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Modelling hourly rates of lake evaporation

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Abstract

The paper presents the initial results of a field study of open water evaporation carried out on three small- to medium-sized lakes in Western and Northern Canada. Lake evaporation was measured directly using eddy covariance equipment; profiles of wind speed, air temperature and humidity were also obtained over the water surfaces. Observations were made as well over the upwind land surface. Relationships were developed between the hourly rates of lake evaporation and those significant parameters (wind speed, land-water temperature and humidity contrasts, and the downwind distance from shore). The result is a relatively simple versatile model for estimating the hourly lake evaporation rates. The model was tested using two independent datasets. Results show that the modelled evaporation follows the observed values very well; the model follows the diurnal trends and responds correctly to sudden changes in environmental conditions.

1 Introduction

Evaporation from open water bodies is an important component of the hydrologic cycle for many watersheds. This is particularly true for boreal and northern regions, for example, in the Western Canadian Boreal region open water represents from 10% to 15% of the surface area; in portions of the Arctic shield open water can represent as much as 20% of the surface area. Open water bodies are distributed throughout these regions; they appear in sizes ranging from small ponds to "great lakes". Many of these lakes act as storage features in complex drainage basins. They can in fact become disconnected and isolated during extended periods of drought, in which case their hydrology becomes dominated by the vertical processes of precipitation and evaporation. The correct representation of the hydrological function of these water bodies is important to the hydrological modelling of these watersheds. Also, the effect of these water bodies on the regional climate needs to be correctly incorporated into the atmospheric and climate models. Since most hydrological and meteorological models operate with time steps of the order of an hour, a reliable approach to the calculation of hourly lake evaporation is necessary for both objectives.

Even though, evaporation from open water remains largely unmeasured as a course of routine, it is still estimated with limited confidence. The major source of difficulty is the fact that the required meteorological parameters are rarely measured over the water surfaces, and the thermal lag between the water and land surfaces renders the land-based measurements ineffective in the parameterization of open water evaporation.

Energy budget approaches, such as Morton's (1983) complementary relationship lake evaporation model, have not proven to be reliable for short-term applications. An appropriate formulation of the transfer processes occurring in the advective boundary layer is required. This was demonstrated by Weisman and Brutsaert (1973), who applied analytical solutions to the advection problem over open water for the unstable case. Blanken et al. (2000), in a study of evaporation over Great Bear Lake showed, that for daily periods, open water evaporation is governed by the wind speed and the vapour gradient over the water. Granger (2000) showed that lake evaporation is largely uncoupled from (or unsynchronized with) the land surface evapotranspiration. The land surface processes follow closely to the pattern of energy supply, and the partitioning of the net radiation is straightforward; the soil heat flux tends to be relatively small for most situations and the turbulent fluxes of sensible and latent heat, for the most part, behave in a similar manner. The partitioning of energy at a lake surface, on the other hand, is more complex. Because of radiation penetration, heat storage effects can be significant. The turbulent fluxes of sensible and latent heat are not necessarily in phase with the radiant energy supply, but are governed by the gradients of temperature and humidity in the boundary layer. These gradients are controlled both by water surface temperatures (affected by radiation and intermittent mixing of the water) and by the processes occurring at the upwind land surface (heating or cooling of the air and evapotranspiration). For these reasons, land surface data alone are insufficient to parameterize the lake evaporation. Information about the lake surface is also required.

Weisman and Brutsaert's (1973) analysis demonstrated that in an advective situation, as is the case for open water, the evaporation rate is not uniform over the water surface, but can increase or decrease from the leading edge. Their analytical solution provided for an evaporation rate that is a function of the distance from the upwind shore. Morton (1983) also provided a method for estimating the change in evaporation as a function of distance from shore for small water bodies. Mahrer and Assouline (1993), using a meso-scale model also demonstrated the horizontal variability of open water evaporation.

Granger (2000), using lake evaporation observations made over Big Quill Lake, in Saskatchewan, showed that the analytical solutions developed by Weisman and Brutsaert (1973) can be applied when the boundary layer over the lake is unstable (temperature decreasing with height). For stable conditions, however, these analytical expressions did not work well and an analysis of the advection under stable boundary layer conditions, such as those encountered over a lake during daytime heating of the adjacent land surface, is required. Assouline and Mahrer (1993) and Liu et al. (2009) also showed that the open water evaporation is greatly affected by the stability of the overlying air, which is governed by the land-water temperature contrast.

The purpose of the present study was to develop relationships between the short-term (hourly) evaporation rates from open water and those significant parameters: wind speed over the water, water surface temperature, the temperature and vapour pressure gradients over the water, atmospheric stability and upwind fetch distance.

2 Study sites

Three lakes, providing a range of fetch distances from 150 m to 11 000 m, were chosen for the study. The largest of these is Crean Lake, located within the Prince Albert National Park in Saskatchewan. A small island, near the centre of the lake provided a stable and secure platform for the instrumentation tower, with access to nearly the full spectrum of wind directions and a range of fetch distances from 3600 m to 11 000 m.

Observations at Crean Lake were obtained for the open water seasons from 2005 to 2008.

Landing Lake, near Yellowknife, NWT, with the instrument tower established on a rock outcrop in the lake, provided fetch distances ranging from 150 m to 900 m. Observations at Landing Lake were obtained for the period 2007 to 2008.

For the 2009 season, the northern portion of Whiteswan Lake (known as Whiteswan4), in Northern Saskatchewan was also instrumented; the instrument tower was set up on a long, narrow spit extending into the lake. This site provides fetch distances from 300 m to 4000 m.

For each lake, the instrumentation included a direct measurement of evaporation (using eddy covariance equipment), short-wave and net all-wave radiation, at least two levels of air temperature, humidity and wind speed, wind direction, and infrared water surface temperature. For each lake, a water temperature profile was established near the centre of the lake. Near each lake, an instrumented tower over the land surface (away from the edge of the lake) provided the necessary parameters: radiation fluxes and atmospheric parameters (wind speed, wind direction, air temperature and humidity). All parameters were recorded on half-hour intervals. Figure 1 shows the position of the instrumentation on each lake, and Table 1 presents the locations of the lake and land towers, as well as the size characteristics of the study lakes.

2.1 Data control and analysis

The turbulent fluxes of latent and sensible heat over the water surface were measured directly with an eddy covariance system, consisting of a three dimensional sonic anemometer and a krypton hygrometer. Some corrections were applied to the eddy covariance measurements; these included coordinate rotation (Kaimal and Finnigan, 1994) the WPL adjustment (Webb et al., 1980), adjustments for sonic path length, high frequency attenuation and sensor separation (Massman, 2000; Horst, 1997) and oxygen extinction for the krypton hygrometer. Data from the meteorological tower over the water surfaces allowed for a second, independent determination of lake evaporation using profile measurements of wind speed, air temperature and vapour pressure. Granger and Hedstrom (2006) showed that there is good agreement between the two methods. This allowed for additional quality control and gap-filling of the direct eddy flux measurements of evaporation. Wind speed, temperature and humidity data from the land tower provided the contrast between the land and water surfaces.

2.2 Modelling evaporation rates

All evaporation models are based on the representation and parameterization of one or more of the conditions required for evaporation to occur; these are:

- there must be a supply of water at the surface;
- there must be a source of energy to ensure the phase change from liquid to vapour, and
- there must be a transport mechanism to carry the water vapour away from the surface.

For land surface evaporation, most models in fact represent all three conditions; the moisture availability is parameterized using soil moisture or a "stomatal resistance", the net radiation absorbed at the surface is the available energy, and a vapour transfer function based on wind speed is applied. For lakes, however, the supply of water at the surface is non-varying, and so is not a useful parameter. Also, since the net radiation penetrates the water surface, the energy is absorbed at depth and is not immediately available for the phase change at the surface; there is likely very little relationship between the available energy and the turbulent exchanges of heat and water vapour in this case. This leaves only the vapour transport mechanism to work with in the development of an open water evaporation model.

The rate of evaporation from an open water surface is governed by the vapour pressure gradient above the surface and by the efficiency of the transport mechanism; the efficency of the exchange is controlled by the wind speed and the stability of the boundary layer. Since all small- to medium-sized lakes, or most open water surfaces, represent advective situations, the vertical humidity gradient is controlled by the horizontal gradients of temperature and moisture, or the lake-land contrast. Since most lakes are not uniform in shape, the fetch distance and wind direction may also be significant. These are the factors that were examined in the model development.

The approach used in the model development was one of successive regression: the most significant parameter was identified, and a relationship developed between it and the evaporation rate. The effects of the other parameters on the relationship were then incorporated in order of decreasing importance. Figure 2 demonstrates the relative importance of the following parameters on the hourly evaporation rates: wind speed, the land-water humidity contrast, the land-water temperature contrast, and the net radiation.

Figure 2a shows that, in fact, unlike that for land surfaces, there is very little relationship between the available energy and the hourly evaporation from open water. The wind speed shows, by far, the strongest relationship with evaporation. Although the vapour transfer function is defined by the vapour pressure gradient, the temperature gradient (or land-water temperature contrast) actually shows a stronger relationship; this is likely due to the strong effect of stability on the evaporation rates.

Hence, the model development proceeded from the relationship between wind speed and evaporation; this relationship was then modified to include the effects of the land-water temperature and humidity contrasts.

The data from Crean Lake (2006, 2007, 2008), Landing Lake (2007, 2008) and from Whiteswan4 Lake (2009) were used for the model development. The data were separated into stable and unstable categories; stable cases were defined as those for which the land-based air temperature was greater than the water surface temperature. Since lake evaporation includes advection, the effect of the fetch distance, or the distance travelled by the wind over the water, was also included in each step.

The relationship between the wind speed over the water surface, u, and the evaporation rate is the basis for the model. Although Fig. 2b shows a nonlinear over-all trend, for any specific set of conditions, such as a narrow range of land-water temperature difference, the relationship is linear:

$$E = a \cdot u \tag{1}$$

where u is the 2 m wind speed over the water [m/s]; E is expressed as an energy flux [W/m^2].

The coefficient, a, was determined as a function of the horizontal gradients (land-water contrast) of temperature and vapour pressure, and of the fetch distance over the open water.

$$\begin{aligned} a &= f(\partial T, \partial \mathrm{VP}, X) \\ \partial T &= T_{\mathrm{a(land)}} - T_{\mathrm{sf(water)}}, [^\circ\mathrm{C}] \\ \partial \mathrm{VP} &= \mathrm{VP}_{\mathrm{sf(water)}} - \mathrm{VP}_{\mathrm{a(land)}}, [\mathrm{kPa}] \\ X &= \mathrm{fetch} \cdot \mathrm{over} \cdot \mathrm{water}, [\mathrm{m}] \end{aligned}$$

The coefficient, a, takes the form:

$$a = b + m \cdot \partial T + n \cdot \partial \mathrm{VP} \tag{2}$$

Figure 3 shows the effect of fetch distance on the coefficients, m and n, respectively; the relationships for both stable and unstable conditions are shown.

For stable conditions over the water, i.e. $T_{\mathrm{a(land)}} > T_{\mathrm{sf(water)}}$:

$$\begin{aligned} b &= 3.395 + 0.0008 \cdot X \\ m &= -4.584 + 0.420 \cdot \ln(X) \\ n &= 20.256 - 0.0011 \cdot X \end{aligned} \tag{3}$$

For unstable conditions over the water, i.e. $T_{a(\text{land})} < T_{sf(\text{water})}$:

$$\begin{aligned} b &= 2.373 + 0.0002 \cdot X \\ m &= -1.758 + 0.0904 \cdot \ln(X) \\ n &= 26.525 - 0.0008 \cdot X \end{aligned} \tag{4}$$

Equations (1)–(4) represent a relatively simple series of expressions which can be applied to the calculation of hourly evaporation rates from open water; they require as inputs, the wind speed, the surface temperature of the water, the air temperature and humidity above the adjacent land, the wind direction and the relationship between lake fetch and wind direction are also required.

2.2.1 Model verification and discussion

Two datasets were available for the model verification. The first dataset included the evaporation data collected on Crean Lake in 2005. this dataset was not used in the model development since there was no land-based tower deployed adjacent to the lake during this first observation season. However, land-based data from the "Mixedwood" forest site, south of Waskesiu Lake, were still available and were used in the verification calculations. Although the Mixedwood tower is not adjacent to Crean Lake, the study, for which the tower had been deployed, showed that the boreal forest is relatively "uniform" in that the above-canopy temperature and humidity does not vary greatly over the region (Pomeroy et al., 1997). A second dataset involved the evaporation data collected over Quill Lake, Saskatchewan in 1993 (HEATMEX Experiment, unpublished).

Equations (1)–(4) were applied to the half-hourly observations from Crean Lake and the Mixedwood tower for the period May to September 2005. Figure 4 shows the comparison between measured and calculated half-hourly evaporation rates (expressed in energy units of W/m^2) over Crean Lake for 4 consecutive days. The figures show that the modelled evaporation follows the observed values very well: the model follows the diurnal trends and responds correctly to sudden changes in environmental conditions (13 and 14 August).

Figure 5a shows the comparison between measured and calculated evaporation rates (W/m^2) for all the time periods in the 2005 dataset; Fig. 5b shows the comparison between the calculated and measured cumulative seasonal evaporation, expressed in mm of water. Figure 5a shows excellent agreement, with an R^2 value of 0.86, for the 2250 data points. Figure 5b shows that the seasonal total modelled evaporation is in very close agreement with the observed evaporation, with a total divergence of 7 mm over 84 days between the two.

The model (Eqs. 1–4) was also applied to the hourly observations from the Quill Lake HEATMEX Experiment in 1993. The "measured" lake evaporation values were obtained using profile data from a tower located near the centre of the lake. For the Quill Lake test, the land-based data were obtained from an instrument tower located on the western shore of the lake. In this case, all calculations were made for hourly values.

Whereas Crean and Whiteswan4 Lakes are surrounded by boreal forest and Landing Lake (NWT) is surrounded by forest and rock, Quill Lake is a classic Prairie lake, surrounded by open fields and pasture land. For this reason also, Quill Lake represents a good test for the transferability of the model.

Figure 6 shows the comparison between measured and calculated hourly evaporation rates (W/m^2) over Quill Lake for 4 consecutive days in 1993. The figures show that the modelled evaporation follows the "measured" values very well; it also responds correctly to the diurnal variations as well as to sudden changes in environmental conditions (1 September).

Figure 7a shows the comparison between measured and calculated evaporation rates (W/m^2) for all the time periods in the 1993 dataset; Fig. 7b shows the comparison between the calculated and measured cumulative seasonal evaporation, expressed in mm of water. Although the comparison for the 1800 data points produces a smaller R^2 value (0.75) than for the Crean Lake data, the agreement is still very good. The seasonal total modelled evaporation is in very close agreement with the observed evaporation, with a total divergence of 8 mm over 75 days.

3 Summary and conclusions

Three successful field campaigns were carried out for measuring and modelling evaporation from Crean Lake.

The data collected, along with data from a smaller northern lake, allowed for the development of a model capable of calculating the lake evaporation rates for hourly time periods. The model validation, on Crean Lake for 2005 and on Quill Lake for 1993, showed that the model does provide accurate and reliable results. The modelled evaporation follows the observed values very well; it also responds correctly to the diurnal fluctuations as well as to sudden changes in environmental conditions.

Obtaining reliable hourly operational estimates of evaporation from individual lakes, using this method, is feasible if water surface temperature measurements are made available. Further study will be required to extend the limits of the model to lake fetches less than 150 m and exceeding 10 000 m. The application of this type of lake evaporation model within meteorological or climatological models will require the development of a technique for characterising lake size and shape.

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Table 1. Characteristics of three study lakes.

Lake	Observation period	Location of Flux Tower	Range of Fetch Dist.	Location of Land Tower	Distance to Land Tower
Crean Lake, PANP	2005	54.06353° N, 106.19170° W	3600 m–11 000 m	53.8926° N, 106.12066° W	19.2 km
Crean Lake, PANP	2006–2009	54.06353° N, 106.19170° W	3600 m–11 000 m	54.00806° N, 106.20035° W	6.2 km
Landing Lake, NWT	2007–2009	62.55915° N, 114.41365° W	150 m–900 m	62.59559° N, 114.43857° W	4.2 km
Whiteswan4 Lake, Sask.	2009	54.17640° N, 105.1642° W	300 m–4000 m	53.98711° N, 105.11773° W	21.3 km

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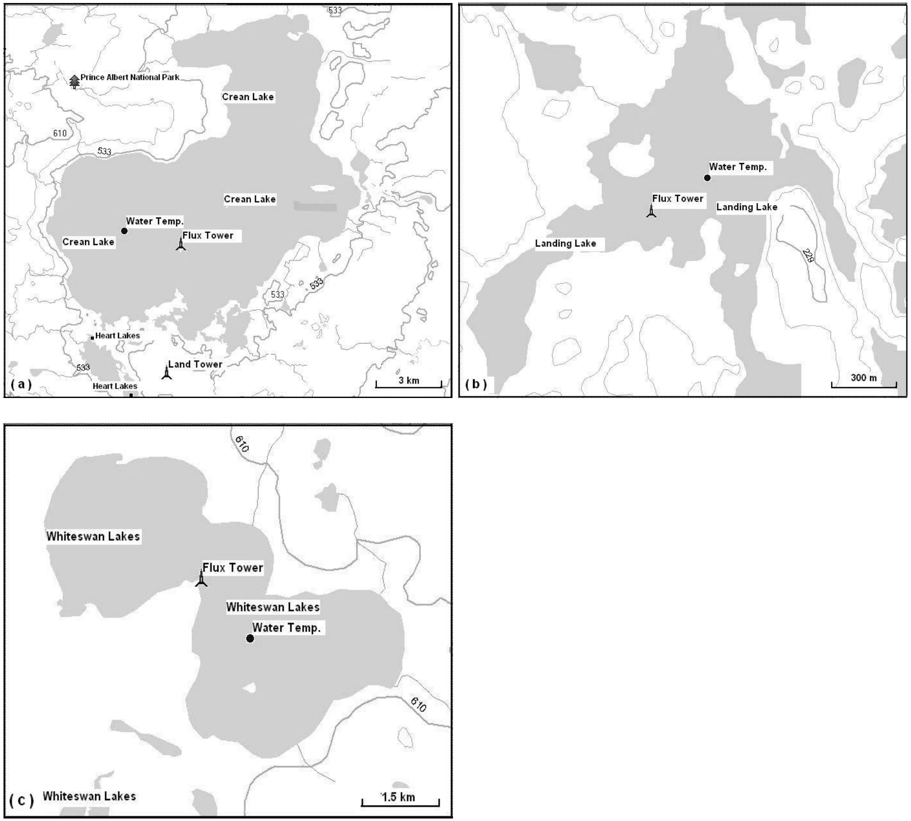

Fig. 1. Instrumented Lakes showing location of instrument towers; **(a)** Crean Lake, PANP, SK; **(b)** Landing Lake, NWT; **(c)** Whiteswan4 Lake, SK.

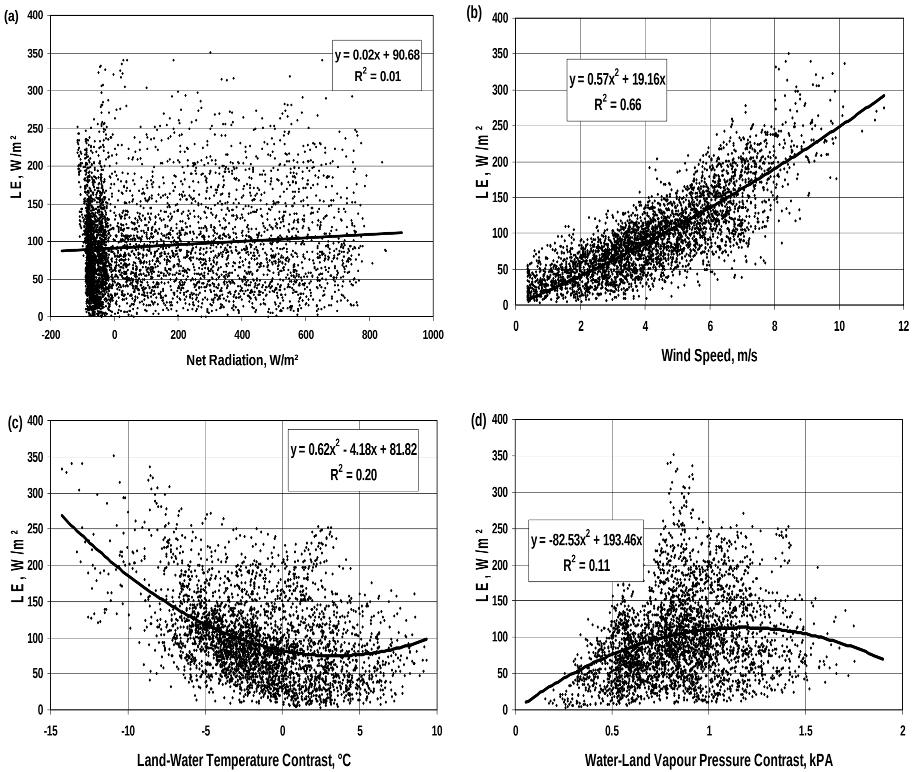

Fig. 2. The observed relationship between the hourly evaporation over Crean Lake, 2006, and **(a)** net radiation, **(b)** wind speed, **(c)** land-water temperature contrast, and **(d)** water-land vapour pressure contrast.

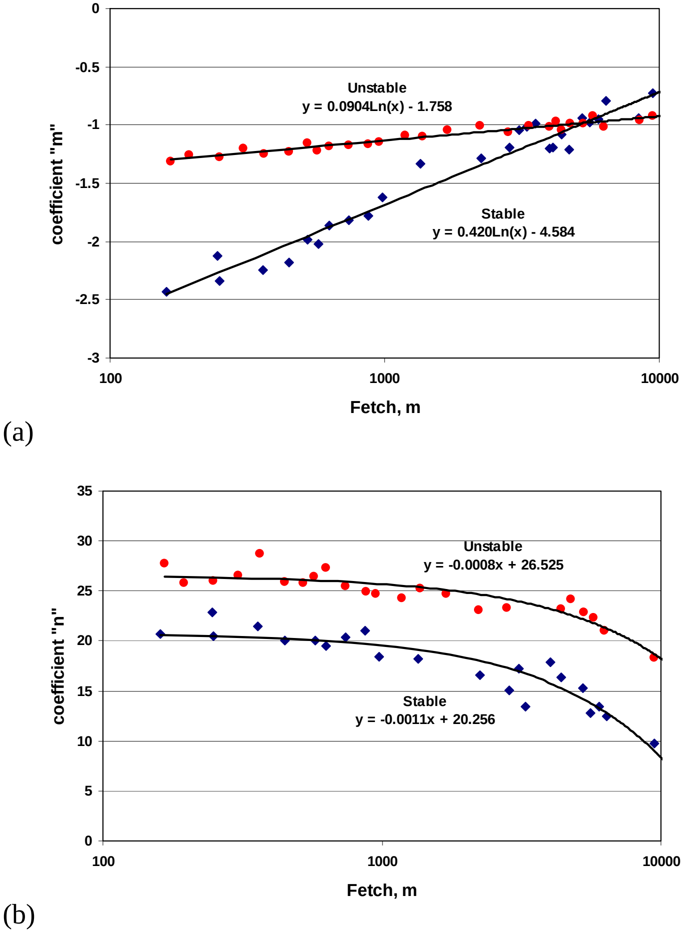

Fig. 3. The coefficients *m* and *n* (from Eq. 2) plotted against the fetch distance from the lake shore, for stable and unstable conditions.

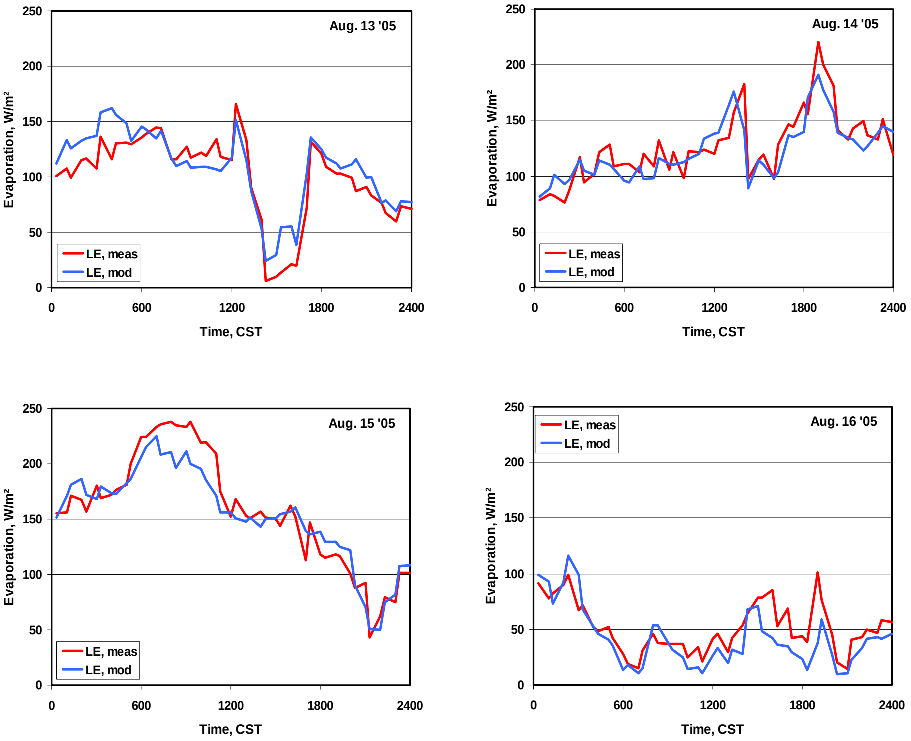

Fig. 4. The measured and calculated half-hourly evaporation rates for 4 consecutive days on Crean Lake (13–16 August 2005).

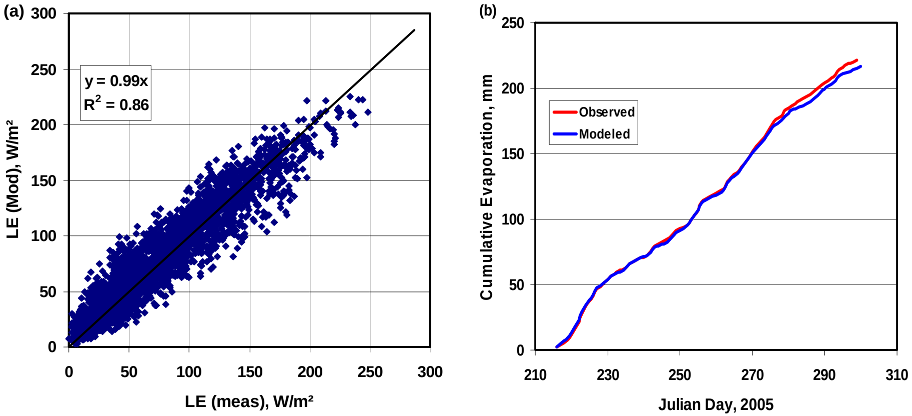

Fig. 5. Comparison between the measured and calculated evaporation from Crean Lake, 2005; **(a)** half-hourly evaporation rates, W/m^2; **(b)** cumulative evaporation, mm.

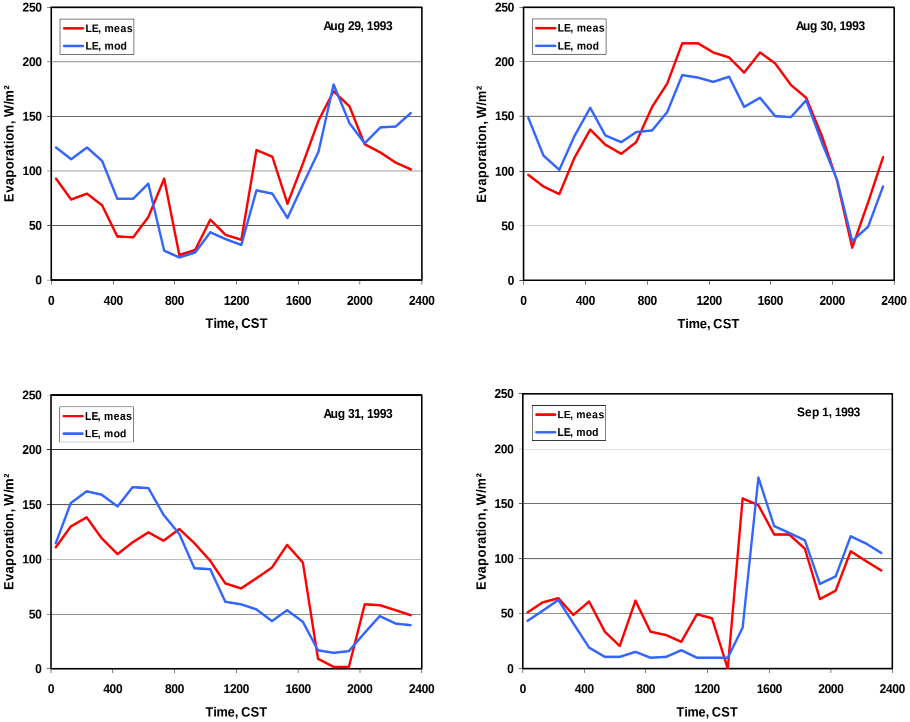

Fig. 6. The measured and calculated hourly evaporation rates for 4 consecutive days on Quill Lake (29 August–1 September 1993).

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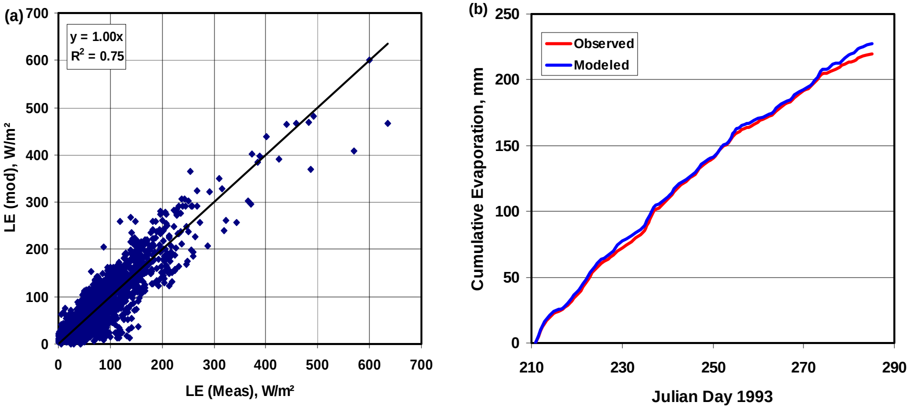

Fig. 7. Comparison between the measured and calculated evaporation from Quill Lake, 1993; **(a)** hourly evaporation rates, W/m^2; **(b)** cumulative evaporation, mm.