11.11 SPATIALLY DISTRIBUTED WATER SURFACE TEMPERATURE MODELING FOR THE GREAT LAKES

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1. INTRODUCTION

A growing concern over the potential effects of a possible change in the future climate continues to motivate research into cycles, variability, and trends in the temperatures of the Great Lakes. These temperatures have a major influence on the water balance of the Great Lakes watershed through evaporation and the forcing of atmospheric effects. Before a future temperature structure and cycle can be estimated, the present water temperature climatology must be sucessfully simulated. On the other hand, evaporation estimates for the Great Lakes require water surface temperature data over long time periods. The simulation of water surface temperature has long been recognized as an important tool for lake resource management.

Models with varying degrees of complexity have been generated to fill this role. GLERL developed a one-dimensional heat storage model and one-dimensional ice thermodynamic model for the Great Lakes (Croley, 1989, 1992; Croley and Assel, 1994), which provides multiple, long-period and continuous simulations for mixed-layer development, water column turnover, heat-temperature hysteresis, seasonal heating and cooling cycles, ice thickness, and ice concentration. Hostetler and Bartlein (1990) presented and validated a one-dimensional eddy diffusion model for simulating the seasonal variation in lake temperature and evaporation.

In the past, there were insufficient data describing temperature distribution from observations, so the above models did not consider the spatial variation of the surface temperature. In reality, the lake surface temperature is spatially and temporally variable, reflecting (and influencing) variations in the net heat input and lake hydrodynamics. Improved algorithms are now available for extrapolating overlake winds from a limited number of shore locations (Schwab, 1989), observations of spatially distributed lake temperatures from NOAA/AVHRR satellites (Schwab et al., 1992) and existing ice cover data (Assel, 1983). They enable development of spatially distributed water temperature models and ice cover models for the Great Lakes.

In this paper, we describe the development of a spatially distributed thermodynamic model which includes a water temperature model and an ice cover model. It will provide a tool for simulating and forecasting spatially distributed temperature and ice cover for the Great Lakes on a seasonal to interannual time scale. As such, it will serve as a component of the Great Lakes Advanced Hydrologic Prediction System (Croley, 1998) for producing probabilistic outlooks of hydrologic state variables over multi-seasonal timescales. It will also be a component of the Coupled Hydrosphere-Atmosphere Research Model (Lofgren and Croley, 1995) for simulation of possible climatic scenarios.

2. MODEL DESCRIPTION

The water temperature model is based on a 1-D eddy diffusion model in which the vertical transfer of heat is simulated by eddy conductivity and convective mixing (Hostetler and Bartlein, 1990). The model is run at each grid point and provides a simulation of the spatially distributed surface temperature. The Great" Lakes experience significant ice cover during the winter season. In order to continue temperature and evaporation simulation throughout the year, a lake ice model (Patterson and

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Hamblin, 1988) is coupled with the water temperature model.

The thermodynamic model incorporates the physics and thermodynamics that govern the flow of heat among water, ice, and the atmosphere. The model uses as input air temperature, dew point temperature, wind speed, and cloud cover. The formulation of the energy fluxes at the water and ice surface is taken from Quinn (1979) and Croley (1989). As overwater data are not available generally, overland data are used with a correction for overwater conditions. A full-depth convective mixing scheme is included in the model, based on the assumption that static instabilities due to temperature variation will not exist in freshwater lakes for any extended period of time. Instabilities are eliminated by mixing the excess heat into adjacent layers of the lake.

The model was run at grid points of 10 km resolution, with depth determined from the bathymetric data. Isothermal initial conditions were used.

3. SATELLITE AND METEOROLOGICAL DATA PROCESSING

Water surface temperature images, derived from the NOAA/AVHRR satellite instrument, are available to GLERL through its CoastWatch program on an operational basis from 1990 to present. The satellite images are mapped to a Mercator projection and resampled to a 512x 512 grid with 2.56 km resolution. We interpolated these data onto the 10 ISm grid.

Meteorological observational data from stations in the Great Lakes region were routinely collected from 1948 to 1995 at one-day intervals. The observational network is comprised of 100 fixed stations, including 85 U.S. stations and 15 Canada stations. Data on air temperature, wind speed, humidity, and cloud cover were taken from these stations surrounding each lake. In order to ensure the quality of the database, the stations were chosen to give an areally balanced distribution about each lake with as complete a record as possible for the period 1948-1995.

We used an inverse distance weighting technique to interpolate meteorological variables onto the model grid and developed daily gridded fields for the meteorological variables for many years. These gridded data were then used as input for the model.

4. MODEL RESULTS

We conducted a simulation from April 1991 to December 1995 and made a comparison between simulated water surface temperature and satellite observed temperature. To conserve space in this paper, we will only give the result of the simulation for Lake Michigan in 1993. Model runs for other lakes are pending. There are a total of 27 x 52 grid points of water representing Lake Michigan. The time step adopted in the model is 1 hour. To conceptually account for transport of heat by 3-dimensional dynamics, the heat fluxes at the water-atmosphere interface are adjusted by amounts that vary seasonally and geographically. These adjustments do not change from one year to the next (Manabe et al., 1992).

Figure la shows the simulated surface temperature for October 28, 1993. The output of the model indicates that in fall, the surface temperature increases from the western lake to the eastern lake and produces a minimum at the west-central area of Lake Michigan. Because the west wind dominates during that season, the surface current has an eastward component and brings warm water from west to east. upwelling of water from depth causes cooling of the surface in the western take. These dynamical considerations are qualitatively accounted for by the prescribed heat flux adjustment described in the previous paragraph. Using these adjustments, the simulated spatial pattern of water surface temperature compares well with the satellite observations (Figure ib).

Figures 2a and 2b compare the distribution of simulated and satellite observed temperatures for May 9, 1993. They reveal that in spring, there is a minimum in surface temperature in the deep water areas, and surface temperature increases more quickly in nearshore areas than offshore areas. The model basically produces a good simulation of water surface temperature during the spring turnover period, but it overestimates the temperature in the deep water areas.

The geographical distribution of surface temperature does not deviate significantly

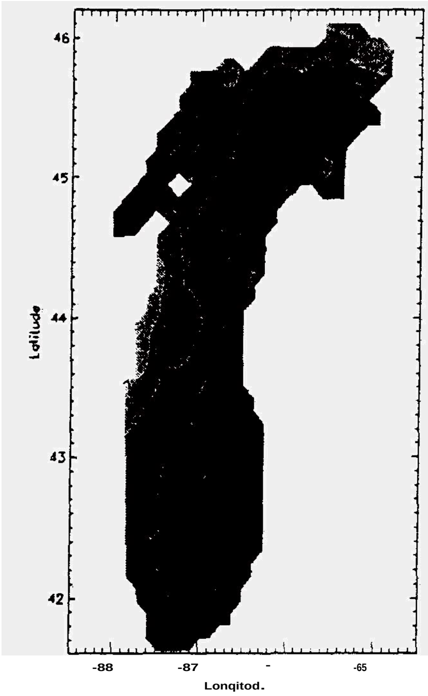

Figure la. Simulated surface temperature for Lake Michigan on October 28, 1993. Contour interval of 1 C.

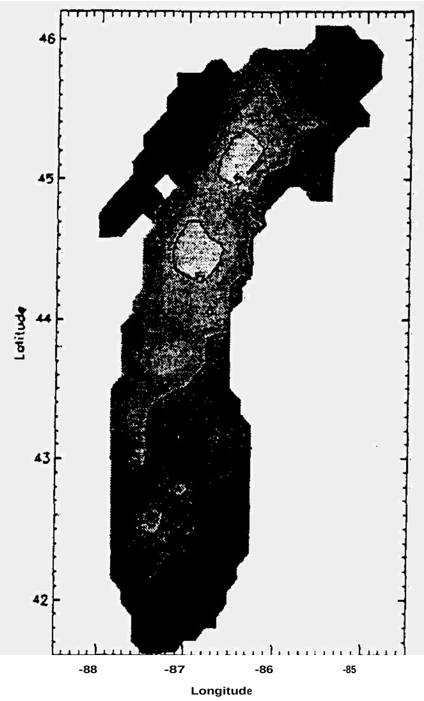

Figure 2a. Simulated surface temperature for Lake Michigan on May 9, 1993. Contour interval of 2°C.

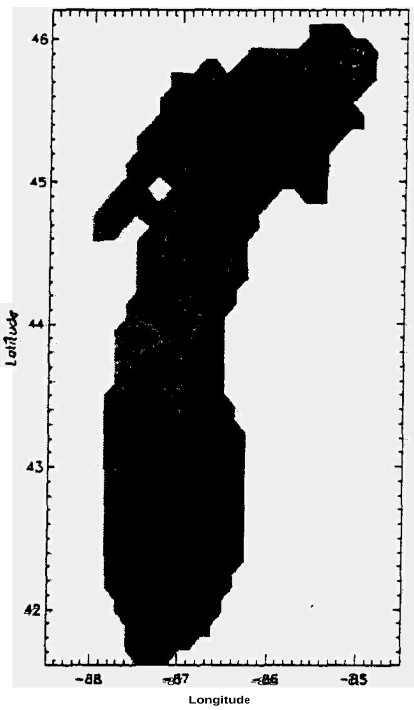

Figure lb. Satellite observed surface temperature for Lake Michigan on October 28, 1993. Contour interval of 1 C.

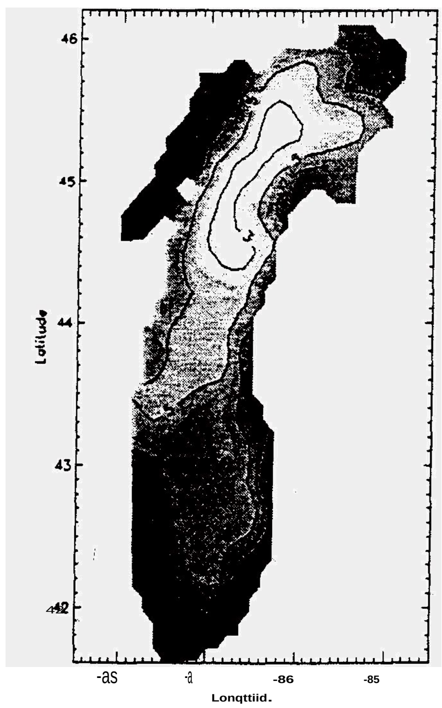

Figure 2b. Satellite observed surface temperature for Lake Michigan on May 9, 1993. Contour interval of 2 C.

from the satellite observation. In addition, the model is numerically stable over long periods and runs with sufficient speed for long-term simulation.

5. SUMMARY

This paper describes the development and validation of a water temperature model for the Great Lakes. This model is keyed to simulate horizontally and temporally varying surface temperature. An ice cover model is coupled with the water temperature model, forming a spatially distributed thermodynamic model for the Great Lakes. This model can be used to give long-term or short-term simulations of water surface temperature and ice cover for the Great Lakes.

In addition to the experiments discussed in this paper, we calculated the Root-Mean-Square-Error (RMSE) between model simulated output and satellite observations. The values of RMSE are generally around 1.0 C. RMSEs deviate a little more during the spring turnover period. Further work is necessary to reduce the RMSEs by improving the model, especially improving ice cover simulation.

6. ACKNOWLEDGMENTS

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