

## VALIDATION OF THE COUPLED HYDROSPHERE-ATMOSPHERE RESEARCH MODEL (CHARM)

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### 1. INTRODUCTION

The sensitivity of hydrology to climatic forcing in the Laurentian Great Lakes region has been studied previously using the results of general circulation models (GCMs) to drive surface hydrology models without any direct feedback between them (Croley 1990, Hartmann 1990). This method is limited in that the spatial scales of the hydrologic processes of interest are much smaller than the scales resolved by the GCMs. In addition, effects of the Great Lakes on the atmosphere are potentially very important, in view of their role as very large potential sources of water in the midst of a continent and their large heat capacity. Feedback between the lakes and atmosphere is not considered when using one-way forcing, as in previous studies. It is suspected that increased evaporation from the lakes due to greenhouse warming would lead to increased precipitation over their drainage basins if such feedbacks were incorporated into a model.

An alternative approach, which considers these problems, is to couple hydrologic models to limited-domain mesoscale atmospheric models, nested into larger-scale meteorological conditions (Dickinson et al. 1989, Bates et al. 1993, Giorgi et al. 1994). Our purpose is to design this type of model for the Great Lakes region, but with a greater emphasis than in other efforts on the prediction of hydrologic state variables, river flows, and net basin supplies, by using process models which were designed for hydrologic applications. This paper briefly describes efforts to develop and validate such a model, with an atmospheric component coupled to models of land surface hydrology and lake thermodynamics developed at the Great Lakes Environmental Research Laboratory (GLERL) specifically for application to the Laurentian Great Lakes and their watersheds. This modeling system is known as the Coupled Hydrosphere-Atmosphere Research Model (CHARM).

### 2. MODEL

CHARM is built from three major components: 1) the Regional Atmospheric Modeling System (RAMS), developed at Colorado State University and ASTeR, Inc., 2) the Large Basin Runoff Model (LBRM), developed at GLERL, and 3) the Lake Evaporation and Thermodynamics Model (LETM), developed at GLERL.

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#### 2.1. Atmospheric model

The version of RAMS (Pielke et al. 1992) used here is based on a non-hydrostatic cloud model described by Tripoli and Cotton (1982). It is a limited-area model which can be nested into larger-scale meteorological data provided by observations or by GCMs. We use a single grid with 53 grid boxes of 40 km each in the zonal direction (2120 km) and 43 grid boxes in the meridional direction (1720 km), covering a region surrounding the Great Lakes (Fig. 1). We use 22 vertical layers in terrain-following surfaces, with the model top at 16.7 km geopotential. Large-scale rain and snow are simulated by using a cloud microphysics scheme and convective precipitation is handled by a modified Kuo scheme. Solar and longwave radiation are simulated by the scheme of Chen and Cotton (1983). RAMS's intrinsic land surface parameterization has been disabled in favor of the LBRM, and alterations have been made to use lake surface temperatures predicted by the LETM.

#### 2.2. Lake model (LETM)

The LETM (Croley 1989, 1992) uses the lakes' net heat exchange at the surface to update the total heat content of the lake. A temperature of 3.98 degrees Celsius (the temperature of maximum density of fresh water) is used as a base value, with daily quantities of heat added at the surface following the spring turnover, or removed following the autumn turnover. These doses of heat are diffused downward with time, using near-surface wind as an aging function, and are eventually eliminated as the next turnover is approached. The LETM also includes a lake ice model (Croley and Assel 1994).

#### 2.3. Land surface model (LBRM)

The atmospheric component of CHARM interacts with the surface components by exchanging momentum, energy, and moisture. The LBRM (Croley 1983a,b) is used for simulating the moisture storages and fluxes over land areas. It has been significantly modified to meet the demands of coupling with an atmospheric model, as discussed in subsection 2.4.

The LBRM simulates 5 water reservoirs: snowpack, upper soil zone, lower soil zone, ground water, and surface storage. Each of these was defined over each of 121 river basins that drain into the Great Lakes. The snowpack is supplied by snowfall and depleted by snowmelt. The other reservoirs interact through water fluxes among themselves and ultimately from the surface storage reservoir out of the

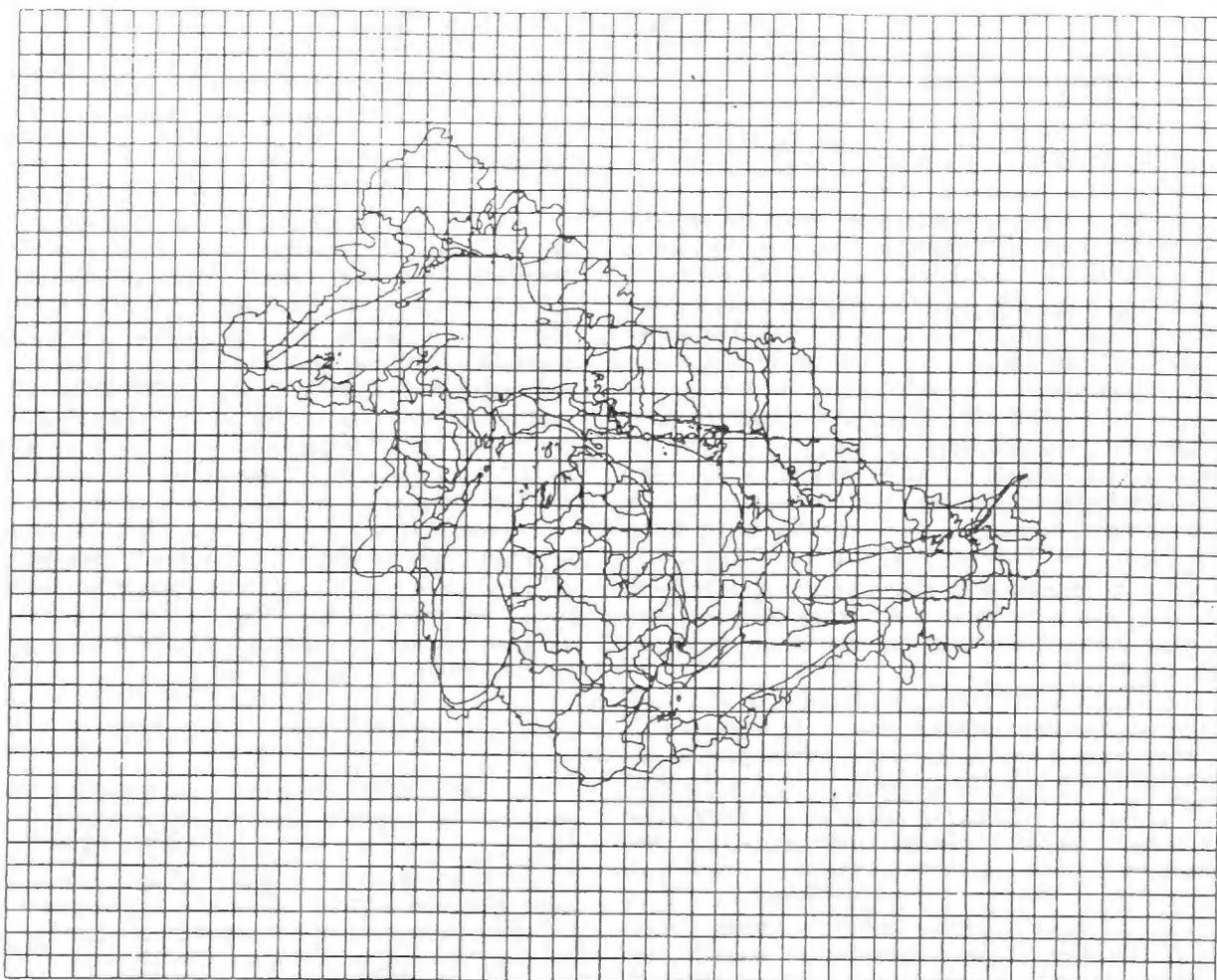


Fig. 1. Map of CHARM domain used in this paper, showing Great Lakes and river runoff basins, overlaid with a 53 x 43 grid of 40 km resolution.

drainage basin, with each of these fluxes taking the general form

$$F_n = \alpha_n S_n \quad (1)$$

where  $F_n$  is the flux,  $S_n$  is the storage in the source reservoir, and  $\alpha_n$  is a parameter pertaining to that particular flux which is constant in time but varies among the drainage basins. In addition, the upper and lower soil zones have evapotranspiration to the atmosphere in the form

$$e_n = \beta_n e_p S_n \quad (2)$$

where  $e_n$  is actual evapotranspiration,  $\beta_n$  is a parameter for each drainage basin, and  $e_p$  is potential evapotranspiration. A set of 5  $\alpha$  parameters, 2  $\beta$  parameters, an additional parameter governing snowmelt, and another governing  $e_p$  were calibrated for each of the 121 drainage basins, by minimizing

the root mean square difference between modeled river flow and observed flow at river gages.

#### 2.4. Coupling

The coupling of the LETM to RAMS is relatively straightforward. RAMS already used the water surface temperature and percentage of land in each grid square to calculate the fluxes of latent and sensible heat and longwave radiation from water surfaces. For our simulation, the lake surface temperatures are initialized by running an LETM simulation off-line up to the desired starting date for a CHARM simulation. During the CHARM run, running totals are kept of evaporation and net heat flux from the water in each grid box, along with near-surface wind. Consistent with its calibration, which ignored diurnal variation in lake

temperature, the LETM is invoked at 24-hour intervals, using these accumulated values of heat input (or loss), evaporation, and wind speed, averaged over the lake surface. The LETM currently treats temperatures as a lumped quantity for each lake, but plans are underway to incorporate a 2-dimensional distribution of lake surface temperature.

The coupling of the LBRM to RAMS presented greater challenges. RAMS requires that fluxes of latent and sensible heat be calculated on the basis of grid boxes, whereas the LBRM is defined on irregular river drainage basins (Fig. 1). The current solution to this is to define the snowpack, upper soil zone, and lower soil zone reservoirs (those that interact directly with the atmosphere) on the grid mesh, with parameters for each grid box calculated as a mean of the parameters from the drainage basins, weighted by the amount of the grid box which falls inside each basin. Outside of the Great Lakes Basin, median values of all parameters are used. Fluxes from these reservoirs into the ground water and surface storage reservoirs are accumulated over 12-hour periods, after which they are averaged over the river drainage basins, so that ground water and surface storage can be calculated for the drainage basins.

Another serious difficulty is that the potential evapotranspiration ( $e_p$  in (2)) used a complementary formulation when the original LBRM was calibrated (Croley 1983a). This formulation partitions the incoming solar radiation into latent heat release and other fluxes (sensible heat flux plus net outgoing longwave radiation), with the "other fluxes" being equivalent to  $e_p$ , and the actual evapotranspiration (2) often equal to many times the potential rate. This formulation does yield realistic evapotranspiration rates over periods of weeks and longer. However, it is not suitable for use with an atmospheric model in which instantaneous surface fluxes can heavily influence dynamics. A bulk aerodynamic formulation of  $e_p$  is used instead, giving a measure of the capacity of the boundary-layer turbulence to carry water vapor away from the surface. The surface energy and water budgets also act to regulate evapotranspiration over longer time periods. This distinction in the definition of  $e_p$  means that we will also need to re-evaluate the  $\beta$  parameters (see (2)).

Another difficulty is that the influence of surface characteristics such as albedo and roughness on evapotranspiration is implicitly accounted for by the  $\beta$  parameters, but these characteristics can also influence the fluxes of sensible heat and radiation at the surface (Lofgren 1993). At present, surface albedo and roughness are considered to be spatially uniform over all land when calculating the energy budget, neglecting their influence on sensible heat and radiative fluxes. On the other hand, inclusion of a spatial distribution of these surface characteristics would result in "double-counting" of their influence on evapotranspiration. An additional concern is that there are large spatial discontinuities in the LBRM parameters.

### 3. RESULTS OF VALIDATION RUN

The period of 1-10 June 1991 was arbitrarily chosen as an initial validation case. The LBRM and LETM models were initialized by running them up to the end of 29 May.

Using the National Meteorological Center's Medium Range Forecast analysis for initial and lateral boundary conditions for the atmosphere along with these initial conditions for the surface, the model was run from 00 GMT 30 May until 00 GMT 11 June. The first two days were considered a spinup period and the results were ignored.

Figure 2a shows the observed precipitation rate during this period over the United States portion of the domain, for which we had station data available. It reveals that this was a relatively quiet period in terms of precipitation in the region. However, there were severe difficulties with the stable (non-convective) precipitation parameterization which resulted in the simulation of slow-moving and anomalously heavy rainfall events. Figure 2b shows that one of these occurred during the period of interest, crossing the southern part of Lake Michigan and extending toward the east. These anomalous rain events are also associated with strong warming and drying of the planetary boundary layer. The cause of these effects is being investigated further. One clue of potential importance is the relatively light precipitation over the cool surface of Lake Michigan itself. Some remaining candidate solutions for this problem include turning on RAMS's parameterization of pristine ice crystals, which may reflect more sunlight from precipitating regions, and using the time-split scheme for acoustic waves, rather than slowing the acoustic wave speed to avoid violating numerical stability conditions.

One precipitation feature whose location was well-simulated is the precipitation maximum over western Wisconsin, although the amount of rainfall there is less in the model than observed. The rainfall maximum in southern Minnesota is not well-simulated, perhaps due to its proximity to the lateral boundary of the model.

The model's near-surface temperature (not shown) exhibits a warm bias of 2-3 degrees Celsius compared to observations. This is opposite to the cold bias of RAMS noted by Snook and Cram (1994) when using the Chen and Cotton (1983) radiation scheme. Perhaps use of the RAMS pristine ice crystal parameterization will also improve the temperature field.

### 4. PLANS FOR FUTURE STUDIES

Further validation of meteorological variables simulated by CHARM will be done primarily using short test cases (4-7 days) under a variety of active and quiet conditions in various seasons. Results will be compared both with observed meteorology and with a similar coupled model for the Great Lakes region being developed by P. Sousounis and H.-Y. Chuang of the University of Michigan. Validation of hydrologic aspects of CHARM and re-calibration of  $\beta$  parameters for the LBRM will likely require longer integrations of the coupled model.

Anticipated numerical experiments will address questions regarding the energy and moisture budgets of the surface of the Great Lakes and surrounding drainage basins and the overlying atmosphere. Possible investigations include studies of how much of the water evaporated from the Great Lakes basin is recycled as precipitation within the basin in

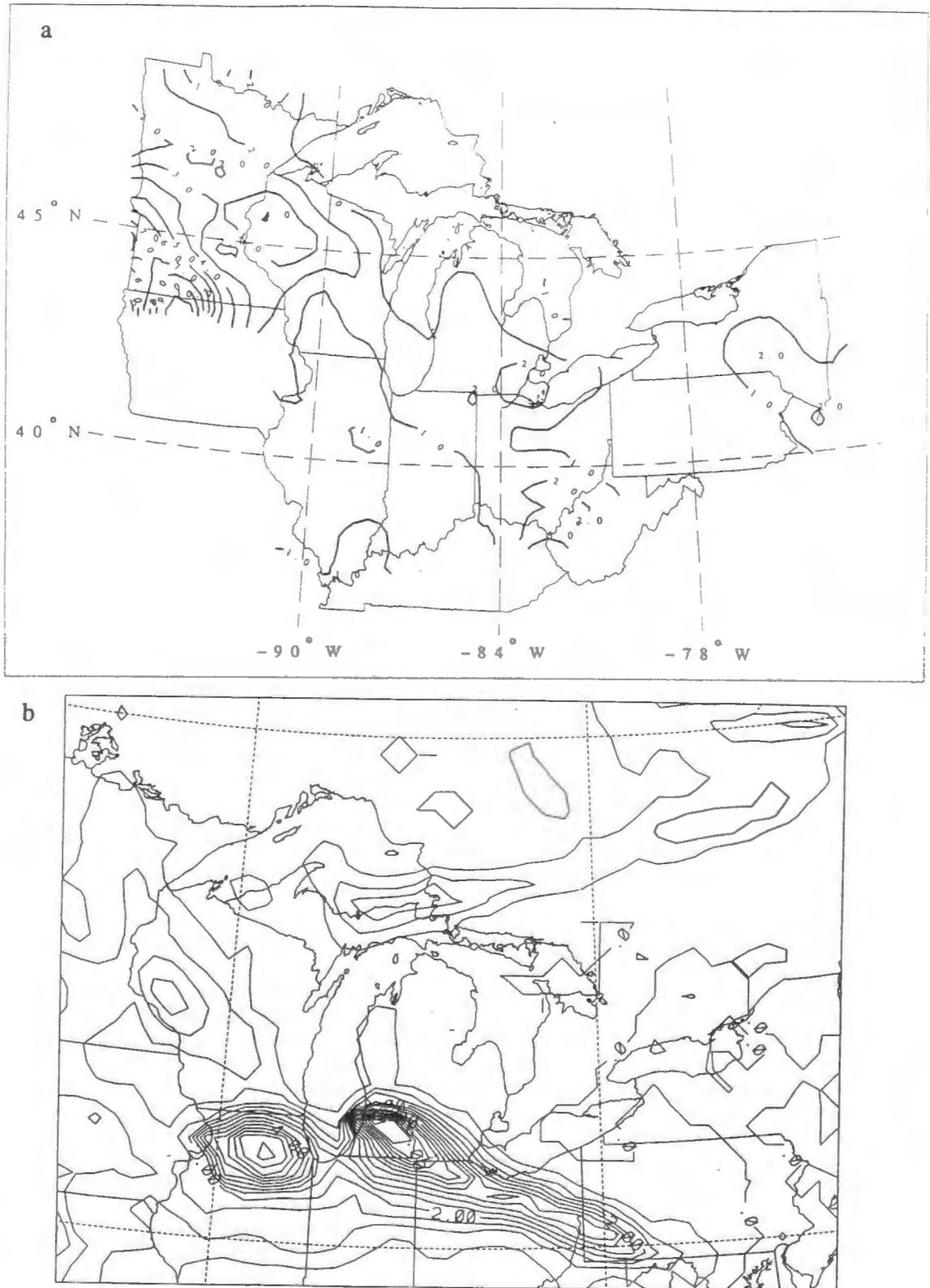


Fig. 2. (a) Observed and (b) simulated average precipitation for the period 1-10 June 1991. The contour interval is 1 mm/day. The observations are interpolated from station data at United States stations. The outermost 5 grid spaces of the model domain, in which observed lateral boundary conditions are imposed, are omitted.

each season, large-scale effects of the Great Lakes on atmospheric circulation over North America and the North Atlantic, and sensitivity of the atmosphere and surface to various perturbations in climate forcing, including greenhouse warming.

## 5. ACKNOWLEDGMENTS

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