TEMPERATURE AND ENERGY FLUX PATTERNS AT THE GREAT LAKES WATER SURFACE

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ABSTRACT
A two-dimensional thermodynamic model was developed that uses meteorological measurements and satellite-derived surface temperatures to estimate energy flux patterns at the water surface. The model is used in either a simulation mode or a real-time mode. The simulation mode uses the two-dimensional model in combination with GLERL's one-dimensional lumped evaporation and heat storage model to simulate past daily energy flux patterns. The real-time mode uses daily surface temperature patterns derived from cloud-free NOAA/AVHRR satellite images. The model was tested in the simulation mode for a 30-year period. The energy fluxes (shortwave radiation, net longwave radiation, latent and sensible heat flux, and advection) were calculated for each day and gridpoint, and an average value for each day of the year was calculated from the 30-year period. Long-term energy fluxes should balance; indeed the 30-year average is within ± 5.0 W/m² on all lakes, except Superior (-11.3 W/m²).

1.0 INTRODUCTION

Knowledge of energy fluxes at the water surface is crucial to understand a multitude of processes in a lake and its environment. Evaporation is a major part of the water balance equation. In the Great Lakes region, evaporation is in the same order of magnitude as precipitation and runoff. It therefore represents a significant component of the Great Lakes hydrologic cycle. Models of the spatial structure and distribution of energy fluxes and evaporation are essential to understand mesoscale and local atmospheric, limnologic, and hydrologic processes.

Most existing models which describe the energy exchange between the water and the atmosphere treat the lake as a homogeneous entity without spatial variations (Scherzer, 1987; Marti et al., 1986; Barry et al., 1983, Croley, 1989). However, meteorological and limnological parameters that determine the energy fluxes are spatially and temporally variable. While the temporal variability of the energy fluxes and the energy balance is well known from a multitude of studies and measuring sites, the spatial patterns of the thermodynamic fluxes however are not well investigated (Schneider et al., 1990).

Estimating the energy fluxes at the water surface requires knowledge of surface temperature and ice cover. These two parameters are not generally measured at limnological or meteorological sites. Remote sensing techniques render direct and synoptical measurements of the whole lake surface and, given an unobscured view to the lake surface, facilitate the determination of mean lake wide surface temperature and ice cover. Alternatively, modeling surface energy fluxes and heat storage in a lake (Croley, 1989, Barry et al., 1983) can enable one to track surface temperature and ice cover. However, these models do not provide spatial patterns of these parameters.

The main obstacle in developing two-dimensional energy flux models is the lack of two-dimensional data sets, especially of water surface temperature and ice cover maps. With the advent of remote sensing satellites two-dimensional surface temperature data now are available. By combining two-dimensional surface temperature and ice cover data with two-dimensional meteorological data sets, we have the means to calculate the energy flux patterns directly rather than interpolate patterns from point measurements (Schneider, 1992; Schneider and Mauser, 1992).

A model is desired to estimate the spatial patterns of temperature, ice cover, evaporation and energy fluxes. To enable long-term simulations, the model must be computationally inexpensive, and restricted to widely available meteorological data sets. The model must be able to use available remotely sensed surface temperature and ice cover data for real-time calculations of the energy fluxes and its patterns. As a first effort, a newly developed two-dimensional energy flux model was combined with an existing lumped evaporation model to estimate Great Lakes surface temperature patterns in simulation and forecasting modes.

2.0 THERMODYNAMIC MODEL

The total energy exchange \( Q_{tot} \) between atmosphere and lake surface can be expressed as:

\[
Q_{tot} = Q_i - Q_r + Q_a - Q_s + Q_e + Q_l + Q_o
\]  

where \( Q_i \) is the incident shortwave radiation, \( Q_r \) is the shortwave radiation reflected from the water surface, \( Q_a \) is the net longwave radiation, \( Q_s \) and \( Q_l \) are the latent and sensible heat transfer, respectively, \( Q_e \) is the energy exchange by advection due to precipitation or evaporation, \( Q_o \) are other terms (geothermal heat transfer, kinetic energy exchange by wind) which are neglected here. Given the required meteorological and limnological parameters, the heat fluxes can be calculated for each gridpoint, yielding two-dimensional patterns based on direct calculation, rather than spatial interpolation of fluxes at selected points. The formulation of the energy fluxes is described in more detail elsewhere (Schneider and Croley, 1994). The two-dimensional thermodynamic model discussed here calculates the energy fluxes for each gridpoint using only generally available meteorological data (air temperature, dewpoint temperature, cloud cover, wind speed) and water surface temperature and ice cover. The meteorological data are routinely measured at different measuring sites around the lake and spatial patterns may be extrapolated utilizing statistical methods.

Water surface temperatures are available at GLERL from airborne and satellite observations. However, the utility of remotely-sensed surface temperature measurements for evaporation and heat flux estimates is limited due to several reasons. First, remotely-sensed data require a multitude of processing steps including calibration of the data, geocorrection, atmospheric correction, cloud detection and masking. This processing often can not be performed by research and planning agencies without special remote sensing equipment and expertise. Second, remote sensing data are limited to cloud free weather conditions. Third, remote sensing is a relatively new data acquisition method so that long-term data bases are not generally available.

Comparisons of surface temperature patterns from different years reveal that they are very similar from year to year. For instance spring-warmup creates patterns closely related to the bathymetry of the lake. With increasing thickness of the well mixed and homogeneous epilimnion in summer and fall, patterns related to lake circulation and, thus, to the mean wind direction prevail. Winter patterns reveal small horizontal temperature gradients from warm areas in deep lake parts (due to high energy storage) to cool in the shallow parts. While daily temperature patterns are sometimes strongly influenced by the current meteorological situation, weekly or monthly temperature patterns are virtually stable from year to year. This observation suggests the use of a long-term "normal" temperature and ice cover data base to define the horizontal temperature and ice cover patterns, for the simulation of energy fluxes if actual observations of surface temperature and ice cover are not available. The "normal" values would be calculated as long-term averages, for each day of the year, for each grid defining the spatial domain of.
3.1 SATELLITE IMAGE PROCESSING

Surface temperature images derived from the NOAA/AVHRR satellite have been available to GLERL through its CoastWatch program on an operational basis since 1990. To prepare the datasets required by the two-dimensional energy flux model several processing steps have to be performed and are briefly discussed here.

The satellite images received by GLERL are calibrated, quality controlled, earth located and atmospherically corrected by NOAA’s National Environmental Satellite, Data, and Information Service (NESDIS), mapped to a Mercator projection, and resampled to a 512x512 pixel grid (Maturi et al., 1993). Only fully atmospheric corrected images of NOAA/AVHRR-11 were used in this study.

GLERL’s basic satellite data set consists of AVHRR lake surface temperature maps. Albedo measurements of band 1 and 2 are frequently available. The mapping of the satellite data to a Mercator projection is based upon satellite orbital data. Errors in the orbital parameters can lead to mapping inaccuracies usually of 5 to 10 km (Leshkevich et al., 1993). These errors are corrected with an automatic correction algorithm (Schwab et al., 1992).

Figure 2 gives an overview over the processing steps performed to derive cloud free water surface temperature data from CoastWatch satellite images. The data received by GLERL have not been tested for cloud contamination. To extract meaningful lake surface temperature data from these satellite measurements, the data are tested for cloud cover and cloud contamination by using a four-step automatic cloud testing procedure. Cloud free lake surface temperatures for each lake is extracted from the original satellite images and used in further image processing steps if at least 33% of the lake surface tested cloud free. Small cloud-contaminated areas are filled using an inverse square distance weighting method, by averaging cloud-free pixels located within a maximum distance of 7 pixels from the cloud contaminated grid point. The results of these automatic processing steps are visually checked and corrections are performed manually, if necessary.

Cloud free CoastWatch images and images acquired by the Atmospheric Environment Service Canada (AES) (Irbe, 1993) where used together with the normal ice cover described in the NOAA Great lakes Ice Atlas (Assel et al., 1983) to build a normal temperature and ice cover data base for the Great Lakes. Processing of the normal
the lake surface. The use of such normal patterns is only admissible for monthly simulations or for averaging monthly simulations over many years. Shorter time intervals can result in large differences between the actual and these normal patterns.

Figure 1 outlines the main components of the two dimensional thermodynamic model. The model uses meteorological measurements from different sites and either satellite-derived surface temperatures (real-time mode) or normal temperatures and ice cover and a lumped heat storage model (simulation mode) to estimate energy flux patterns at the water surface.

![Diagram of the energy balance model](image)

**Figure 1 Outline of the Energy Balance Model**

### 3.0 DATA PROCESSING AND DATA SOURCES

The energy fluxes at the Great Lakes water surface and their spatial patterns are calculated on a daily basis using gridded meteorological and limnological data. To maintain compatibility with the CoastWatch satellite temperature images, the grid and projection used for the CoastWatch full region is used here. The grid cell size is 2.56 km at mid-latitude mapped to a Mercator projection. Meteorological measurements from different measuring sites around the lakes are used to extrapolate meteorological input parameters for each gridpoint.
temperature and ice cover data base is described in detail elsewhere (Schneider et al., 1993). This data base is used in the simulation mode in conjunction with modeled mean lakewide surface temperature to define the spatial patterns of water temperature and ice cover.

In the real-time mode daily temperature and ice cover patterns are required by the energy balance program. Due to cloud cover, the satellite measurements are inhomogeneous in space and time. To derive a homogeneous surface temperature data set from the satellite images, all cloud contaminated pixels in images with 33 or more percent cloud free surface area are filled by extrapolating the spatial pattern from previous or following images. NOAA/AVHRR satellites enable two surface temperature images per day (daytime and night time overflight), during cloud free periods. However, clouds frequently prevent surface temperature observations totally. The two dimensional thermodynamic model requires temporally homogeneous data sets. Therefore temperature patterns must be extrapolated from cloud free satellite observations for days when clouds prevented remote measurements. Frequently only one image, daytime or nighttime image, is available. Using daytime or nighttime satellite observations only results in considerable differences between mean daily temperature and actually satellite derived temperature. To better estimate the mean daily temperature, the temperature patterns where defined by a weighted gliding mean over three or more satellite observations previous to and after the day of interest. This procedure gives temperature values which are closer to the actual daily mean, reduces residual cloud contamination and enables extrapolation of temperature patterns if no observation was available on the day of interest.

3.2 EXTRAPOLATION OF METEOROLOGICAL PATTERNS

Daily meteorological measurements from different measuring sites around the lake were used to generate spatial patterns of meteorological parameters. Up to twelve meteorological measuring sites were used to extrapolate the spatial structure. As overwater meteorological data are not generally available, overland data are used and corrected for overwater conditions.

The overland measurements are extrapolated for each grid point using a weighted mean. The weight \( w_i \) is proportional to the inverse square distance of grid point and measuring site. Figure 3 illustrates the extrapolation technique for the meteorological measurements for Lake Erie.

The meteorological parameter for a given grid point is estimated from the overland meteorological measurements using the following equation:

\[
W_{(x,y)} = f \left( \sum_{i=1}^{N} w_i * L_i \right)
\]

where \( W_{(x,y)} \) is the meteorological parameter over water at grid point \((x,y)\), \( f \) is the overwater correction function, \( w_i \) is the weight at gridpoint \(x,y\) for meteorological measuring site \(i\), \( L_i \) is the meteorological parameter measured at site \(i\) and \(N\) is the number of meteorological sites.

The weight for each station is expressed as:

\[
w_i = \frac{x_i^{-2}}{\sum_{i=1}^{N} x_i^{-2}}
\]

where \( x_i \) is the distance between meteorological site and grid point.
The correction of overland meteorological data is based on a study by Phillips and Irbe (1978) who studied overwater data available from specially placed data buoys on Lake Ontario during the International Field Year for the Great Lakes (IFYGL). Phillips and Irbe (1978) related overwater data to air stability, fetch length in the wind direction, overland wind speed, duration of air overwater, overland air temperature, surface temperature and overland dew point temperature. Their regressions for overwater corrections are used here by replacing the fetch (and derived quantities) with averages over the data set for each stability class, similar to other efforts (Derecki, 1981).

4.0 DEFINITION OF DAILY TEMPERATURE AND ICE COVER PATTERNS

Lake surface temperature is the integrated expression of past meteorology. Compared to the spatial patterns of meteorological parameters, lake surface temperature patterns change rather slowly, due to the high heat capacity and the high density of water. While the temporal course of heating and cooling of the lake slightly shifts from year to year, the temperature patterns typical for a given phase in the annual heating and cooling cycle are very similar from year to year. This does not imply, that a comparison of temperature patterns on a day by day basis from multiple years reveals the exact same spatial patterns. The daily spatial patterns are very much affected by the actual meteorological situation. Nevertheless, the dominant temperature patterns of a longer time period (weeks, months) are very similar each year. This observation is the basis for deriving two dimensional temperature patterns for use in the absence of actual remote sensing data. Assignment of temperatures from a statistical database (derived from multiyear observations) allows derivation of spatial patterns without detailed models of lake dynamics or explicit measurements of surface temperature patterns.

We used the following approach to define temperature and ice cover at each grid point and day of the simulation period. The daily spatial mean temperature and ice cover were modeled by using GLERL's one-dimensional evaporation and heat storage model (Croley, 1989, 1992). This model solves the energy flux and heat storage equations. In the ice free period, the normal temperature and ice cover data base is searched to find the mean normal temperature that best fits the modelled mean. Each mean temperature value except for the minimum and
maximum temperature occurs at least twice per year, once in the heating period and once in the cooling period. The temperature patterns in the heating period however are very different from the temperature patterns in the cooling period. Thus, the search is limited to a period of 30 days before and 30 days after the day of the year being processed, to make sure that the assigned temperature pattern agrees with the annual heating and cooling cycle.

Figure 4 illustrates the assignment of temperature and ice cover patterns for an arbitrary lake. The lumped evaporation and energy flux model calculated a mean lakewide temperature of 9.71°C for 24 May 1970. Searching the normal temperature data set 30 days prior and 30 days after 24 May (hatched area) yielded the best match on day 132 of the normal annual cycle (12 May) with a temperature value of 9.75°C. The temperature of each grid point was taken from day 132 of the normal temperature image and decreased by 0.04°C to exactly match the modeled mean.

The lumped evaporation model assumes, that ice only forms when the lake-wide mean surface temperature reaches 0°C. Thus during the ice covered period, the mean lakewide temperature cannot be used to find the appropriate temperature and ice cover pattern. The mean lakewide ice cover is used instead. Similar to temperature development, ice cover patterns during the freeze up period are different from ice cover patterns during the melting period. Thus, the normal ice cover is searched for the pattern with the smallest difference with the mean modeled ice cover and a comparable temporal position between first and last ice day.
The best temporal match is defined as the day with the same relative distance between first and last ice day. The normal data set is then searched for 30 days before to 30 days after the best temporal match day. Figure 4 shows the assignment of the ice cover pattern to a modeled lake-wide mean ice cover of 45.5% on 3 Jan. 1970. The length of the normal ice covered period is 110 days with the first ice day on day number 351 (17 December). The model indicated 115 ice-covered days with the first ice day on 29 December. The best temporal match to 3 January 1970 is day 357 (23 December). The normal data set is searched for the best match of mean lake-wide ice cover between day 351 (only 6 days prior to the best temporal match, since search is restricted by ice onset) and day 22 (30 days after the best temporal match). The best match was found on day 358 of the normal annual cycle (24 December) with a normal ice cover of 45.1%. The ice cover of each grid point was taken from day 358 of the normal ice cover image and increased 0.4% to exactly match the modeled mean.

5.0 APPLICATION

The two dimensional thermodynamic model was used and tested in the simulation mode for all Great Lakes including Lake St.Clair for a 30 year period (1956-1985) to define the long term mean patterns of energy fluxes, evaporation and heat balance. Figure 5 shows the location of the meteorological sites used to model the horizontal patterns of the meteorological parameter. Mean lake-wide surface temperature and ice cover for each day of the year from 1956 to 1985 were modeled by using GLERL's lumped evaporation and heat storage model. These mean lake-wide values were combined with the normal temperature and ice cover of the Great Lakes to define the
two-dimensional structure of temperature and ice cover. The energy fluxes (shortwave radiation, net longwave radiation, latent and sensible heat, and advection) then were calculated from the 30-year period. Table 1 shows the mean, standard deviation, minimum and maximum of the two dimensional annual energy balance, energy fluxes, and evaporation for each Great Lake, including Lake St. Clair. Lake Huron and Georgian Bay are separated by a shallow bar and they develop different temperature profiles, surface temperatures, and ice cover. These lakes therefore are treated separately.

Long-term energy fluxes should balance; indeed the 30-year average is zero, within ±5.0 W/m² on all lakes except Superior (Table 1). The 30 year average energy balance for Lake Ontario, Lake Erie, and Lake Michigan is better than 2 W/m². The positive energy balance in Lake St. Clair can be attributed to neglecting lake inflow and outflow. Lake St. Clair is the smallest and shallowest lake and is more affected by heat advection. The outflow of Lake St. Clair is warmer than the inflow, resulting in a negative net energy flux which is being ignored. The negative long-term mean energy balance for Lake Huron, Georgian Bay and especially Lake Superior, are most likely due to errors in surface temperature introduced in the matching of modeled and normal ice cover. Ice cover in the one dimensional evaporation and heat storage model can only exist if the mean lakewide water surface temperature is equal to 0°C. However, significant ice cover is observed on the lakes at temperatures greater than 0°C and this is reflected in the normal ice cover data base. Thus, matching the ice cover predicted by the one dimensional model with the normal ice cover results in mean lakewide surface temperatures higher than 0°C, which leads to increased sensible and latent heat fluxes as well as net longwave radiation.

Spatial differences of the energy balance (Maximum in Table 1 minus the minimum) exceed 25 W/m² for all lakes. Lake Huron has the largest spatial differences the energy balance of 50 W/m². Lake Michigan and Lake Superior are very similar with 44.7 and 44.6 W/m², respectively. Significantly smaller horizontal energy balance differences were calculated for Lake Ontario (29.9 W/m²) and Lake Erie (25.8 W/m²). Spatial differences of the energy balance are maintained by the transport of water and energy due to lake circulation.

A comparison of the standard deviation of the energy balance pattern with the energy flux patterns reveals, that the latent heat flux exhibits the largest part of the energy balance variation, indicating that latent heat flux patterns are very important for understanding the energy balance spatial pattern. Lake Huron and Lake Superior show also high standard deviation for the incident radiation pattern. The standard deviation of all other energy fluxes, reflected radiation, and net longwave radiation are only a small fraction of the energy balance spatial variation.

### 6.0 DISCUSSION

A model was presented which uses remote sensing data to estimate the energy fluxes at the water surface. The model was tested in the simulation model for a 30 year period. For most lakes the mean annual energy balance is well balanced, which supports the validity of the energy flux formulation. Modeled long-term heat storage and evaporation are in good agreement with values in the literature (Hutchinson, 1957; Derecki, 1976; Scherzer, 1978). Results of a similar two dimensional energy flux calculations for Lake Constance/Germany support the validity of the strong dependency of the energy balance patterns from the latent heat flux (Schneider, 1992).

The negative long-term energy balance for Lake Superior results from model deficiencies; the one-dimensional evaporation and heat flux model (lumped model) predict ice cover only for a mean temperatures of 0°C. In the two-dimensional model, ice cover exists in some places (at a water temperature of 0°C) with ice-free water in other places (at water temperatures exceeding 0°C), yielding a lake-wide mean greater than 0°C. This results in higher energy losses than for the 0°C water assumed in the lumped model for the same ice cover, due to increased latent and sensible heat flux and increased net longwave radiation losses. The lumped model (used to determine mean lakewide surface temperature and ice cover) underestimates the ice cover especially during freezeup and meltdown periods. As the two dimensional surface temperature and ice cover patterns indicate, mean lakewide temperatures frequently exceed 0°C even though considerable ice cover can be observed.
Table 1 30 year annual average energy balance, energy fluxes and evaporation
Energy fluxes in W/m², Evaporation in mm

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</tbody>
</table>
The energy balance patterns apparently are determined through most of the year by latent heat flux patterns. In winter and spring, sensible heat flux and reflected radiation contributes largely to the patterns of the energy balance. Ice cover patterns have a significant influence upon patterns of sensible heat flux and reflected radiation. Surface temperature is an integrated expression of past meteorology and changes more slowly than meteorology. We observed that the patterns of sensible and latent heat were more similar to temperature patterns than to meteorological patterns. Therefore knowledge of water surface temperature patterns is crucial for determining energy flux patterns.

The meteorological data show simple patterns, which are a consequence of the spatial interpolation method used. These patterns, most likely, do not reflect the true spatial structure of the meteorology. Some meteorological parameters, such as cloud cover, are accessible to direct two-dimensional remote measurements. Other parameters can be better represented with improved spatial extrapolation models. Direct spatial measurements are preferred to modeled patterns. Spatial estimates of radiative fluxes can be improved considerably by including hourly cloud cover from GOES satellites.

Although we feel, that the surface temperature and ice cover patterns are adequately simulated for long-term estimates, a more sophisticated extrapolation of two-dimensional temperature and ice cover patterns will enable short-term simulations and forecasts. They will also enable simulation of atmospheric conditions different from those given for the normal temperature and ice cover data base. This "more-sophisticated" extrapolation should consider recent meteorology and limnology that affect water temperature and ice cover.

7.0 ACKNOWLEDGEMENTS

This work was completed while K. Schneider held a postdoctoral research fellowship of the National Research Council (NRC) and the Cooperative Institute of Limnological and Ecosystems Research (CILER) at NOAA/GLERL in Ann Arbor. Surface temperature images were available through NOAA's Coastal Ocean Program and the Canadian Atmospheric Environment Service. Special thanks go to D.J. Schwab, G.A. Leshkevich, and G.C. Muhr (GLERL) for the support with CoastWatch products. The technical support of T. Hunter (GLERL) is greatly appreciated.

8.0 LITERATURE


