original calibrations of the models used arbitrary (but fixed) initial conditions. GLERL should have determined initial conditions also in the calibrations, but that was unfeasible; there is little confidence in calibrated parameter sets that suggest very slow groundwater storages (half-lives on the order of several hundred years in some cases) since only 10 to 20 years were used in the calibrations. Therefore, the best present hydrology estimates are initial conditions on the same order as those assumed for the calibrations for those few subbasins.

Average monthly meteorological outputs were supplied for each month of the year by the CCC as resulting from their second-generation GCM; see *McFarlane* (1991). While available every 3.75° latitude by 3.75° longitude, *Louie* (1991) interpolated monthly averaged data to 1° latitude by 1° longitude by weighting original values inversely to the square of their distance from each new location. GLERL computed $2xCO_2$ monthly adjustments at each location, used them with historical data to estimate the $2xCO_2$ 41-year sequences (1948-88) for each Great Lake basin, and then used the $2xCO_2$ scenario in simulations similar to the base case as before.

GCM Linkage Problems

The hydrological study results from the EPA and IJC studies should be received with caution as they are, of course, dependent on the GCM outputs with inherent large uncertainties in the GCM components, assumptions, and data. Transfer of information between the GCMs and GLERL's hydrologic models in the manners described above involves several assumptions. Solar insolation at the top of and through the atmosphere

on a clear day are assumed to be unchanged under the changed climate, modified only by cloud cover changes. Over-water corrections are made in the same way, albeit with changed meteorology, which presumes that over-water/over-land atmospheric relationships are unchanged.

Heat budget data from GCM simulations for Great Lakes grid points may not adequately describe conditions over the lakes due to the coarse resolution of the grids. GLERL's procedure for transferring information from the GCM grid is an objective approach but simple in concept. It ignores interdependencies in the various meteorologic variables as all are averaged in the same manner. Of secondary importance, the spatial averaging of meteorologic values over a box centered on the GCM grid point (implicit in the use of the nearest grid point to each square kilometer of interest) filters all variability that exist in the GCM output over that box. If GCM output were interpolated between these point values, then at least some of the spatial variability might be preserved. The interpolation performed by *Louie* (1991) from the original GCM grid to a finer grid reduced this problem, but it still exists in the use of the finer grid with the hydrology models. Of course, little is known about the validity of various spatial interpolation schemes and, for highly variable spatial data, they may be inappropriate. Furthermore, much of the variability at the smallest resolvable scale of GCMs is, unfortunately, spurious.

Spatial and temporal variabilities of the base case and $2xCO_2$ data sets are the same in the EPA and IJC studies. The methodology does not address changes in variabilities that would take place under a changed climate. The method of coupling used herein does not reproduce seasonal timing differences under a changed climate from the GCMs but preserves seasonal meteorological patterns as they exist in the historical data. This is a result of applying simple ratios or differences to calculate one from the other. This implicitly ignores spatial and temporal phase and frequency changes consequent in the $2xCO_2$ GCM simulations. For example, a changed climate alters the movement (direction, speed, frequencies) of air masses over the lakes. This implies an alteration of the seasonal temporal structure for storms and cyclonic events as well as the intensities of storms. The above method only allows modification of the latter. Seasonal changes induced by the changed meteorology because of a time-lag storage effect are observable, however. Shifts in snowpack or in the growth and decay of water surface temperatures are examples. Changes in annual variability are less clear, again as a result of using the same historical time structure for both the base case and the changed climate scenarios.

MCC Methodology

While the EPA and IJC studies looked at changes in the mean values of hydrologic variables, changes in ***variability*** were unaddressed. This variability is the singular key problem for shipping, power production, and resource managers. GLERL and the Midwest Climate Center (MCC) now are investigating the effects of shifts in the daily, seasonal, inter annual, and multi-year climate variability on lake net supply behavior, as well as related changes in mean supplies. They are doing this by utilizing data for climates which actually exist and that resemble some of the $2xCO_2$ GCM scenarios. These are located to the south and west of the Great Lakes. Lengthy (at least 40 years) and detailed records of daily weather conditions at about 2000 sites are

available to represent physically plausible and coherent scenarios of alternate climates. Such data sets incorporate reasonable values and frequencies of extreme events, ensuring that the desired temporal and spatial variabilities are represented, and are being transposed over the Great Lakes.

MCC supplied the data and GLERL transposed them to the Great Lakes by relocating all meteorologic station data and Thiessen-weighting to obtain areal averages over the 121 watersheds and 7 lake surfaces for all days of record (1948-1992). GLERL also reduced all historical data (base case) within the Great Lakes (1900-1990). This involved extensive error checking and data correction for thousands of stations, and regeneration of areal averages. Since the Great Lakes affect the climate near the shoreline but these effects are not present in the transposed data sets, MCC prepared maps of generalized seasonal lake effects on the area's meteorology, to be applied to the transposed climates.

The Great Lakes hydrology of each transposed climate is estimated, as before, by applying the system of hydrological models to these data sets directly and comparing outputs for each transposed climate to a base case derived with the models from historical meteorological data.

Coupled Hydrologic and Atmospheric Research Model (CHARM)

The linkage between GCM and hydrology models allows no feedbacks between these independent models. This is also true with the use of transposed climates. That is, the hydrology does not interact with the transposed climates, other than through use of the estimated lake-effect maps derived under the present climate. 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. However, their use with GCM outputs does not allow the GCM simulations to benefit from these refined processes. The feedback from the land and lake surfaces' hydrometeorological properties cannot exist without incorporating the regional hydrology models into the atmospheric models.

Modelers are turning their attention to mesoscale atmospheric models to enable better assessment of local to regional effects. The leading approach now is to embed mesoscale atmospheric models within GCMs for a region of interest and to couple relevant surface hydrology models to the mesoscale atmospheric model (*Dickinson et al.*, 1989; *Giorgi*, 1990; *Hostetler et al.*, 1993). This allows both the use of more relevant scales for regional impact estimation and the consideration of dynamic linkages between the atmosphere and the surface, now recognized as essential in describing the hydrology and meteorology of an area. This approach has generally been limited in the past to 50-km grids or larger because of the complexity of the modeling system that is required and because of the computer power that was required. The science panel of the GEWEX Continental-Scale International Project and the WMO-CAS Working Group on Numerical Experimentation launched their joint Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS). The National Center for Atmospheric Research (NCAR) is currently exploring the possibility of operating their atmospheric, hydrologic, and lake flux models embedded in their GCM at scales finer than 50 km.

To estimate impacts associated with both large and fine scales of parameter changes, the Great Lakes research community can address these scales separately. This offers the advantage that we can begin *now* to look at large-scale parameter changes (such as lake levels, lake-wide heat storage, and annual and monthly water and energy balances) by combining *existing* process models appropriate to these scales. This can be underway while fine-scale parameter changes are investigated. They will require more development and integration of process models. Thus, we have two components to physical modeling of climate-change impacts over the Great Lakes. The first is the integration and use of existing Great Lakes hydrologic process models (lumped-parameter, applying to irregular-shaped areas over spatial scales of 30-100 km for the land surface and 100-300 km for the lake surface and temporal scales of 10-100 days). The second is the development and integration of fine-scale second-generation (gridded) surface hydrologic process models (at scales from 1 km to 30 km) with atmospheric mesoscale models.

Large-Scale Parameter Changes. We must explore linkages to atmospheric models for existing large-scale irregular-area surface models that already represent excellent portrayals of the hydrology and lake thermodynamics in the Great Lakes. Since hydrological models exist now for large-scale parameter change estimates, large-scale couplings will be useful in beginning derivative studies (such as socio-economic, food-web dynamics, and other secondary impacts identified as dependent on large-scale parameter changes). They will also prove useful as a starting point for subsequent second-generation joint atmospheric-hydrological parameterizations and in the verification of same and of like developments by other investigators. They will also be useful as a base-line for comparing multiple approaches in modeling the atmosphere and hydrology.

GLERL, in cooperation with the Air Resources Laboratory (ARL), is now linking their hydrology models with the Regional Atmospheric Modeling System or "RAMS" (*Pielke*, 1990; *Lyons et al.*, 1990, 1991a,b). The combination will be used for large-scale parameter investigations, requiring assessment of the temporal and spatial incompatibilities that exist between mesoscale meteorological and regional hydrology models. A modest target is to arrange for coupled modeling by using a 40-km grid, with time steps of 90 seconds in the atmospheric component, coupled to some components of the surface models defined over irregular areas on 12- to 24-hour intervals. RAMS-predicted atmospheric momentum, temperature, moisture, and precipitation fields will be input to the large-scale hydrological models which will use these fields to update sea surface temperature, soil moisture, and snowpack variables. These hydrological parameters will then be input into RAMS to drive the surface energy fluxes over both land and water.

Large-Scale Model Couplings. Since there is some overlap in function between parts of the atmospheric model and the surface models, decisions are required about which model should be used for some purposes. The Large Basin Runoff Model was modified to use potential evapotranspiration calculated by the Richardson number-dependent mixing length method of Quinn (1979) and will be recalibrated as part of CHARM. A Richardson number-dependent scheme for evaporative and sensible heat fluxes (Quinn, 1979) was included in RAMS for consistency with the Lake

Evaporation and Thermodynamic Model.

Most approaches for coupling define land surface parameterizations spatially over a surface grid that matches that used by the mesoscale model. This offers the advantage of direct coupling of relevant fluxes between the atmosphere and the surface. However, it introduces problems in the representation of surface hydrology that does not bear directly on the atmospheric modeling. For example, surface runoff models, defined over the hydrological basin or watershed, offer much better representation of runoff than do spatial models that represent the hydrology at grid points.

GLERL is able to determine how much of each grid box overlaps with each sub-basin for the Large Basin Runoff Model and each lake for the Lake Evaporation and Thermodynamics Model. GLERL gets a weighted average over each grid box of the parameters related to the upper and lower soil zones. By using these parameters, GLERL solves for the snowpack, snowmelt, upper and lower soil zone storage, runoff, percolation, interflow, and deep percolation at each of the grid boxes. This calculation is made at every atmospheric timestep because the snowpack and upper and lower soil zone storages are considered to be directly interactive with the atmosphere.

Since the groundwater and surface storage do not interact directly with the atmosphere, their prediction is done separately at longer time intervals, and is represented on the basis of the irregular sub-basin areas rather than the artificial grid of the atmospheric model. At 12-hour intervals, the fluxes into the groundwater and surface storage reservoirs are combined from the grid over each sub-basin by using weights complementary to those just mentioned (i.e., the fraction of the subbasin in each grid cell); the groundwater outflow and stream flow and updated groundwater and surface storages then are calculated for each sub-basin.

Likewise, the fluxes of shortwave and longwave radiation and latent and sensible heat into the lake surfaces are calculated at each grid point at each timestep. The total heat flux and wind speed for 24 hours are then combined from the grid over each entire lake. The total heat storage in the lake and the lake surface temperature are then calculated. A 24-hour timestep is necessary for the Lake Evaporation and Thermodynamic Model, as it was calibrated using this timestep, and thus ignored diurnal variations in the net heat flux. Work is in progress to modify the LETM to make it synchronous (i.e. lake surface temperature will respond immediately to surface heat flux) and more appropriate for diurnally varying forcing.

Second-Generation Fine-Scale Atmospheric-Hydrologic Integrations. Only when sufficiently fine grids become available for surface hydrology models will surface runoff at points into the lakes be directly estimable from purely gridded models. These fine grids will be approached in the next few years. Likewise, lake heat storage models for the Great Lakes exist at several levels, from one-dimensional superposition models to three-dimensional circulation models. Again, researchers are approaching fine grids that are usable in long continuous simulations.

Two fine-scale approaches are possible now. The first uses developing atmospheric-hydrologic mesoscale models to estimate joint meteorology and hydrology for surface areas of interest in the Great Lakes and then refines the hydrological estimates through use of the better-calibrated GLERL hydrology models for the Great Lakes. This approach is similar to that taken in linking hydrology models to GCM

outputs, described previously. Again, there is no dynamic interaction between the final hydrology models and the atmospheric model. Outputs from the joint atmospheric-hydrologic mesoscale model are inputs to the hydrology models. However, better agreement should be possible since the scales of both sets of models are closer than was true in the GCM-hydrology model studies. NCAR has asked GLERL to use their joint atmospheric-hydrologic mesoscale model outputs for the Great Lakes in this manner to study climate change impacts.

The second fine-scale approach consists of developing second-generation fine-scale Great Lake hydrologic and lake thermodynamic models on finer grids to interface directly with atmospheric models applied at ever-finer resolution and of assessing the importance of two-way runoff-atmospheric interactions unique to CHARM. These will complement similar efforts elsewhere (NCAR) that use alternate models. The matching of spatial and temporal scales between models will proceed at different levels. Linkage will begin with coarse irregular spatial and temporal scales, where existing hydrological models are established over large areas in the Great Lakes (as in the above section), and proceed to finer scales as hydrological models are redeveloped in atmospheric-hydrologic studies. Comparisons will be made between scales to see what is resolved and what process refinements make no difference with regard to different uses (water level estimation, sea breeze predictions, and so forth). Both the atmospheric and hydrological models will be run in three dimensions on the same grid. The grid spacings will be reduced from 30 km to 15, 10, 5, and 1 km scales. For the smaller scales, non-hydrostatic physics and explicit cloud microphysics will be employed. To start out, interactions will be performed at the time step of the atmospheric model (between 5-90 seconds depending on the horizontal resolution of the grids). Sensitivity experiments will be performed to determine an optimum update frequency between the atmospheric and hydrologic models since it may not be necessary to interact the models every time step.

Summary

Earlier assessments used atmospheric GCM outputs as meteorologic scenarios to drive process models for generating hydrologic scenarios. Climate change effects were inferred by comparing process model outputs for a base case with the changed climate scenario. As the linkage methods of these assessments constrained spatial and temporal meteorologic variabilities to those present in the historical records, impact assessments began with the transferrence of existing climates to the Great Lakes. ***Meteorologic scenarios (from CCC GCM outputs and MCC transposed climates) and the associated hydrologic scenarios (from GLERL's hydrologic process models) are available for current studies of secondary impacts in the Great Lakes.*** Lack of feedback between surface process models and atmospheric models is still a problem.

Researchers are now developing and verifying multi-scale hydrologic models, with appropriate links to mesoscale atmospheric models, using spatially extensive observations based upon satellite and in-situ measurements and supported by field experiments. These linked models are slated to be embedded in GCM or other boundary condition simulations to assess climate change effects. GLERL is working with ARL to investigate alternative CHARM possibilities. Now underway are a large-scale coupling, that employs GLERL's existing irregular-area surface models, and a

series of finer-scale couplings where surface models are defined over the same (surface) grid as used in the mesoscale atmospheric models. GLERL also plans to work with existing and developing coupled atmospheric-hydrologic mesoscale models over the Great Lakes by refining hydrologic estimates with more-detailed hydrologic and lake surface flux models.

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5.2 PHYSICAL/CLIMATE SYSTEMS BREAKOUT GROUP PARTICIPANTS

Facilitator: In Young Lee, Argonne National Laboratory
Recorder: Alan Bratkovich, NOAA/GLERL

Brent Lofgren, NOAA/GLERL
Michel Slivitsky, University of Quebec
Rosanne Fortner, Ohio Sea Grant Education, Ohio State University
Ken Kunkel, Midwestern Climate Center, Illinois Water Survey
Paul Louie, Atmospheric Environment Service
Deborah Lee, NOAA/GLERL
William Schertzer, National Water Research Institute
Raymond Assel, NOAA/GLERL
Tom Croley, NOAA/GLERL
Tim Willoughby, U.S. Geological Survey
Ted Bailey, International Joint Commission

5.3 BREAKOUT GROUP REPORT

5 Year Research Plan and Products:

1. Develop 50-200 years BP (before present) climatology for all relevant fields.
   - identify spatial and temporal reporting/averaging intervals
   - identify target parameter fields
   - identify more specific focal sites?
   - should fields be spatially contiguous?
   - define priorities; including anthropogenic effects/impacts
   - agree upon a base climatology (more than one?) for group- wide analysis
   - complete first iteration in 2 years; update every 2 years

2. Develop "historical reconstruction" of climatology 1000- 4000 years BP.

3. Develop a derived-field data base and test scenarios; metadata.
   - incorporate into group-wide climatology

4. Define relationships between physical climatology and longer-term
   - variability in other (environmental and socio-economic) parameter fields.

5. Develop regional-scale atmospheric-surface-property dynamically coupled model components & evaluations.

6. Develop fine-scale (resolution), common-grid model for atmospheric-surface-property interaction.

7. Develop appropriate measurement/monitoring strategies for both model development (numerical and statistical) and testing.

8. Develop "high impact" forcing-response scenarios.
- IJC study results; review and recommend further work

"Catastrophic events accelerate political processes/responses."
- Should there be a specific effort to address the above?
- Flip-side: What parameter ranges induce "crisis" action- response?

9. Work to improve adaptability and range-of-applicability of existing model components (both numerical and statistical)
- remove "black box" relationships where possible.
- add process-specific subcomponents that are dynamically motivated.

10. Use more than one GCM to develop climate scenarios.

Other Products:

Suite of variables from various regional-scale models
Distributed and aggregated spatially and temporally
Result summaries for non-physical scientists
Community models
Generalized indices customized for impact studies
Result summaries for non-physical scientists

Critical Issues:

Demand by impact studies
Will there be climate change?
Do we know its large-scale characteristics?
Dissemination of information with users understanding limitations
Physical systems:
-Lake circulation
-Lake thermal structure
-Ice cover
-Water supply, lake levels, flows
-Lake water management
Quantification of uncertainty and variability
Water quality

Research Objectives:

Regional-scale models of coupled physical system:
- -Atmospheric thermodynamics and circulation
- -Lake thermodynamics and circulation
- -Ice cover
- -Land surface hydrology and water supply
- -Improve methodology for all of above
- -Large-scale studies now, finer scale later

Evaluation of previous work (GCMs and process models driven by GCMs)--are they good enough?
Define the present climate, including variability
Monitoring of climate, water, and hydrologic variables
Develop datasets of surface properties for models
Develop community models for distribution to scientific users
Feedback from other man-made factors (trends in consumption, diversion, irrigation, etc.)
Development of appropriate products for impact studies
Can large lake conditions be used as a proxy of climate change?

RESEARCH ISSUES

Make presently-available data more applicable to localized impact studies.
Identify socio-economic impacts and their data needs.
Quantify uncertainty to accompany data.
Improved visualization.

Great Lakes Climate Change Project

Research Priorities for Assessing the Impacts of Climate Change in the Great Lakes Basin

March 1994

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

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Great Lakes Commission

Great Lakes Climate Change

Research Priorities for Assessing the Impacts of Climate Change in the Great Lakes Basin

Proceedings of the Great Lakes Climate Change Workshop conducted on December 6-8, 1993 Ypsilanti, Michigan

Edited by

Clare M. Ryan, Frank H. Quinn, and Michael J. Donahue

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