Dynamical Modeling of Great Lakes Regional Climate

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Overview

This project focused on three things this year:

1. Testing of a reformulated version of the Coupled Hydrosphere-Atmosphere Research Model (CHARM) based on the Regional Atmospheric Modeling System (RAMS) version 4.4.
2. Porting CHARM to the iJet massively parallel computer, located at the Forecast Systems Laboratory in Boulder, CO.
3. Evaluating the response of CHARM to simple prescribed changes in land cover in the Great Lakes Basin Item 1 was carried out with moderate success. As always in the area of atmospheric modeling, deficiencies remain in this model.

Item 2 is largely accomplished. However, some details of the system for running this need to be worked out, primarily finalizing the selection of data to be retained through "on-the-fly" analysis and finally taking the leap of faith to delete the full dataset. These steps are necessary parts of the logistics of running the model on this remote system in order to keep the requirements for data storage in Boulder and for bandwidth between Boulder and Ann Arbor within bounds. Item 3 is the one that has produced interesting results. The main experiment of this type that has been carried out has been to reduce the surface roughness of all land surfaces within the model domain to a surface roughness corresponding to tall grass. The initial hypothesis was that this would reduce lake-effect precipitation by reducing the intensity of deceleration and consequent convergence of near-surface winds on the downwind side of the lakes. However, this prescribed perturbation actually increased the amount of precipitation in the lake-effect zones." with "However, this prescribed perturbation actually increased the amount of precipitation on the inland edge of some lake-effect zones. The mechanism for this appears to be that the low-level wind speeds increase overall, meaning that the rate of upward motion due to the topography at the downwind side of the lake is also increased. When conditions are conducive to lake-effect precipitation, this increases the amount of precipitation falling in these regions.

Project Rationale

Previous work at GLERL (between 1989and 2005) was undertaken to evaluate the impact of greenhouse warming on the water budget of the Great Lakes Basin. Such studies included one-way coupling of the lakes and land to a proxy of the atmosphere created by simple manipulation of the output from general circulation models with global domains and no resolution of the Great Lakes at all. As a result of the lack of realistic surface-atmosphere feedback under this scheme, the Coupled Hydrosphere-Atmosphere Research Model (CHARM) was developed to enable an assessment of the impact of greenhouse warming on the Great Lakes region, with simulated lakes allowed to directly feed back into the atmosphere through exchange of heat and moisture, while fully accounting for runoff from land surfaces. Development of a second generation of CHARM is now well underway. This version includes horizontally distributed modeling of lake temperatures, improved calibration of cloud microphysical processes in order to reduce the excessive cloudiness previously simulated, and heat flux adjustment to bring lake temperatures into better agreement with observations. Improved microphysics should help to reduce the necessary magnitude of the flux adjustments.

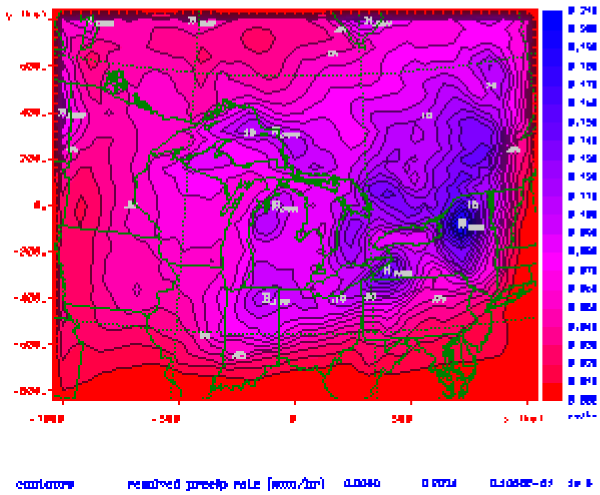
The possible range of applications of CHARM is very broad, but a few are of greatest interest because of their public impact. Foremost is the question of greenhouse warming effects on Great Lakes water quantity, which can be addressed for the first time with full coupling between the atmosphere and the surface. Other questions of interest include the effects of land use change on the climate and hydrologic characteristics of the Great Lakes basin in historical times, with major transitions including that from natural, largely forested cover to agricultural use and later to more widespread urban development.

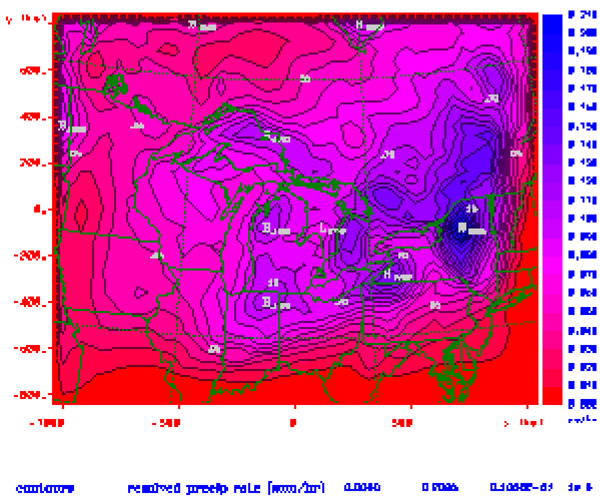
2005 Accomplishments

A new version of the Coupled Hydrosphere-Atmosphere Research Model (CHARM) was developed. This uses as its basis version 4.4 of the Regional Atmospheric Modeling System (RAMS), compared to version 3a in the previous CHARM. The newer version also has the Croley formulation for 1-dimensional horizontally-lumped temperature structure of the Great Lakes replaced with a 2-dimensional array of 1-dimensional models using the formulation of Hostetler and Bartlein (1990). The inclusion of this lake formulation is not only for the Great Lakes, but also for the fraction of other grid spaces appropriate to their coverage of water. This gives some improvement in one of the biggest problems with the previous version of CHARM-excessive cloudiness during the wintertime. However, somewhat opposite problems are springing up-excessive heat and dryness during the summer. Soil moisture initialization appears to be important for remedying this problem, and is being pursued.

Most components are in place for porting CHARM and its execution to the iJet system located at the Forecast Systems Laboratory (FSL). This parallel computing system has 768 nodes, each with a 2.2 GHz Pentium 4 Xeon dual processor, and is ranked 103rd worldwide for computing speed. Accessing computing time on this system is quite easy, but the main limitation in using it is that any input and output data must go over the internet, consuming bandwidth both at FSL and GLERL. With the greatest bottleneck being in the output, this necessitates analysis and reduction of the data as part of the whole simulation process, and internet transmission of only a smaller fraction of the data. Refinement of this process is needed before initiating full-scale use of iJet. FSL's newest parallel processing system is called eJet, and because it uses 64-bit processing, compatibility is not yet certain. Its per-node specifications are superior to iJet, but the number of processors available is fewer-296. The utility of eJet will be investigated.

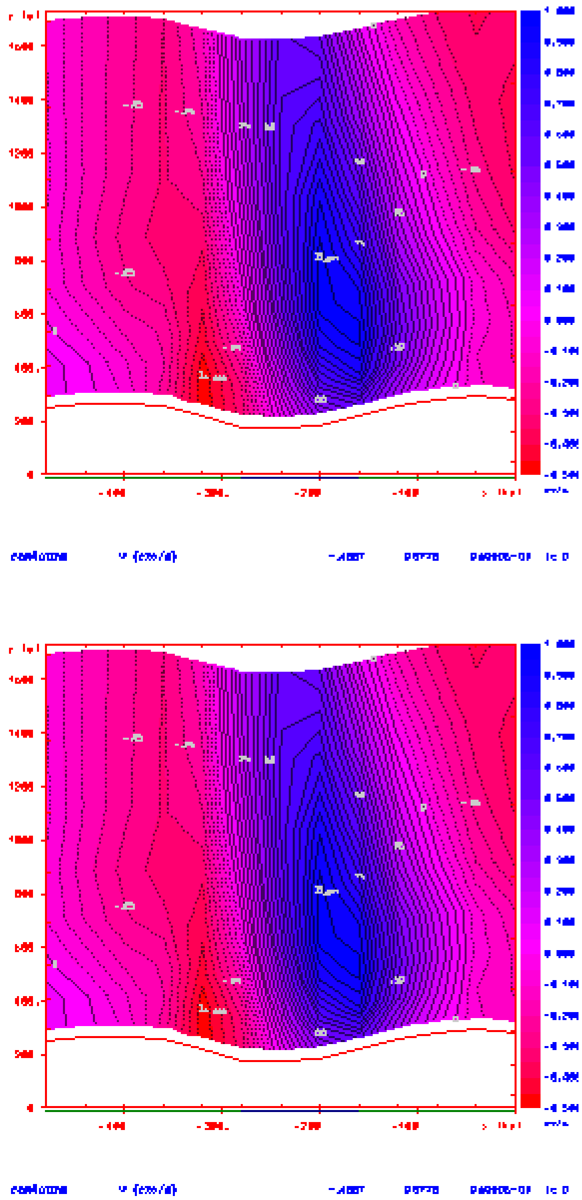
The most notable simulation experiment that we carried out with CHARM during FY2005 was to compare a simulation with a default set of land surface characteristics with one having reduced surface roughness. In the reduced surface roughness case, no land area is given a roughness length of greater than 0.1 m, which is the value ordinarily used for a tall grass vegetation type, compared to 2.0 m for broadleaf evergreen trees, a dominant type in much of the Great Lakes region.





FY05 Figure 1 (top): *Precipitation during January 1993 with standard land surface parameters and (bottom) with surface roughness reduced to tall grass values.*

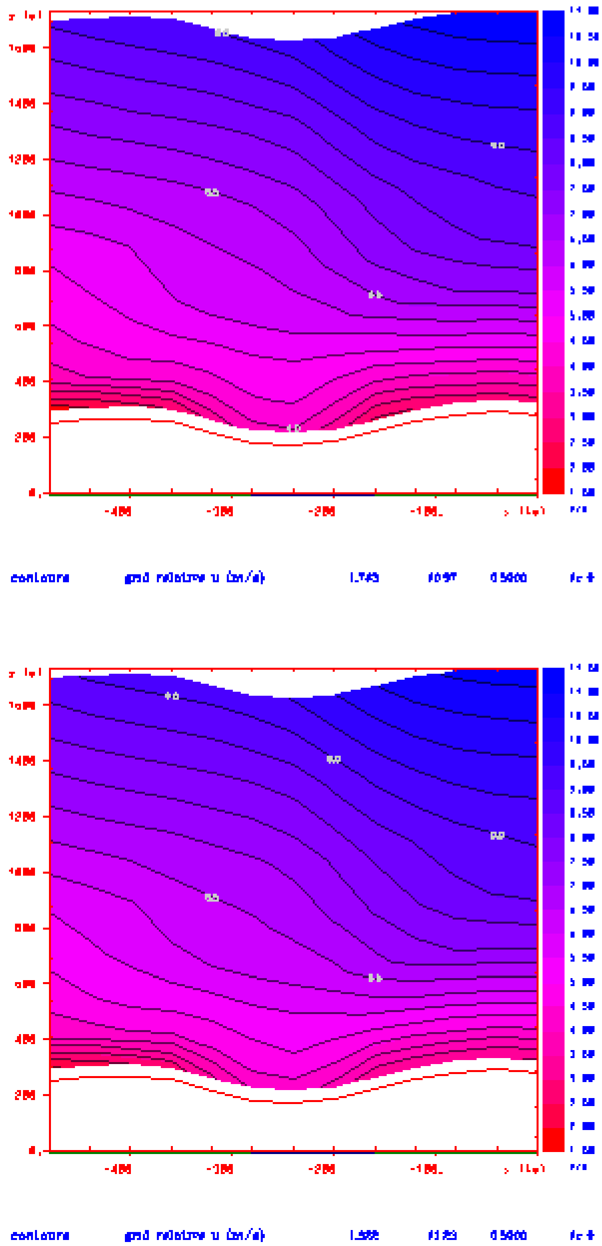
In contrast to the initial hypothesis that decreased roughness would lead to reduced convergence of low-level winds on the downwind sides of lakes, resulting in reduced lake-effect precipitation, the precipitation in lake effect zones is increased (Fig. 1). Although this effect is visually subtle in the Figure (a system still needs to be developed to plot differences between model-simulated cases), it is consistent among various lake-effect regions.



***FY05 Figure 2**:. Vertical profiles of mean vertical velocity for January 1993 taken along an east-west transect (in model coordinates) at approximately 43° N latitude. The low area near the center of the figure is Lake Michigan. (top) With standard land surface parameters and (bottom) with surface roughness reduced to tall grass values.*

As expected, increased precipitation is associated with increased upward motion. This is illustrated in Fig. 2, where there is upward motion on the downwind (eastern) side of Lake Michigan, which is in the center of each panel. This upward motion is more intense in the right panel, where the land surface roughness is lower. Again, this change is small but consistent throughout all of the lake effect zones.

If we would expect reduced surface roughness to result in decreased low-level convergence and reduced upward flow, why do we see the opposite? The basic reason seems to be that reduced surface roughness results in increased west-to-east wind speed (Fig. 3), and thus greater upward forcing by the slope on the downwind side of the lake. Even if that slope is a gentle one, under the proper conditions, it can trigger lake effect precipitation. The changes in vertical velocity in Fig. 2 are broadly consistent with the orographic slope multiplied by the change in horizontal wind speed illustrated in Fig. 3. Another feature of note in Fig. 3 is that, above the lowest 400 m or so above the ground, the zonal wind is greater east of the lake than over and west of it, as a result of the return flow from the vertical motion countering the ambient flow over the lake. This makes for stronger shear with height on the downwind side of the lake.



***FY05 Figure 3**: Vertical profiles of mean zonal (eastward) velocity for January 1993 taken along an east-west transect (in model coordinates) at approximately 43° N latitude. The low area near the center of the figure is Lake Michigan. (top) With standard land surface parameters and (bottom) with surface roughness reduced to tall grass values.*

Additional work related to this project was initiated during 2005 in cooperation with Prof. Yongkang Xue of UCLA and Dr. Shufen Sun of the Chinese Academy of Sciences, to test a lake temperature model developed by Dr. Sun on Lake Mendota and Lake Michigan. This is still in the data-gathering phase.

Hostetler, S. W., and P. J. Bartlein, 1990: Simulation of lake evaporation with application to modeling lake level variations of Harney-Malheur Lake, Oregon. *Wat. Resour. Res*., 26, 2603-2612.

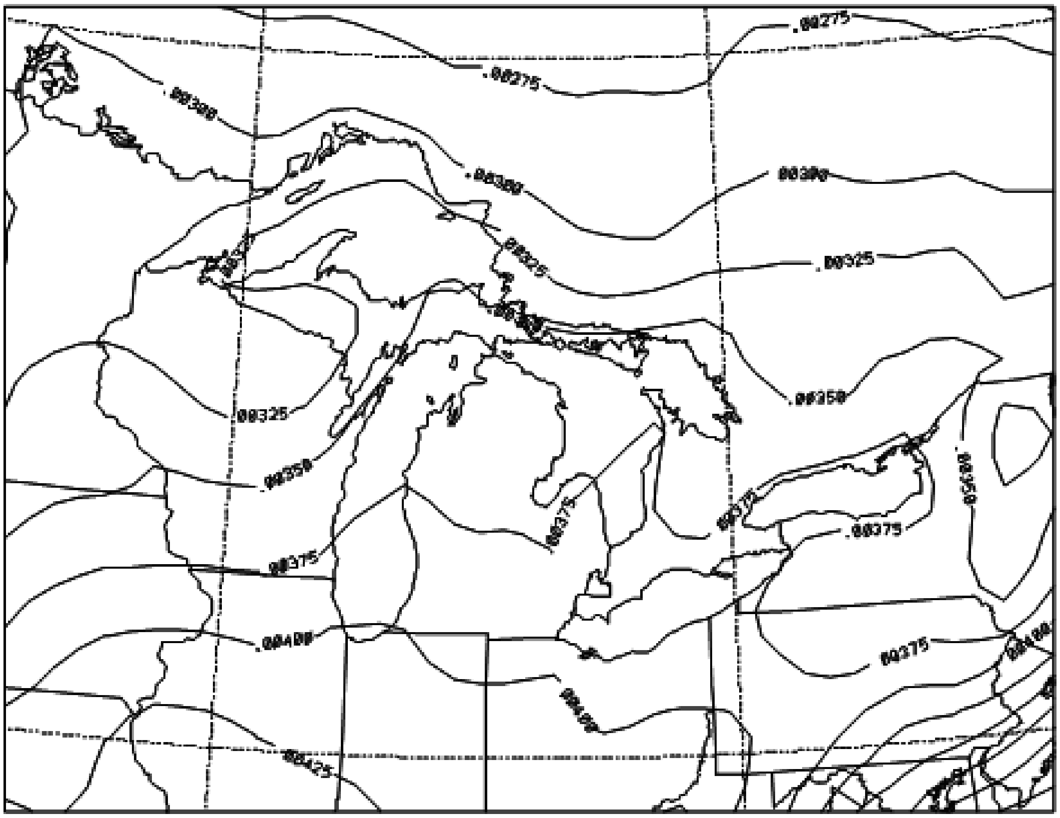
2004 Accomplishments

The Coupled Hydrosphere-Atmosphere Research Model (CHARM) is nearing completion of its reconstruction and, as FY 2004 closes, a pair of companion manuscripts is within a very short margin of being submitted, on the subject of the enhanced-greenhouse gas scenario runs of the older version of CHARM.

The two manuscripts that are about to be submitted present general information on the outcome of simulations using CHARM. The magnitude of warming in air temperature expected over a century time scale is about 4-5° C. Changes in wind speed and direction are modest. Annual precipitation increases on the order of 10-20%. However, although evapotranspiration from the land portions of the watersheds increases somewhat, evaporation from the lakes themselves does not increase.

An interesting aspect of this is the role played by water in the ice phase. The wintertime water vapor mixing ratio at the lowest model level in the 1989 case (Fig. 1a) generally has lower values than in the 2095 case (Fig. 1b), due to warming. But also note the shape of the contours near the Great Lakes, particularly those that cross near the middle of Lakes Michigan and Huron. In Fig. 1a, there is a strong signature due to the lakes. With prevailing winds from the west, the air picks up more moisture as it goes across the lake, with the maximum reached at the eastern edge of the lake. Just beyond that, there is a sharp drop off in water vapor mixing ratio (it is released into lake effect precipitation). In the 2095 case (Fig. 1b), this signature in the contours is much less prominent—both the buildup of water vapor over the lake and the drop off at the eastern edge are less prominent. This indicates that the lakes are less important as water sources in the 2095 case than in the 1989 case. A primary reason for this is the contrast between the snow-covered ground and the liquid lakes in the 1989 vs. the lack of snow on the ground in the 2095 case. A snow-free surface is a better source of water vapor than a snow-covered surface for two reasons. First, the snow has high albedo, thus reflecting much of the solar radiation that fuels evapotranspiration. Second, water in the ice phase has a lower water vapor pressure than liquid water at the same temperature.

a. DJF H2O mixing ratio 1989 case



b. DJF H2O mixing ratio 2095 case

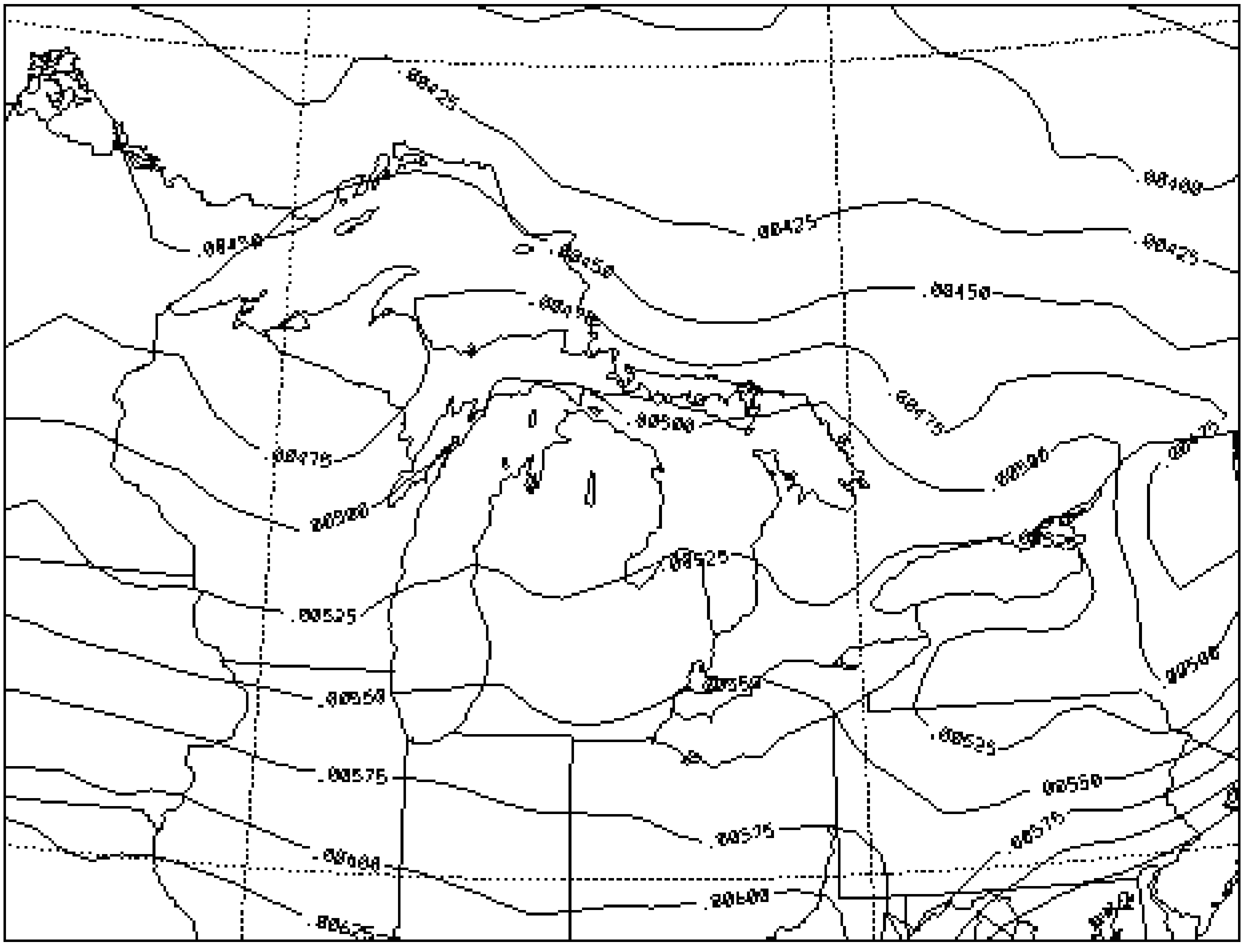


Figure 1: *Mean water vapor mixing ratio at the lowest model level (about 48 m above the surface) during December, January, and February in the (a) 1989 case and (b) 2095 case.*

This departs somewhat from one of the initial hypotheses about what would change by modeling the effects of greenhouse warming within a coupled dynamical model of the Great Lakes basin rather than an off-line hydrologic model driven by input from a separate general circulation model. It was thought that one of the main things that needed to be incorporated was the recycling within the drainage basin of water evaporated from the Great Lakes, notably in the form of lake effect precipitation. However, it seems much more important that the expected increase in evaporation from the lakes is inhibited by the inflow of moist air from the surrounding continent. As a result, the annual mean net basin supply to the lakes increases by 15% (Lake Superior) to 105% (Lake Huron).

Some shortcomings remain with CHARM. One that again puts the ice phase in an important place is that CHARM has a general warm bias during the winter. As a result, little ice forms on the Great Lakes, even in the 1989 case. Because ice is an inhibitor of evaporation, it would be expected that as ice disappears with time, evaporation would increase as a result. However, the lack of ice in the base case renders this mechanism null. However, this characteristic points out a possibility that trends in the hydrology of the Great Lakes due to greenhouse warming may reverse, or at least have an inflection point as the point in time is reached that the ice is gone. Until that time, the trend is likely to be less ice and more evaporation with time; after that time, there can no longer be a trend in ice, and the trend in evaporation will likely be weaker or reversed.

Work is progressing on getting the next version of CHARM ready for use. Much of the work has been done on getting the CHARM-specific modifications made to the current version of RAMS—RAMS 4.4. We have also uploaded RAMS 4.4 to the iJet parallel cluster located at the Forecast Systems Laboratory in Boulder, and expect to be testing it soon, with system problems at their end being an impediment.

2003 Accomplishments

Model runs using the CHARM model to simulate the regional climate of the Great Lakes basin are complete for time periods centered at 1989, 2030, and 2095. These model simulations feature full coupling between the atmospheric component of the model and the lake and land surfaces. The resultant net basin supplies to the lakes contrast sharply with the results from uncoupled simulations of the Great Lakes hydrology as forced directly by general circulation models (GCMs). Several factors contribute to this difference. One factor that can be considered realistic, which is accounted for by a coupled model but not an uncoupled one, is that the trend toward a moister atmosphere overlying warmed lakes inhibits evaporation from the lakes in the future cases. Another is that evaporation from the lakes can be transferred into precipitation within the drainage basin. A third is that an increase in precipitation in the future will be concentrated in very heavy precipitation events. Because the uncoupled model multiplies all precipitation events in a given month by a fixed ratio, heavy precipitation events are only marginally increased under that method.

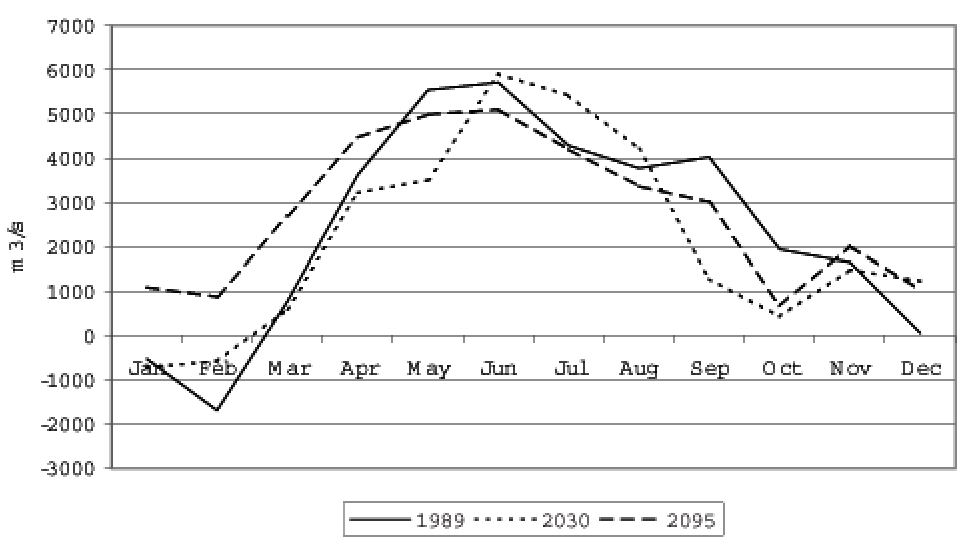


***Figure 2**: Annual cycle of net basin supply in the Lake Superior Basin from CHARM simulations centered at 1989, 2030, and 2095.*

This figure shows the general increase in net basin supply for the Lake Superior basin, especially during the winter months (reduced negative net basin supply). This shift occurs somewhat at the expense of summertime net basin supply. This is a characteristic that is shared in many simulations of future climate in areas that experience an accumulation of snowpack and peak runoff at the time of snowmelt. The snowpack, as a source for replenishment of soil moisture and groundwater, is spent earlier in the season.

An opposing factor (it would tend to reduce net basin supply in the future) that is not well handled by the coupled model is the ice cover influence on evaporation. An expectation of reduced ice cover under greenhouse warming conditions would allow greater evaporation from the lakes during late winter. However, because of a wintertime warm bias in the CHARM model, there is little ice formation on any of the lakes even in the 1989 model case, thus negating this effect. Despite this and some other shortcomings of CHARM, it should be regarded as more faithfully depicting the feedbacks that are inherent within the earth-air-water hydrological system than an uncoupled model.

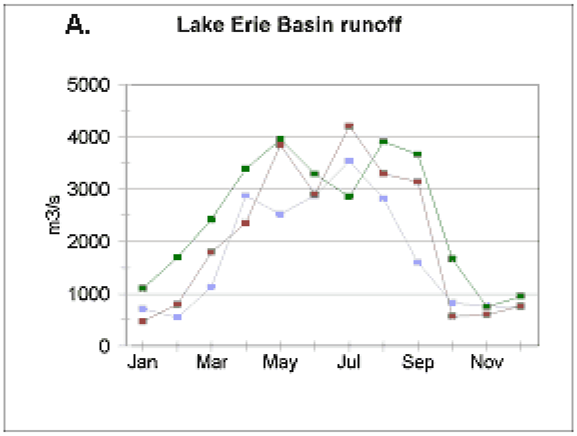
The paper “A Model for Simulation of the Climate and Hydrology of the Great Lakes Basin” has undergone extensive revision in light of reviewers’ comments and is resubmitted. Some short model runs were devised to give some additional tests to the land surface scheme used in CHARM.

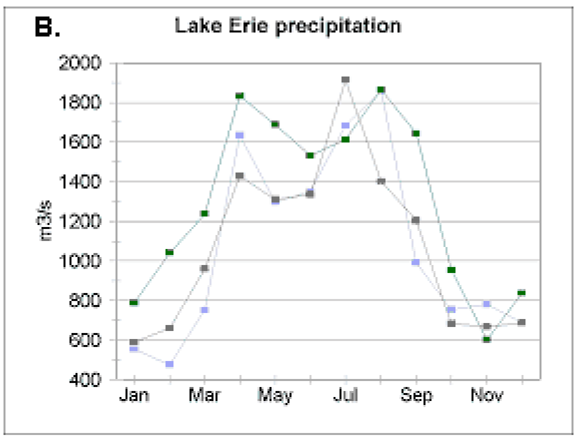
Analysis is largely complete of model runs covering the years 1984-1993, 2025-2034, and 2090-2099, and writing has begun on the results of these. The figure included as part of the executive summary is an example of the output of these model runs. At least two, and perhaps three, papers are expected from this effort-on validation of the model for the 1984-1993 period, on the atmospheric effects of enhanced greenhouse gas concentration in the future model cases, and on its hydrologic effects.

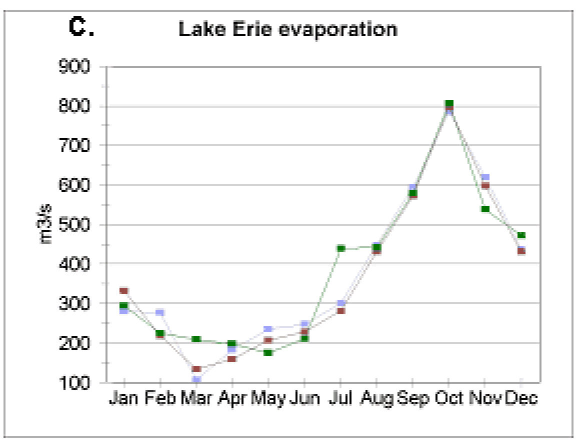
As an accessory to this project, “Global Warming: Assessing Hydrology on Regional and Smaller Scales” was written for peer review and publication by the American Society of Civil Engineers. It is intended as a guide to the needs and pitfalls of assessing the effects of climate change on managed water systems.

2002 Accomplishments

Model runs are complete for scenarios of simulated greenhouse warming, using 9-year time periods centered at 1989, 2030, and 2095.







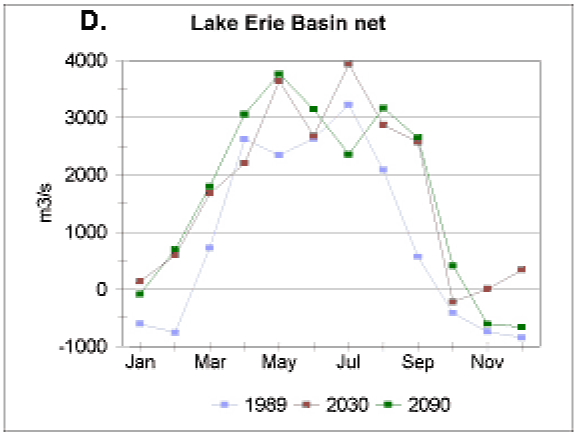


Figure 3*: The annual cycle for CHARM model runs centered at 1989, 2030, and 2095 of the Lake Erie basin's (a) runoff from the land portion of the basin, (b) over-lake precipitation, (c) over-lake evaporation, and (d) net basin supply. All quantities are integrated over the relevant area and expressed in units of cubic meters per second.*

The results show that it is very possible that increased concentrations of greenhouse gases will actually increase the net basin supply of water to the Great Lakes (Fig. 3. With the Lake Erie drainage basin used as an example, the runoff from the land portion of the basin (Fig. 3a) and the precipitation directly over the lake (Fig. 3b) are both shown by CHARM to increase in the 2030 and 2095 cases. The evaporation from the lake is little changed (Fig. 3c). The overall result is an increase in net basin supply (Fig. 3d) that is especially pronounced during the spring and fall and much less during the summer.

Analysis of these cases will continue and is expected to result in the submission (likely to Journal of Climate) of three manuscripts during calendar year 2003. The first will have as its topic the validation of the 1989 case against observed climate. The second will deal with the effect of greenhouse warming on atmospheric variables in the Great Lakes basin

Progress was made toward implementing a parallel version of CHARM on the Forecast Systems Laboratory's massively parallel, distributed-memory computer called iJet, largely through the efforts of summer fellow Nitin Jaiswal. Additionally, a new computer was acquired for in-house use with a shared-memory dual-Pentium processor architecture. This machine replaces the older HP workstation.

Accomplishments

The Coupled Hydrosphere-Atmosphere Research Model (CHARM) is a system that combines a mesoscale atmospheric model, a land hydrology model, and a lake thermodynamic model. Testing of several variants of CHARM over a two-year historical period (1993-1994) was completed as a preliminary step in model development. Because modeling of climate on a regional scale is an immature field of science, existing mesoscale models intended for simulation over time periods of a few days have needed to be modified to make them suitable for purposes of climate simulation. Excessive low-level cloud formation in the Regional Atmospheric Modeling System (RAMS) model (which forms the atmospheric basis for CHARM), was discovered during FY 1998 as a result of evapotranspiration continuing during conditions of supersaturation of surface air. This was further revealed during FY 1999 to be manifest in the model partially because of its explicit formulation of vegetation temperature. This problem has been removed from the model simply by prohibiting evaporation in the presence of supersaturated surface air. Another improvement was allowing greater infiltration of precipitation into the soil, which creates more realistic conditions in terms of soil moisture, surface air temperature, and evapotranspiration. The combination of these two modifications causes CHARM to validate very well with observations in terms of near-surface air temperature, and adequately in terms of precipitation and air pressure. This validation allowed CHARM to proceed into the phase in which it is applied to scenarios, primarily greenhouse warming. A third modification ensured that heat energy is conserved within the soil, but this made little difference in the model output.

The dynamical modeling of the region is a very time-consuming process, and has suffered some significant setbacks have been experienced due to data loss and some characteristics of the model code that have caused calculations of the saturation mixing ratio of the air to be non-convergent.

Progress was made on the development of a model giving a two-dimensional representation of lake surface temperature of the Great Lakes, for use as a component of CHARM, although full implementation has not occurred. By artificially adding prescribed amounts of heat at the surface, which conceptually represent lateral transport of heat within the lake, good agreement is achieved between modeled and observed lake surface temperatures. However, research will continue in an effort to reduce the large negative magnitude of the annual, spatial average of the imposed heat flux required to attain agreement with observations. As an adjunct to this work, a climatology was compiled of the various heat fluxes from the surface of the Great Lakes based on satellite-observed lake surface temperatures. This is documented in Lofgren and Zhu (1999).

Products

Publications

In revision: Lofgren, B. M., 2005: Laurentian Great Lakes future climate scenarios using the Coupled Hydrosphere-Atmosphere Research Model (CHARM). Part I: Atmospheric characteristics*. Int. J. Climatol*., under revision.

Lofgren, B. M., 2005: Laurentian Great Lakes future climate scenarios using the Coupled Hydrosphere-Atmosphere Research Model (CHARM). Part II: Hydrologic response. *Int. J. Climatol*., under revision.

In preparation: Lofgren, B. M. 2005: *Mechanisms of interaction between surface roughness and lake-effect precipitation.*

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Hydrology, 85th Annual Meeting, American Meteorological Society, San Diego, CA, 9-14 January 2005. Available on CD-ROM.

Lofgren, B. M., 2004: *Global warming influence on the Great Lakes: More precipitation but less water?* 18th Conference on Hydrology, 84th Annual Meeting, American Meteorological Society, Seattle, WA, 11-16 January 2004, available on CD-ROM.

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Lofgren, B. M., 2003: A model for simulation of the climate and hydrology of the Great Lakes basin. *J. Geophys. Res*., submitted.

Lofgren, B. M., 2003: Global warming: Assessing hydrology on regional and smaller scales. In *Technical Committee Report on Climate Variability, Climate Change, and Water Resources Management.* American Society of Civil Engineers, submitted.

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Lofgren, B.M., 1997. Simulated effects of idealized Laurentian Great Lakes on regional and large-scale climate. *J. Climate*, 10, 2847-2858.

Conference Proceedings

Lofgren, B. M., 2003: Simulation of possible future effects of greenhouse warming on Great Lakes water supply using a regional climate model. *Proceedings, American Meteorological Society 17th Conference on Hydrology*, Paper J5.14 (available on CD-ROM).

Reports

Upper Great Lakes Plan of Study Team, 2002: *Upper Great Lakes Plan of Study: For Review of the Regulation of Outflows from Lake Superior*, International Joint Commission, 72 pp. + 5 annexes.

Presentations

Lofgren, B. M., 2005: *Development of the second-generation Hydrosphere-Atmosphere Research Model (CHARM) for the Laurentian Great Lakes region*. 19th Conference on Hydrology, 85th Annual Meeting, American Meteorological Society, San Diego, CA, 9-14 January 2005.

Lofgren, B. M., 2005: Climate *modeling on the Great Lakes that is both wrong and useful*. Seminar, Ann Arbor, MI, March 17, 2005. NOAA, Great Lakes Environmental Research Laboratory.

Lofgren, B. M., 2005: *Development of Next-Generation Great Lakes Regional Coupled Hydrosphere-Atmosphere Research Model (CHARM).* 48th Conference on Great Lakes Research, International Association for Great Lakes Research, Ann Arbor, MI, 23-27 May 2005.

Lofgren, B. M., and T. E. Croley II, 2005: *Climate and Hydrologic Research at the Great Lakes* Environmental Research Laboratory (GLERL). NWS Sub-Regional Climate Services Meeting, Champaign, IL, 2-3 August 2005.

Lofgren, B. M., 2005: *Broader impacts of climate change: Putting the puzzle together. Understanding Michigan Great Lakes Research Needs and Looking Forward*: A Panel Discussion, an offshoot of the IAGLR Conference, sponsored by Michigan Great Lakes Protection Fund, 26 May 2005, Ann Arbor, MI.

Brochures

Lake Level Modeling under Climate Change