COUPLED HYDROLOGIC ATMOSPHERIC RESEARCH MODEL (CHARM)

Thomas E. Croley II and Brent M. Lofgren[1]

ABSTRACT: Atmospheric impacts on surface hydrology have been explored by using general circulation models (GCMs) to drive surface hydrology models with no dynamic feedback between them. However, embedding mesoscale atmospheric models within GCMs and coupling relevant surface hydrology models to the mesoscale models, allows more relevant scales for regional impact estimation and the consideration of dynamic linkages between the atmosphere and the surface. Still, large-scale parameter changes, such as lake levels, *can only be estimated indirectly* by using these model outputs as inputs to hydrologic models. The Great Lakes Environmental Research Laboratory (GLERL) estimates large-scale surface hydrological parameters by using models developed for the Great Lakes. Likewise, further refinement of the Regional Atmospheric Modeling System (RAMS) is ongoing at Colorado State University, ASTeR, Inc., and other institutions. To enable direct dynamic estimation of large-scale parameter changes, GLERL is integrating these models into a Coupled Hydrosphere Atmosphere Research Model (CHARM). This paper concentrates on the formulation of CHARM. Results of preliminary testing show that CHARM produces features in the temperature, humidity, and precipitation fields which cannot be resolved by GCMs and may be attributed to the Great Lakes. Careful validation of these results against observed data is in progress.
KEY TERMS: Great Lakes; Coupled Models; Hydrology; Meteorology.

INTRODUCTION

In recent years, the Great Lakes Environment Research Laboratory (GLERL) has simulated the Laurentian Great Lakes water supplies associated with possible global climatic warming due to a doubling of atmospheric carbon dioxide (*Croley and Hartmann*, 1989; *Croley*, 1990; *Hartmann*, 1990; *Croley et al.*, 1991). GLERL coupled their basin runoff and lake evaporation hydrology models with four atmospheric general circulation models (GCMs). This study gave useful but very general ideas of impacts associated with doubling of atmospheric CO_2. However, as in other studies of this type, interpretations were limited by the difference in spatial scales in these models and by the inability to consider dynamic interactions between major subprocesses (meteorology, hydrology, limnology, and so forth). We suspect that global warming will, by increasing evapotranspiration from the Great Lakes and surrounding land areas, also increase precipitation in the region. Such an assertion, and the net result in terms of regional runoff, can only be tested by using a model which has the surface and atmosphere coupled and the Great Lakes and drainage basins well-resolved.

Climate change and other meteorological impacts in the Great Lakes are highly diverse in their effects and in their characteristic temporal and spatial scales. Many socio-economic and biological impacts depend on lake-level or thermodynamic changes which

[1]Research Hydrologist and Atmospheric Scientist, respectively, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, 2205 Commonwealth Blvd., Ann Arbor, Michigan 48105-1593.

occur at large lake-wide spatial scales and at time scales of weeks, months, and longer. Other impacts depend on fine-scale parameter changes, such as small-scale features in lake-atmosphere energy exchange due to coastal upwelling. As mentioned, past research (*Croley and Hartmann*, 1989; *Croley et al.*, 1991) points to the need to couple the processes of atmospheric dynamics and thermodynamics with those of lake thermodynamics and evaporation and land surface evapotranspiration and runoff in order to get an accurate overall picture of the water cycle under either present or changed climatic conditions.

To estimate impacts associated with both scales of parameter changes, the Great Lakes research community can address these scales separately. This offers the advantage that we can *now* begin 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. Thus, we are presently coupling an atmospheric model with existing Great Lakes hydrologic process models (lumped-parameter, applying to irregular-shaped areas over scales of 30-100 km for land surface and 100-300 km for lake surface and 1-30 d). Then, as permitted by advances in computer hardware and software and appropriate process models, attention can be given to processes occurring at scales smaller than approximately 30 km, or simulations of many years.

The next section includes a discussion of the concepts and modeling methods of surface-atmosphere interaction. Next we summarize the three existing models which form the basis of CHARM. Then we discuss the methodology used in coupling these models and present preliminary results. The concluding section includes a list of questions to be addressed in future studies that use CHARM.

INTERACTION OF SURFACE AND ATMOSPHERE

Concepts

The two means by which the atmosphere and the surface (both land and water) influence each other is through the exchange of energy and water. Solar radiation is the ultimate driver of the dynamics and thermodynamics of the atmosphere-surface system. The amount of solar radiation absorbed by the surface and atmosphere is dependent on factors such as cloudiness and surface albedo. The amount of cooling of the atmosphere and the surface by thermal radiation is again dependent on cloudiness, and also on the presence of greenhouse gases such as carbon dioxide and water vapor.

Although energy input to the surface by net radiative heating can be stored temporarily at the surface, especially in water bodies, it is eventually released back to the atmosphere. This is accomplished through the fluxes of sensible heat and latent heat. Sensible heat flux into the atmosphere is the diffusion of warmer air at the surface into the boundary layer of the atmosphere; negative sensible heat flux occurs when the surface is cooler than air in the boundary layer. Latent heat flux is the heat consumed by the evaporation of water, which involves the diffusion of air with high absolute humidity at the surface into the atmosphere's boundary layer. Increased net radiative heating of the surface promotes increased fluxes of sensible and latent heat, with latent heat predominating unless there is a shortage of water.

The moisture budget of the surface thus depends on the regulation of surface evaporation by the surface energy budget. It also depends on precipitation and other atmospheric factors such as the humidity and turbulence of the boundary layer, which influence the evaporation rate. An important influence on precipitation and the humidity of the atmosphere is the advection of water vapor into and out of the atmospheric region. Precipitation and humidity are themselves dependent on the evaporation of water from the surface, making the two-way interaction of surface and atmosphere important.

Modeling

Land-surface and lake-surface hydrology modeling schemes are, naturally, dependent on meteorological information supplied to them either by observationally based "forcing" or from an atmospheric model. Because it does not permit feedbacks between climate and land-surface processes, off-line testing and use of surface parameterizations is unsatisfactory if interactive simulations are the goal. The appropriate consideration of land surface processes must involve determination of interactive dynamics between the atmosphere and the hydrosphere. This was revealed in early studies of climate change.

Modelers are using mesoscale atmospheric models embedded in GCMs to enable better assessment of local to regional effects (*Dickinson et al.*, 1989; *Giorgi*, 1990; *Bates et al.*, 1993). This allows the use of more relevant scales for regional impact estimation and dynamic linkage between the atmosphere and the surface. This approach has generally been limited in the past to 50-km grids or larger because of the complexity of the modeling system and the computing power that is required. These obstacles have been reduced by the development of improved atmospheric, hydrological, and limnological models, and by the advent of inexpensive but powerful modern computers. The National Center for Atmospheric Research (NCAR) tested the operation of their atmospheric, hydrologic, and lake flux models embedded in their GCM at scales finer than 50 km (*Bates et al.*, 1993).

The number of possibilities for research emphasis and formulation of joint atmospheric-hydrologic models is tremendous, leaving room for many separate approaches. Much uncertainty exists in the formulations, and there is diversity in those aspects deemed important in coupling surface and atmospheric processes; there is no "standard" with which to compare these approaches. It is not anticipated that a single "best" scheme will emerge, but enhanced understanding will come from pursuing several approaches to regional climate change impact estimation.

CHARM CONSTITUENT MODELS

GLERL's present simulation models do a very good job of estimating large-scale surface hydrological parameters. GLERL has models closer to practical utilization and estimation of impacts than any other surface hydrology models for the Great Lakes. For example, besides the state variables or parameters associated with land hydrology and lake heat storage (soil moisture, snowpack, water temperatures), which all surface hydrology parameterizations must employ, GLERL's models are already part of a system of models used to estimate lake levels, whole-lake heat storage, and water and energy balances (*Croley and Hartmann*, 1987). GLERL's existing hydrological models have been developed, calibrated, and verified for the Laurentian Great Lakes. These include models for rainfall/runoff [121 daily watershed models (*Croley*, 1983a,b; *Croley and Hartmann*, 1984)] and one-dimensional (depth) lake thermodynamics [7 daily lake surface flux, thermal structure, heat storage, and ice cover models (*Croley*, 1989, 1992; *Croley and Assel*, 1994)]. Models exist also for channel routing, lake regulation, and diversions.

Land Surface Hydrology

The Large Basin Runoff Model [LBRM, see *Croley*, (1983a,b) and *Croley and Hartmann*, (1984)] simulates river outflow for individual sub-basins using the concept of a cascade of five linear reservoirs: 1) the snowpack, whose source is snowfall and whose sinks are snowmelt and sublimation; 2) the upper soil zone, whose sources are rainfall and snowmelt (less surface runoff) and whose sinks are evapotranspiration and percolation; 3) the lower soil zone, whose source is percolation and whose sinks are evapotranspiration, deep percolation, and interflow; 4) groundwater storage, whose source is deep percolation and whose sink is groundwater outflow; and 5) surface storage, whose sources are surface runoff, interflow, and groundwater outflow, and whose sink is stream flow.

The rates of evapotranspiration from the upper or lower soil zone are given by:

$$e_n = \beta_n e_p S_n \tag{1}$$

where e_n is the evapotranspiration rate from reservoir n, e_p is a "potential evapotranspiration" rate, S_n is the amount of water stored in reservoir n, and β_n is the evapotranspiration rate partial constant for reservoir n, which was calibrated separately for the upper and lower soil zones. The potential evapotranspiration is given by a formula involving an exponential function of the mean daily temperature, rather than by a bulk aerodynamic or mixing length formula, which require more complete data on boundary layer wind, temperature, and humidity than are available observationally. Runoff is given by:

$$R = m S_u / S_c \tag{2}$$

where R is runoff, m is rainfall plus snowmelt, S_u is the upper soil zone moisture, and S_c is the upper soil zone moisture capacity (taken equivalent to 2 cm). The reservoirs outflows (percolation, interflow, deep percolation, groundwater outflow, and stream flow) are:

$$F_n = \alpha_n S_n \tag{3}$$

where F_n is the flux from reservoir n, α_n is a parameter calibrated separately for each type of flux (in units of inverse time), and S_n is the moisture storage in reservoir n from which the flux originates.

Lake Thermodynamics

The Lake Evaporation and Thermodynamics Model (LETM) simulations calculate total heat exchange at the surface of the lake with diffusion of heat (or negative heat) downward into the lake, and use a parameterization for lake ice (*Croley*, 1989, 1992; *Croley and Assel*, 1994). In calculating the surface heat exchange, this model uses a parameterization to approximate the effects of clouds on incident solar and longwave radiation. Sensible and latent heat fluxes are calculated by using the Richardson number-dependent mixing length formula given by *Quinn* (1979). Over-lake winds are approximated from observed winds at land stations and used both in the calculation of sensible and latent heat fluxes and as an "aging" function for heat diffusion in the lake.

The maximum density of fresh water occurs at a temperature of 3.98°C. The Great Lakes ordinarily overturn every spring and fall when water temperatures reach this value. Following such an overturning, heat input (or output) at the lake surface becomes stored heat (or negative heat), initially in a thin layer near the surface, then diffusing downward so that the resulting temperature change is smaller, but affects the water to a greater depth. In the LETM, each day's heat input is saved, and its effect on the water temperature profile for subsequent time is determined by an aging function, depending on the surface wind speed integrated over the time since that heat was inserted into the lake. When net heat flux again becomes negative after the water has been heated above 3.98°C (or positive after the water has been cooled below 3.98°C), heat (or negative heat) is removed first from the least "aged" stored heat quantities (i.e., heat stored most recently).

Mesoscale Atmospheric Model

The Regional Atmospheric Modeling System (RAMS), excluding its inherent soil moisture and vegetation models, forms the atmospheric component of CHARM. Developed at Colorado State University, RAMS couples a non-hydrostatic prognostic cloud model described by *Tripoli and Cotton* (1982) with two hydrostatic mesoscale models (*Tremback et al.*, 1985; *Mahrer and Pielke*, 1977). The model can employ a two-way nested-grid scheme to allow for feedbacks between the local-scale circulations and the mesoscale and synoptic-scale flows. Non-hydrostatic physics and explicit cloud model equations allow the finest

mesh resolution to be very high; grid spacing on the order of 1 km has been applied. In a detailed evaluation of mesoscale models, *Pielke et al.* (1990) concluded that the RAMS model was one of the best suited for studies of the atmospheric boundary layer. RAMS is currently run operationally at the National Oceanic and Atmospheric Administration's (NOAA's) Air Resources Laboratory daily over the Chesapeake Bay on a 30 km grid and a 1000 km x 1000 km domain.

RAMS uses the Arakawa C-grid to reduce finite-differencing error. It can be run in one, two, or three dimensions. It uses a terrain-following height-coordinate system. This coordinate system is much like the sigma surfaces used in other mesoscale models which are on terrain-following pressure-type surfaces. We use a vertical domain of 16.7 km to allow for convection. RAMS model physics options include cloud microphysical parameterizations and a Kuo-type convective condensation and precipitation scheme.

The RAMS model can be initialized from spatially inhomogeneous meteorological observations. NOAA National Meteorological Center (NMC) model-gridded data and surface and rawinsonde sites can be interpolated to the model grid, or alternatively, GCM output data can be used for climate scenarios. Information on spatially-varying surface parameters such as soil and vegetation types, terrain height, land roughness, and land percentage can be input.

CHALLENGES AND METHODOLOGY FOR COUPLING MODELS

Since there is some overlap in function between parts of the atmospheric model and the two surface models, decisions are required about which model should be used for some purposes. RAMS has a component which calculates evapotranspiration and diffusion of heat and moisture in the top one meter of soil. Use of this to predict soil moisture storage and evapotranspiration is inconsistent with the use of LBRM for the same purposes. Therefore, we have retained only the part of the RAMS soil model which calculates the heat diffusion, while replacing the soil moisture model with a modified version of LBRM.

The LBRM was modified to use potential evapotranspiration calculated by the Richardson number-dependent mixing length method of *Quinn* (1979). In the original LBRM, the potential evapotranspiration rate in (1) is defined as the water equivalent of the heat remaining after evapotranspiration. Thus, the larger that the actual evapotranspiration rate is, the less that heat is available to drive the process. This complementary concept exists in the atmosphere over large areas and time periods and makes sense in the LBRM when the atmosphere is not otherwise modeled. It causes the actual evapotranspiration amount to be self-limiting over the daily time period used in the LBRM. Now, for the more nearly instantaneous considerations of explicitly modeling the atmosphere, we provide the driving potential evapotranspiration rate as a function of instantaneous humidity, windspeed, and stability. Actual evapotranspiration is no longer self-limiting and must be constrained by the potential rate. Therefore, potential evapotranspiration is now enforced as an upper limit to the total of actual evapotranspiration from the upper and lower soil zones. The potential evapotranspiration now represents the atmosphere's capacity to move water vapor through the Prandtl (constant-flux) layer and into higher parts of the boundary layer. If evapotranspiration were allowed to exceed this potential rate, even for a few hours, it could unrealistically cool the surface, causing large sensible heat fluxes into the surface and potentially leading to large disruptions in circulation.

Since the parameter in (1) was calibrated with the complementary relation between actual and potential evapotranspiration, and since CHARM uses the traditional definition of potential evapotranspiration, we must re-calibrate. To reduce calibration requirements to a practical level, we intend to preserve the spatial variation among the 121 values of β for the upper soil zone and likewise for the lower soil zone. We plan to experiment with adjusting all upper soil zone parameters by a common multiplicative factor and adjusting

all lower soil zone parameters by a second factor. These two adjustments will match CHARM outputs with runoff, moisture storage, and meteorology for selected simulation runs. We expect that better results will be obtained by decreasing the original values of the partial evapotranspiration parameters, thus reducing instantaneous actual evapotranspiration rates so the constraint is invoked less often.

The basic formulation of GLERL's LETM was more easily reconciled with RAMS. RAMS simply requires water surface temperature as input, and calculates the evaporative and sensible heat fluxes using a Richardson number-dependent scheme. The scheme which was included with RAMS was replaced with that of *Quinn* (1979) for the sake of consistency with the LETM calibration.

Most approaches for coupling atmospheric and surface process models define a common grid for the coupling. That is, land surface parameterizations are defined 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 do not bear directly on the atmospheric modeling. Two example problems are surface runoff and lake heat storage. Surface runoff models that are defined over the hydrological basin or watershed offer the best representation of runoff, as compared to real-world data. This is particularly true for the Great Lakes where a suite of basin hydrology models have been calibrated. Likewise, existing lumped-parameter models of the heat stored in an entire lake (considered as a whole), as it diffuses with wind mixing and time, offer the best representation of stored heat at present. In our case, the atmospheric model is defined on a regular grid and uses timesteps of 90 seconds or less, while the surface models are defined on irregular areas (Figure 1) and were calibrated by using the assumption that their forcing functions were constant over each 24-hour period. However, we can determine how much each grid box overlaps each sub-basin for the LBRM and each lake for the LETM.

By using the areas of overlap as a weighting function, we get a weighted average over each RAMS grid box of the LBRM parameters related to the upper and lower soil zones (percolation, lower soil evapotranspiration, interflow, and deep percolation). For example, if a grid box has 25% of its area in sub-basin "A" and 75% in sub-basin "B", the parameters for that grid box will be the sum of 0.25 times those of sub-basin "A" and 0.75 times those of sub-basin "B." Areas outside of the Great Lakes basins have parameters arbitrarily set to the median value from all sub-basins. By using these parameters, we solve for the snowpack, snowmelt, upper and lower soil zone storage, runoff, percolation, interflow, and deep percolation at each of the RAMS 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.

However, the groundwater and surface storage do not interact directly with the atmosphere, and their prediction is done separately at longer time intervals, and is represented on the basis of sub-basins rather than the artificial grid of the atmospheric model. At 12-hour intervals, the fluxes into the groundwater and surface storage reservoirs (runoff, interflow, and deep percolation) 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 are then 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 RAMS grid point at each timestep. The total heat flux for 24 hours is then combined from the grid over each entire lake, along with the wind speed, which is used as an aging function for the diffusion of heat into the lake. The total heat storage in the lake and the lake surface temperature are then calculated. A 24-hour timestep is necessary for the LETM, as it was calibrated using this timestep, and thus ignored diurnal variations in the net heat flux. Work is in progress to

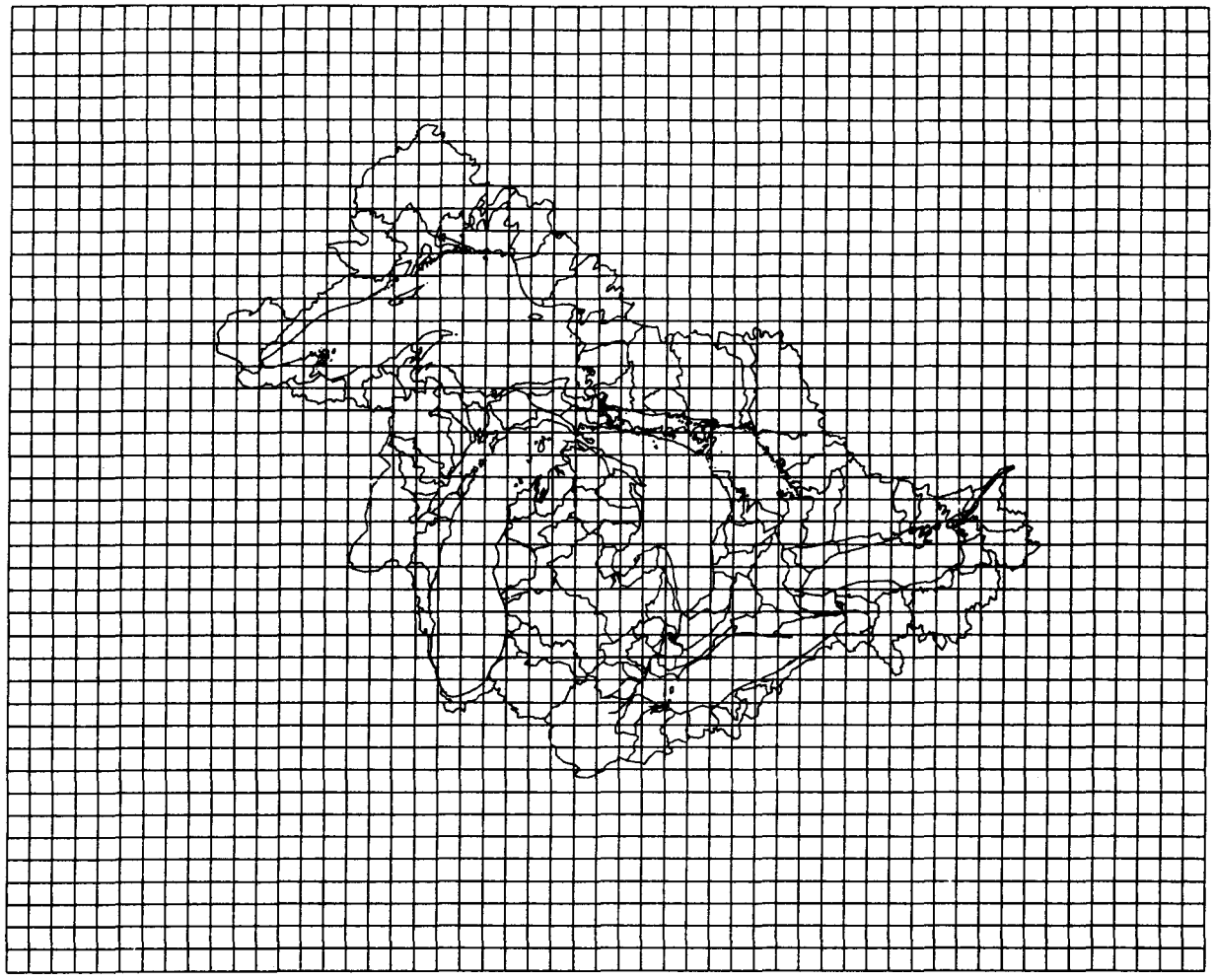

Fig. 1. Atmospheric Mesoscale 40-km Grid Overlain by the Great Lakes Hydrology Models Irregular Areas.

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.

This coupled model represents both the atmosphere and surface hydrology and is drivable by outputs of existing NOAA NMC prognostic models, by archived data, or by representations of future scenarios, as from GCM simulations. The final model has ready application to problems in the prediction of lake conditions, the improved forecasting of lake-effect meteorological phenomena, the projection of areal water balances and hydrology, and the examination of past and future climatic factors.

The atmospheric component of the present version of CHARM is intended to give an accurate representation of atmospheric dynamics and physics at the meso-α scale (~100-1000 km), while depending on prescribed lateral boundary conditions for data on larger scales. Figure 2 shows that output from CHARM has features which cannot be resolved by GCMs. For the arbitrary test period of 16-26 June 1993, there was an east-west oriented band of non-convective rainfall approximately 300 km wide centered on an axis which extends through Wisconsin, the northern parts of Lakes Michigan and Huron, and into Ontario. Additionally, there is lighter but widespread convective rainfall, which is suppressed over southern Lake Michigan and Lake Erie, which are much cooler than the

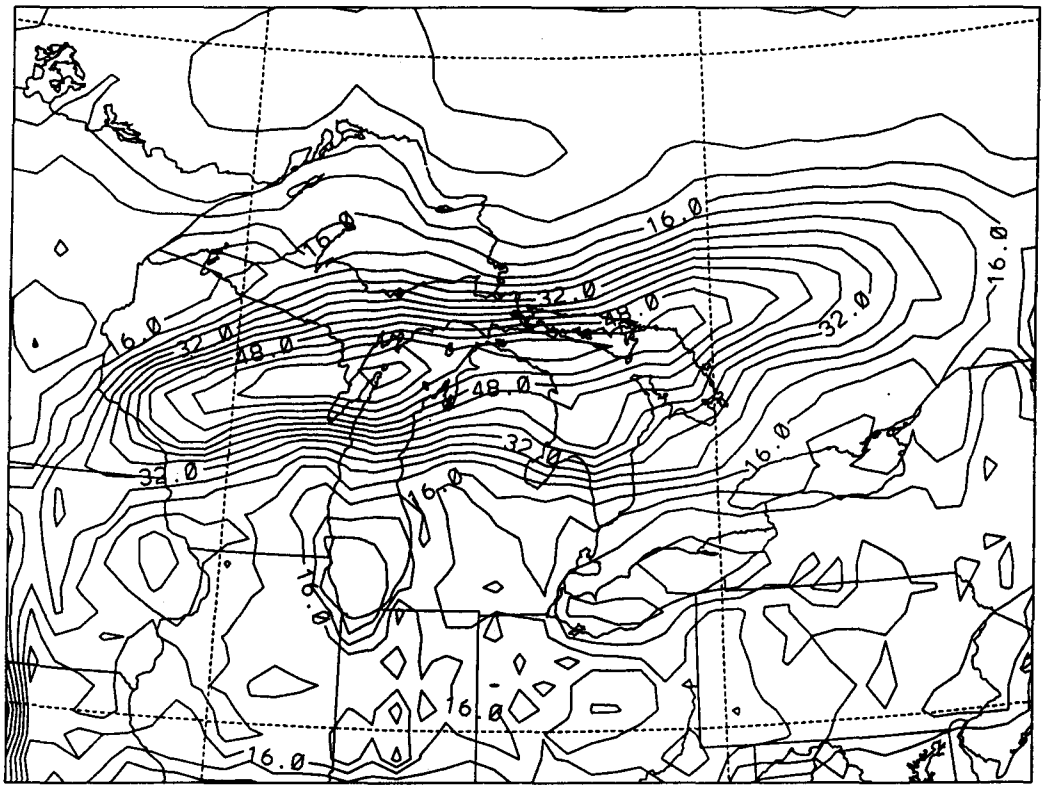

Fig. 2. Precipitation simulated by CHARM for 16-26 June 1993 (contour interval = 4 mm).

overlying air during this season. Results for temperature and humidity (not shown) show features in these fields corresponding spatially to the Great Lakes. Validation of precipitation and other meteorological fields against observations is in progress, to be followed by validation of hydrologic variables.

The atmospheric model puts the greatest demands on computing resources. The domain required to represent all of the Great Lakes and their drainage basins is approximately 2000 km x 1500 km. It is believed that 40 km resolution in the atmospheric model will be adequate to represent the interaction between the atmosphere and the entire lakes and sub-basins. Sixty kilometer resolution may also be adequate, and tests will be run to check this. It is presently feasible to run simulations of seasonal length at 40 km resolution, with simulations requiring under 1/6 of real time, while 60 km resolution requires 1/12 of real time on an HP 735 "Apollo" workstation.

Another consideration is the resolution of the meteorological data used to prescribe lateral boundary conditions for the atmospheric model. It is undesirable to use boundary conditions with much larger granularity than the resolution of the embedded model. For observed data, the typical distance between primary surface reporting stations is about 100 km, while rawinsonde (upper air) reporting stations are typically spaced at 300 km. Present high-resolution GCM climate simulations typically have 300 km grid spacing.

OBJECTIVES AND QUESTIONS TO BE ADDRESSED

We attempt to advance toward a fully interactive model of the surface and atmosphere in the Great Lakes region, with spatial resolution which accurately represents certain hydrologic processes. Toward this end, we have developed an initial version of a

Coupled Hydrologic Atmospheric Research Model (CHARM) from existing atmospheric and hydrologic models, using two-way dynamic interactive feedbacks, and capable of estimating large-scale parameter impacts of climate changes. Output from preliminary tests of CHARM shows that it is capable of producing responses in terms of precipitation, temperature, and humidity which correspond spatially to the Great Lakes. Rigorous validation of results is in progress. In the future, we plan to enhance CHARM with second-generation two-dimensional models of lake thermal flux and new land surface parameterizations for runoff and stream flow.

We plan to use CHARM to address the following questions in the context of a fully coupled land-lake-atmosphere system: *1) What are the current energy and moisture budgets of the Great Lakes and surrounding basins and the overlying atmosphere, on a seasonal basis?* First, we will assure that atmospheric fields are in reasonable agreement with observed values by running short (e.g. 10-day) simulations with differing characteristics of air temperature and storm occurrence. Next, we will verify that simulation of river flows and lake surface temperature are in agreement with observations, and we will finally evaluate moisture and heat fluxes among the components (atmosphere, land, and lakes) of the system. This will require simulations of seasonal time scales to allow the moisture and heat storage quantities to "spin up." *2) What role does atmospheric transport play in the Great Lakes water budget (i.e., how much water is recycled within the basin)?* This will entail further analysis of seasonal runs of CHARM, investigating the atmospheric advection of moisture among the basins of the lakes, and into and out of the domain. Comparison with another experiment, in which the lakes have been removed, may be illustrative. *3) How might climate change affect the regional energy and moisture budgets?* We plan to address this question in the future, by comparing a simulation with present CO_2 concentration to another with doubled CO_2, each using GCM output as lateral boundary conditions for simulations of several years' duration.

ACKNOWLEDGMENTS

This work is GLERL contribution no. 880.

REFERENCES

Bates, G. R., Giorgi, F., and Hostetler, S. W., 1993. Toward the simulation of the effects of the Great Lakes on regional climate. *Monthly Weather Review*, **121**:1373-1387.

Croley, T. E., II, 1983a. Great Lakes Basins (U.S.A.-Canada) Runoff Modeling. *Journal of Hydrology*, **64**:135-158.

Croley, T. E., II, 1983b. Lake Ontario Basin (U.S.A.-Canada) Runoff Modeling. *Journal of Hydrology*, **66**:101-121.

Croley, T. E., II, 1989. Verifiable evaporation modeling on the Laurentian Great Lakes. *Water Resources Research*, **25**(5):781-792.

Croley, T. E., II, 1990. Laurentian Great Lakes double-CO_2 climate change hydrological impacts. *Climatic Change*, **17**:27-47.

Croley, T. E., II, 1992. Long-term heat storage in the Great Lakes. *Water Resources Research*, **28**(1):69-81.

Croley, T. E., II, and Assel, R. A., 1994. A one-dimensional ice thermodynamics model for the Laurentian Great Lakes. *Water Resources Research*, (in press).

Croley, T. E., II, and Hartmann, H. C., 1984. Lake Superior Basin Runoff Modeling. *NOAA Tech. Memo. ERL GLERL-50*, National Technical Information Service, Springfield, Virginia 22161, 284 pp.

Croley, T. E., II, and Hartmann, H. C., 1987. Near Real-Time Forecasting of Large Lake Supplies. *Journal of the Water Resources Planning and Managment Division*, **113**(6):810-823.

Croley, T. E., II, and Hartmann, H. C., 1989. Effects of climate changes on the Laurentian Great Lakes levels. In *The Potential Effects of Global Climate Change on the United States, Appendix A: Water Resources* (J. B. Smith and D. A. Tirpak, Eds.), U. S. Environmental Protection Agency report no. EPA-230-05-89-051, June, 4-1--4-34.

Croley, T. E., II, Louie, P. Y. T., and Mortsch, L., 1991. CCC GCM 2xCO_2 hydrological impacts on the Great Lakes. Final Report Appendix Section, Subtask 19.1.2, Climate Scenario Development, Task 19.1, Climate and Climate Change, Task Group 2, Working Committee 3, Phase II of the International Joint Commission Water Levels Reference Study, December, 25 pp.

Dickinson, R. E., Errico, R. M., Giorgi, F., and Bates, G. T., 1989. A regional climate model for the western United States. *Climatic Change*, **15**:383-422.

Giorgi, F., 1990. On the simulation of regional climate using a limited area model nested in a general circulation model. *Journal of Climate*, **3**:941-963.

Hartmann, H. C., 1990. Climate change impacts on Laurentian Great Lakes levels. *Climatic Change*, **17**:49-67.

Mahrer, Y., and Pielke, R. A., 1977. A numerical study of the airflow over irregular terrain. *Beitr. z. Physik der Atmosph.*, **50**:98-113.

Pielke, R. A., Lyons, W. A., McNider, R. T., Moran, M. D., Moon, D. A., Stocker, R. A., Walko, R. L., and Uliasz, M., 1990. Regional and mesoscale modeling as applied to air quality models. *Proceedings: 18th NATO/CCMS International Technical Meeting on Air Pollution Dispersion Modeling and its Application*, Vancouver, British Columbia, 30 pp.

Quinn, F. H., 1979. An improved aerodynamic evaporation technique for large lakes with application to the International Field Year for the Great Lakes. *Water Resources Research*, **15**:935-940.

Tremback, C. J., Tripoli, G. J., and Cotton, W. R., 1985. A regional scale atmospheric numerical model including explicit moist physics and a hydrostatic time-split scheme. *Preprints 7th AMS Conference on Numerical Weather Prediction*, 17-20 June, Montreal, Canada.

Tripoli, G. J., and Cotton, W. R., 1982. The Colorado State University three-dimensional cloud/ mesoscale model - 1982. Part I: General theoretical framework and sensitivity experiments. *J. de Rech. Atmos.*, **16**:185-220.