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The energy balance and vertical thermal structure of two small boreal lakes in summer

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Two small lakes in Sweden were studied using one-dimensional approach. Their summer energy balance and temperature structure were considered based on measurements and on modelling on different scales. Tämnaren is a vertically-mixed lake because it is very shallow and has a large surface area. Råksjö is small, sheltered and typically stratified during summer. Model adjustments and calibrations were made using detailed micrometeorological input data, considering areal variations. Components of the heat balance were determined in order to solve for water temperature and heat exchange. Absorption of energy inside water was determined on the basis of measurements. The vertical temperature structure was solved using a $k\varepsilon$-model. The results clearly show that sheltering caused by shores must be taken into account. Modifying the wind speed has a strong effect on temperature, especially at greater depths, and on heat balance. An isothermal box lake model, the SLAB model, was used with the same input. Surface temperature is strongly influenced by meteorological conditions, and both models solve it very similarly. Diurnal temperature variations, which can be as much as several degrees, are lost with the SLAB model. The PROBE model is able to solve these variations and the vertical temperature profile. However, if the important boundary effects are not taken into account, neither can be solved satisfactorily. Point measurements gave a residual of –53 W m^{-2} for Tämnaren, and –42 W m^{-2} for Råksjö. When wind was reduced to 80% for Tämnaren, and 60% for Råksjö to account for the net areal effect, the residuals were 0 and –1 W m^{-2} for the lakes. Temperature profiles were also satisfactorily solved.

Introduction

Water temperature, which is the most important physical factor in lakes, has long been used to describe their biological background conditions (Wetzel 1975). Surface temperature has a profound effect on surface energy exchange. Lakes in the boreal zone are generally characterized by thermal stratification. In summer, a thermocline forms separating the warmer epilimnion from the cooler hypolimnion. As surface water temperature increases, heat is released back into the atmosphere. In summer, water is mixed by wind, thus distributing heat and altering the temperature profile. The shape and the volume of the lake affect how heat is distributed, while the surrounding landscape shapes the meteorological fields over the lake.

The evolution of the temperature structure can be described with one-dimensional models that assume horizontal homogeneity. Over a large open-water area the atmospheric boundary layer can be well developed, and disturbances by the shores are negligible. A classical paper by Kaimal *et al*. (1972) described the basic characteristics of surface-layer turbulence. Smith *et al*. (1996) summarized the results of 25 years of research, including important developments in measuring systems. A review article by Högström (1996) summarized the contribution of meteorologists. The two lakes studied here are relatively small, and we have placed special emphasis on the important effects of the shores. The basic coefficients of turbulence are well known. We have not modified them here, which ensures the generality of the results.

The effective length the wind can blow across the lake when the turbulent field has developled is called the fetch. Many lake systems have complicated shapes and the actual fetch distribution describing open lake surface areas is usually too complex to be described. The land–water heterogeneity of the landscape is particularly significant in the boreal zone. Especially Canada, Russia, USA, Finland and Sweden have areas where freshwater lakes are abundant. In Finland, for example, lakes cover about 10% of the surface area with approximately 56 lakes per 100 km^2 (Raatikainen and Kuusisto 1990). In some districts small lakes predominate (almost 99% of the lakes are smaller than 1 km^2). Many larger lakes also have complicated shore forms and islands that cause greater variation in the surface turbulence. The landscapes around the lakes in this study can be regarded as rather typical boreal landscapes consisting of forests and agricultural areas with no high hills (Haldin *et al*. 1998).

Several physical factors distinguish lakes from the rest of the landscape, although their direct effects on climatic conditions are seldom seen. For this reason the components of the heat balance must be solved in order to facilitate comparisons with results obtained with larger scale models. In many lake studies it has not been possible to solve the whole energy balance; often one component has been solved as a residual, or an additional residual has remained. The heat storing capacity and albedo of water differ from those of other landscape elements, thus affecting the amount and rate of heat stored, as well as with the depth and the surface area of the lake (the volume). The transparency of water allows solar heat to be absorbed directly at greater depths.

In contrast to evaporation from land areas, evaporation from lakes is not limited by lack of water. Evaporation is a term in the water balance; exchange of latent heat is a term in the energy balance. Evaporation from natural landscapes and the effects of climate change are beeing studied by the Intergovernmental Panel of Climate Change (IPCC) (McCarthy *et al*. 2001). They have stressed the importance of having explicit meteorological controls in order to avoid misleading estimates of climate change. Among others, Fee (1996) expressed the need for details in the models of small lakes, also when they are used in calculations together with climate model output.

Advanced systems have been developed for calculating areal evaporation. MOREX (Thompson *et al*. 1982) has been used to obtain climate data e.g. in Scottish conditions (Lilly and Matthews 1994) and in northern England (Lockwood *et al*. 1989). Energy balance models within global circulation models were discussed by Pitman and Henderson-Sellers (1996), Yang *et al*. (1998) and Avissar (1998). The Swedish Regional Climate Modelling Programme (SWECLIM) aimed to create an extensive regional modelling scheme ranging all the way from global models to local scale models within the Baltic Area (Rummukainen *et al*. 2004). SWECLIM was primarily interested in creating models of the Baltic Sea (Döscher *et al*. 2002), but freshwater data (Winsor *et al*. 2001) and land area processes were also studied, e.g. by Frech *et al*. (1998). Lakes were also included in the modelling scheme of SWECLIM; Ljungemyr *et al*. (1996) described results for winter. The SWECLIM model system uses basically the same lake models as those used in this study, namely the SLAB model for shallow and the PROBE model for deep lakes, but their model for lake ice was different from the one used in Finland, described by Elo *et al*. (1998).

The subjects of the study were two small lakes, Tämnaren and Råksjö. Their surface fluxes of latent and sensible heat were analyzed by Venäläinen *et al*. (1999). Their results indicated that even these surface fluxes differed from those of the forest, and they also observed differences between the lakes from May to September. According to the results, fluxes from the lakes are different than fluxes from the land area, therefore the areal surface fluxes may be significantly influenced by the presence of lakes.

Lake evaporation has long been studied on the basis of lake-specific adjusted model parameters. Typically, lake measurements have been essential, but many methods have been developed with the goal of reducing the need for empirical lake data. Lake evaporation has been estimated directly with floating evaporimeters and water budgets (Järvinen 1978). The energy balance method has been used to solve evaporation as a residual from other components (Gibson *et al*. 1996, Sacks *et al*. 1994). The solving of the fluxes can be further simplified by using the so-called Bowen relation, which is the sensible heat flux divided by the latent heat flux (Strub and Powell 1987).

Empirical formulae relate evaporation to water vapor pressure at different heights and logarithmic wind velocity profiles. This method is known as the mass transfer method (mass rate of water transfer into air as vapor) or the Dalton law analogy (Järvinen and Huttula 1982). In it, evaporation is given as a function of the wind velocity and the vapor pressure gradient. The lake fetch has often been included in the formula for evaporation as a factor proportional to the length, and empirical values have been determined. The method of using measurements from different heights (the aerodynamical method, where one level typically is the surface) and the energy balance method have been combined in the so-called Penman equation, in which the saturation vapor pressure versus temperature curve is used to calculate evaporation, and the surface temperature is not needed (Bras 1990, Dingman 1994). The flux of sensible heat is usually small and it has often been regarded as being proportional to the latent heat flux. However, in many cases, the estimates produced using this method may be inadequate. For the lakes in this study large amount of data were collected and analyzed. Important disturbances were observed over the lakes, and the fluxes of sensible and latent heat were even going in opposite directions on certain occasions.

Usually, a fully developed boundary layer and horizontal homogeneity are required in order to solve atmospheric turbulence, but according to the Monin-Obukhov similarity theory even that is not strictly required for solving the fluxes over a relatively smooth surface (Vihma 1995a). The formulation of the turbulent surface fluxes used in this study has been developed and tested by Launiainen and Vihma (1990). The routine was also nested into the PROBE lake model and compared with two other routines (Elo 1994) in a study of a deep lake. Absorption of energy inside water was also measured in order to determine the whole energy input more accurately. Both studied lakes are small as compared with those modelled by Ljungemyr *et al*. (1996). The model study results show that small size provides considerable shelter, confirming the areal averaging results reported by Venäläinen *et al*. (1998). Sheltering is also important for Tämnaren. The modelling study aimed to produce generalizable results so as to facilitate comparisons with those of other lake studies.

Material and methods

The study lakes

Tämnaren (60°00´N, 17°20´E) is a fairly large and shallow lake, with a maximum depth of 2 m and a surface area of 37 km^2. Råksjö (60°02´N, 17°05´E) is a smaller lake with a maximum depth of 10.5 m(mean depth of 4.3 m) and a surface area of 1.5 km^2 (Fig. 1).

The data used

The data of this study are included in the NOPEX dataset (Kellner 1999). Some descriptive information was provided by Tourula *et al*. (1996) and Pulkkinen (1995). Additional details were included in the papers of Heikinheimo *et al*. (1999) and Venäläinen *et al*. (1998, 1999). Incoming global and long wave radiation, air temperature, relative humidity and wind veloc-

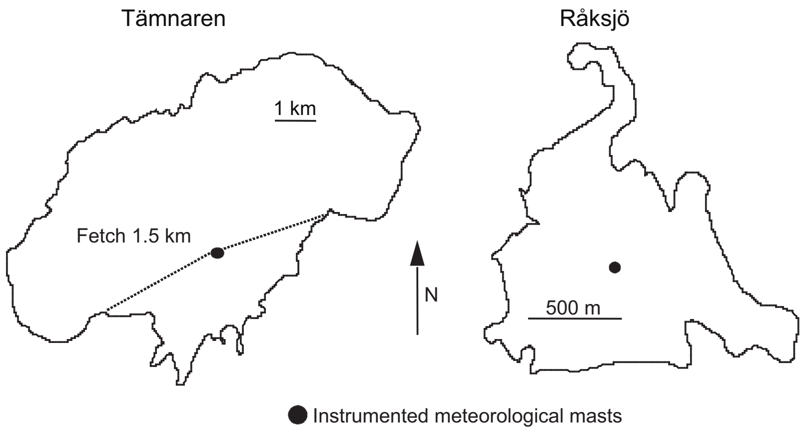

Fig. 1. The study lakes (picture from Venäläinen *et al*. 1998). At Tämnaren the length of the fetch varied from 1.5–5.5 km depending on wind direction. It was determined from two points on the shore as 1.5 km (shown with dashed lines).

ity were measured and used as inputs for the models. Reflection from the water surface was also estimated with measurements. Long wave radiation emitted from water was solved with the calculated surface temperature using the theory of a black body. Net radiation was used for verifications. Cloudiness was calculated using the model of the theoretical clear sky irradiance, and the level was determined according to the measured global radiation. Long wave radiation from the sky was calculated as a function of the measured air temperature and relative humidity and the calculated cloudiness. Measurements of reflected short wave radiation were used to estimate surface albedo.

Surface skin temperature was obtained with an infrared sensor. Lake water temperature was also recorded at several depths in Tämnaren, and a thermistor chain was used in Råksjö. The rate of change of the heat storage (Q) was estimated from the measured temperature profiles assuming a constant temperature at each layer slice over the vertical. These estimates were compared with the calculated temperature profiles. The vertical temperature profile is very sensitive to radiation input, and even small errors in radiation level can have strong effect on the results. The measurements of global radiation and eddy fluxes (including eddy covariance data) were compared and calibrated with measurements over land at meteorological stations near the city of Uppsala, taking into account possible offset error.

Micrometeorological data were recorded at 10-min intervals, and even shorter time intervals were considered during the measurement campaigns. Meteorological data were also intensively analyzed by Venäläinen *et al*. (1999) in order to study the horizontal variations over the lakes. For the lake model, it was more reasonable to use hourly data. Rapid atmospheric changes over the lake cannot have any immediate effect due to thermal inertia. It is important that the data include diurnal variations. Hourly data describe these well, and three-hour data are often also sufficient. Both the models had a calculation time step of 600 sec.

The energy balance

The energy balance for the lakes can be expressed as follows:

$$R + \mathrm{LE} + H + Q = \delta \quad (1)$$

where R is the net radiation (short and long wave components), LE is the flux of latent heat, H is the flux of sensible heat, and Q can be approximated as the rate of change of the heat storage. The terms are considered at the water–air interface, and vectors are positive when they are directed upwards. The heat storage inside the lake is positive when it increases. No other terms were included. Changes of water level and ground water flow were estimated to have such a minor effect on the heat balance that it was possible to ignore them. Heat conduction through the lake bottom was also estimated to be of minor importance, as measurements from other boreal lakes and some test model calculations including it confirmed its minor importance during summer. δ is the possible residual including the missing terms, for perfect balance it is zero. When it was calculated using the lake models, it was essentially zero.

Parameterization of turbulent surface fluxes

According to the formulation by Launiainen and Vihma (1990) used in this study, the profiles of momentum and of latent and sensible heats were solved with universal functions with measured flux values at two heights iteratively. The corresponding bulk exchange coefficients were calculated for each flux at each interval. All different stratification situations were solved according to actual physical conditions, and the results were given directly for the height of 10 meters. The testing included a comparison with the eddy correlation method, which measures the fluxes directly (Venäläinen *et al.* 1998). In it, three components of the velocity field were measured and the actual short-term fluctuations were determined. The vertical fluxes of momentum τ, sensible heat H and water vapor E are given as:

$$\tau = \rho_a \overline{u'w'} \approx \rho_a K_M \frac{\partial u}{\partial z} = \rho_a C_{Dz} u_z^2, \quad (2)$$

$$H = \rho_a \overline{T'w'} \approx -\rho_a c_p K_H \frac{\partial \theta}{\partial z} = \rho_a c_p C_{Hz} \left(T_s - T_z\right) u_z, \quad (3)$$

and

$$E = \rho_a \overline{q'w'} \approx -\rho_a K_E \frac{\partial q}{\partial z} = \rho_a C_{Ez} \left(q_s - q_z\right) u_z, \quad (4)$$

where T is the temperature of air, q its specific humidity, u_z is the horizontal wind component. ρ_a is the density of air, and c_p the specific heat capacity of air. In Eqs. 2–4 the first terms with the superscripts describe the actual variations calculated as co-variances. The lines over the products denote averaging over a short period. The values for K and C with their subscripts are corresponding bulk exchange coefficients. The formulations allow arbitrary observation heights, and the values of the exchange coefficients (C) are calculated for each interval. The fluxes are approximated using recordings from two heights: the water surface (subscript 's' in formulas) and at height z (subscript z) are chosen here. Flux of latent heat (LE), which is part of the energy balance, can be calculated by multiplying the flux of water vapor by the latent heat of evaporation. Evaporation is traditionally given as depth in meters per area per day.

The PROBE model

The PROBE lake model (Svensson (1978), Sahlberg (1983), Sahlberg (1988)) uses the PROBE program. Modifications of the surface exchange and solutions of the energy balance of the model during summer for a deep lake using synoptic data were presented by Elo (1994) and Elo *et al*. (1998). The model is based on the equation solver for vertically one-dimensional, transient boundary layers

$$\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial z}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial z}\right) + S_\Phi, \quad (5)$$

where Φ is a dependent variable, t is time, z a vertical co-ordinate, Γ_Φ an exchange coefficient, and S_Φ a source or sink term. The lake is described with a hypsographic curve as a pile of boxes of height Δh, with the largest on the top having the surface area. All the equations are solved for each layer and time step, first solving for temperature and horizontal velocities. The heat is assumed to be distributed evenly in each box. For the heat diffusion,

$$\frac{\partial}{\partial t}\left(\rho c_p T\right) = \frac{\partial}{\partial z}\left[\frac{\mu_{eff}}{\rho \sigma_{eff}} \frac{\partial}{\partial z}\left(\rho c_p T\right)\right] + S_1, \quad (6)$$

where c_p is the specific heat at a constant pressure and ρ is the density. The water is internally heated by short wave radiation, which is absorbed in the water column, expressed in the source term S_1. This can be described with an exponential bulk form $(1 - \eta)e^{-\beta z}$, where η is the fraction of short wave radiation absorbed at the surface, and β is the extinction coefficient, μ_{eff} is the dynamical effective viscosity (sum of turbulent and laminar components), and σ_{eff} is the effective Schmidt number. The coefficients in Eq. 6 are related to the $k\varepsilon$-model for turbulence: the turbulent kinetic energy k and its dissipation rate ε are included and solved with Eq. 5. The model has second-order closure; the turbulent eddy viscosity μ_T is calculated in the form $\mu_T = C_\mu \rho k^2/\varepsilon$, where C_μ is an empirical constant. The constants used by the turbulence model were summarized by Omstedt *et al*. (1994).

The SLAB model

The SLAB model is similar to the model described by Ljungemyr *et al*. (1996). The lake is a well-mixed box having a uniform temperature. Temperature changes are regulated by the sum of the fluxes through the surface:

$$\frac{\partial T_w}{\partial t} = -\frac{1}{\rho c_p D}\left(\mathrm{LE} + H + R\right) \qquad (7)$$

where T_w is the temperature of the water in the box, derivative ($\partial/\partial t$) is taken with respect to time, and D is the depth of the described lake-box. Ljungemyr *et al*. (1996) found that the lake could be represented as a box having the same surface area as the lake and the same thickness as the mean depth of the lake. Surface fluxes were calculated in the same way as with the PROBE model. The simulated temperature was used directly as the surface temperature.

Light climate in the water

Total short-wave radiation directed towards the water surface was measured with global radiation sensors. Also radiation reflected upwards from the surface was measured. The spectral composition of light was determined with LICOR-sensor measurements made at both lakes in 1994, both inside and above the water. At Råksjö intensive series of measurements were taken, while two measurements were made at Tämnaren. Part of the radiation is absorbed at the very surface, and the rest, mainly light, is attenuated as it penetrates into the water, scattered and absorbed by the water and its constituents. The spectral irradiance of upwelling and downwelling radiation was measured at different levels in the water in order to determine light attenuation (Spinrad *et al*. 1994). Most of the energy of light is transformed into heat in the water column. In this study, the measured spectra in water were divided into five bands, and separate values of β were calculated for each to determine attenuation inside water. The corresponding incoming spectral atmospheric short wave radiation was also estimated based on measurements.

In studies of the behavior of light inside the water, the waveband is defined as 400–700 nm, which is effective for photosynthesis (PAR = Photosynthetically Active Radiation). Then, η has the value of 0.42 (the band 700–800 nm is assumed to be absorbed already at the surface). Because the PAR band can be detected by the human eye, PAR attenuation is often determined with Secchi disk observations. In clear, alpine lakes the productive layer can be as much as 2–3 times deeper than the secchi depth. Nordic waters are typically dark and the productive layer depth is about the same as the secchi depth, and even in the clearest waters in Finland it is not more than twice the secchi depth.

The effectiveness of energy used for photosynthesis is typically 1%–2% of the entire PAR range (Wetzel 1975). For littoral zones in shallow lakes the portion of the energy used in photosynthesis may be relatively slightly larger, but it is usually ignored. Photosynthesis also depends on the temperature, but temperature is also usually higher when there is a lot of light. The amount of nutrients limiting and controlling photosynthesis also plays a role. Under special conditions, blooming can be extensive and the vertical illumination profile can be affected. This may also affect the temperature profile.

Results

For modelling, the measurements at the lake were considered both vertically and horizontally. Vertical changes were important for wind velocity between the heights of 4 m and 10 m. The largest differences in humidity and temperature were found close to the water surface. Horizontal variations in the meteorological data showed the importance of sheltering along the shores. Fine-interval meteorological data (10 minutes) from 1994 were used in order to test calculations with the $k\varepsilon$-model during the stratified period. If these measured data had been used directly, overturn would have occurred very soon. By reducing the wind, it was possible to maintain the stratification, and diurnal stratification could also be seen reasonably well. The model output was easily improved when the wind speed was reduced to 80%–60% of what was measured at the lake.

Water temperature was studied with the $k\varepsilon$-model in order to solve all components of the heat balance. It was possible to include horizontal variations in the modelling scheme using areal averaging, which adequately represented the temperature profile throughout the summer. The results were compared with those produced by the one-layer model, which essentially represents the surface with the same heat intake volume as the lake. The system is very sensitive: the emitted long wave radiation is proportional to the fourth power of the calculated surface temperature and radiation balance is easily affected. As water readily stores heat, longer-term averages of the parameters are needed. However, when the surface energy balance is determined with meteorological measurements, a residual usually remains. It was possible to diminish the residual by reducing the wind velocity corresponding to areal averaging. With the same approach to reduction, it was possible to solve the model of temperature stratification for Råksjö. As Tämnaren has a larger surface area, a smaller reduction of wind velocity was reasonable. It was also possible to solve the heat balance with this smaller reduction.

Light absorption

The extinction coefficients for lakes Råksjö and Tämnaren were measured (Table 1). The value of $\eta = 0.54$ was based on the measurements, and some infrared radiation was penetrating deeper below the surface in beyond the PAR range. In this study, heating by light was directly related to the amount of energy absorbed in the water, and the extinction coefficients were determined according to the measurements. Values for both of the lakes were rather similar. The observed secchi depth was about 1.8 m (± approximately 0.02 m) in Råksjö. Tämnaren is very dark, and a secchi depth of 0.5 m was typically obtained.

Horizontal variations

Very often, horizontal variations have been regarded as the main reason for the residual in the energy balance. This has frequently been due to the lack of suitable measurements to estimate the effect. In this study, a large amount of data was available for analysis of the variations over the lakes. Measurements over different fetches were compared with each other and with the model calculations describing the forest–lake boundary done by Venäläinen *et al.* (1998). According to the results for Råksjö, a reduction to 60% was optimal. This reduction gave reasonable stratification results and the energy balance residual was minimized over a longer period. For Tämnaren a reduction to 80% was suitable.

Inside the water, horizontal variations have effects because of the large volume of water. This can be seen especially when the temperature is changing e.g. at formation and outbreak of stratification: the heat that is transferred into or from deeper layers can cause temperature differences locally and temporally. During the day the surface temperature often rises considerably, but the differences are usually soon smoothed. It was possible to use aircraft measurements (described by Samuelsson and Tjernström 1999)

Table 1. Measured absorption coefficients inside the water, also divided into wavebands with the measured percentage value of the intruding short wave radiation.

	Wavelength band (nm)					Total PAR	Total
	400–450	450–500	500–600	600–700	700–800		
i	1	2	3	4	5		
Percentage of F_i for i	13	14	28	24	21		
Råksjö β_i	7.0	3.8	1.6	1.1	2.0	2.2	2.6
Tämnaren β_i	7.0	4.4	2.1	1.3	2.0	2.4	2.8

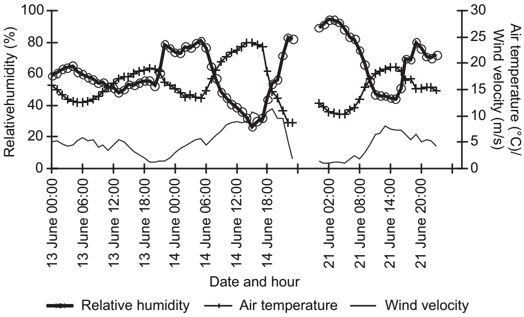

Fig. 2. Surface observations made on a float on Tämnaren on 13, 14 and 21 June 1994. Measurements were made at the height of 4 meters and the values are hourly averages.

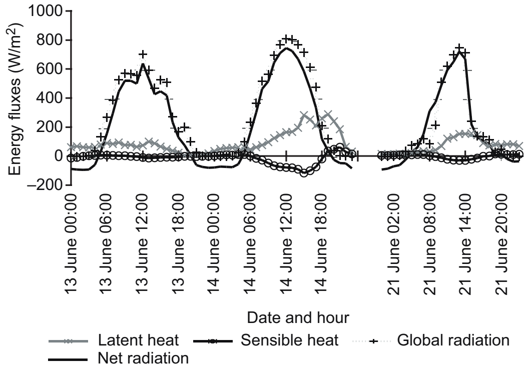

Fig. 3. Surface observations made on a float on Tämnaren on 13, 14 and 21 June 1994. Latent and sensible heat fluxes were calculated using the Monin-Obukov similarity theory, accounting for stability with parameterization by Launiainen and Vihma (1990). Values are hourly averages.

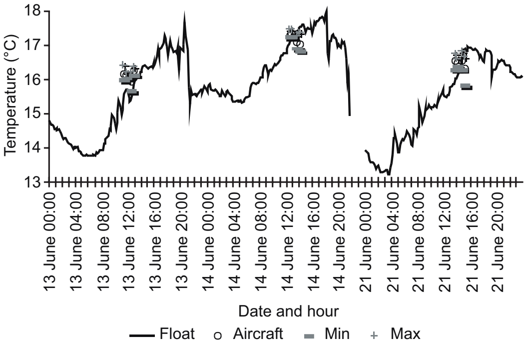

Fig. 4. The lake surface temperature in Tämnaren on 13, 14 and 21 June 1994 as measured from the float using an infrared sensor and as measured from aircraft flying at the altitude of 100 m. Aircraft values represent a mean value at about 1500 m distance near the measuring float. Minimum and maximum values are the lowest and highest measured values along that path.

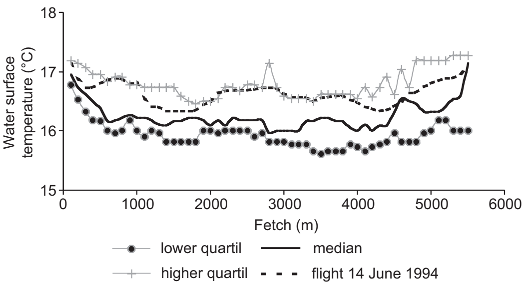

Fig. 5. Lake surface temperature as a function of fetch at Tämnaren. Measurements were made from an aircraft at the height of 100 m on 13, 14 and 21 June 1994. The horizontal variations are described with the median and the interquartile range. Measurements from the first flight on 14 June 1994 are also shown.

in order to estimate the spatial variation over the surface temperature for Tämnaren. Flight measurements gave results over the whole lake practically simultaneously. They were made on 13, 14 and 21 June 1994 (Figs. 2–5). 14 June and 21 June 1994 were windy days, and 10-minute mean wind speeds at the height of 4 m occasionally exceeded 10 m s^{-1}. A cold front passed the float on the afternoon of 14 June 1994, which can be seen as a sharp drop of the air temperature. Measurements of global radiation indicate the presence of some clouds on that day. The morning of 21 June 1994 was quite clear, whereas on 13 June 1994 there were cumulus and cirrus clouds. The lake surface temperature data obtained from the aircraft corresponded well to the data from float measurements (Fig. 4). The largest difference, 0.9 °C, was observed on 13 June 1994 during the first flight but otherwise the difference was only about 0.5 °C. However, even a difference of 0.5 °C would be enough to cause a large heat storage difference, 12 W m^{-2} during the day for half a meter of water, which compares well to the term for sensible heat. Daily averages were used and the daily variation was smoothed in order to calculate of the rate of the change of the heat content.

The measurements from fligths at the height of 100 m were analyzed (Fig. 5). Even though the measurements were taken on three different days, the variations were small. The spatial variation in the middle of the lake was about

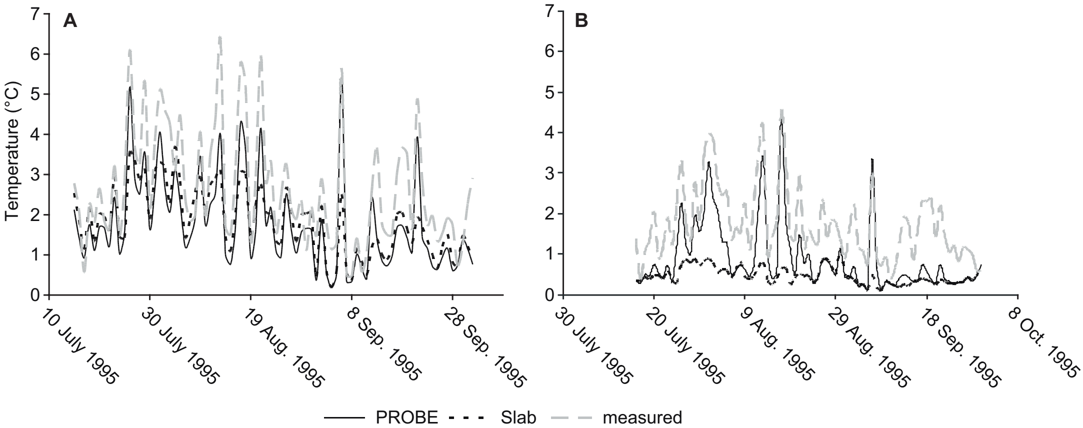

Fig. 6. Daily surface temperature variations, calculated with two models (PROBE and SLAB) and measured in summer 1995 in (**A**) Tämnaren, and (**B**) Råksjö.

0.5 °C and over the entire lake less than 1 °C. Near the shores uncertainty in positioning the aircraft is about the same size as pixel elements. It is possible that the values were no longer from the water surface, which may have caused an increase in the apparent temperature near the lakeshores. The lake surface temperature was relatively homogeneous and the 24-hour temporal variation was much larger than the spatial variation over the lake.

Råksjö is relatively shallow and sheltered, and stratification is stable over the entire lake. Due to its small surface area, large temperature variations were not expected (it would also been impossible to resolve them from an aircraft).

Lake surface temperature

Infrared sensors were used to measure the skin surface temperature, which is typically slightly lower than the temperature measured from the surface layer at a depth of about 10–20 cm. The hourly values were used to determine surface temperature at the lakes (Table 2). After May, the surface of Råksjö was warmer than that of Tämnaren on account of its greater depth. Its surface temperature rose and was still 0.8 °C warmer in September. For shallow Tämnaren, temperature variations were larger throughout the period, and they were larger in both lakes during heating in May and cooling in August.

The observed and modelled (calculations made without modification for wind speed) daily surface water temperature variations approximately from the end of July to October are shown in Fig. 6. The SLAB model smoothes the variations strongly, and its results were much better suited for Tämnaren, which also resembles a box. The PROBE model with vertical resolution followed daily changes much better for both lakes. The PROBE model even gave peaks that were about 4 °C higher than those produced by the SLAB model being much closer to the measured values. Even higher peaks that may have possibly been caused by periods of direct sunshine were measured.

The lakes are located close to each other and the weather is rather similar over both of them, but there are also differences between them. Maxima and minima were seen in input global radiation, especially when it was not very windy. The shallow lake followed the changes of

Table 2. Means (absolute vales of SD) of the surface temperature (°C) of lakes Råksjö and Tämnaren, measured with infrared sensors in 1995.

	Råksjö	Tämnaren	Difference
May	10.0 (3.5)	10.1 (4.1)	–0.2
June	17.9 (1.2)	17.6 (1.6)	0.3
July	19.6 (1.3)	19.2 (1.7)	0.3
August	20.0 (2.3)	18.8 (3.2)	1.2
September	13.2 (1.3)	12.4 (1.9)	0.8

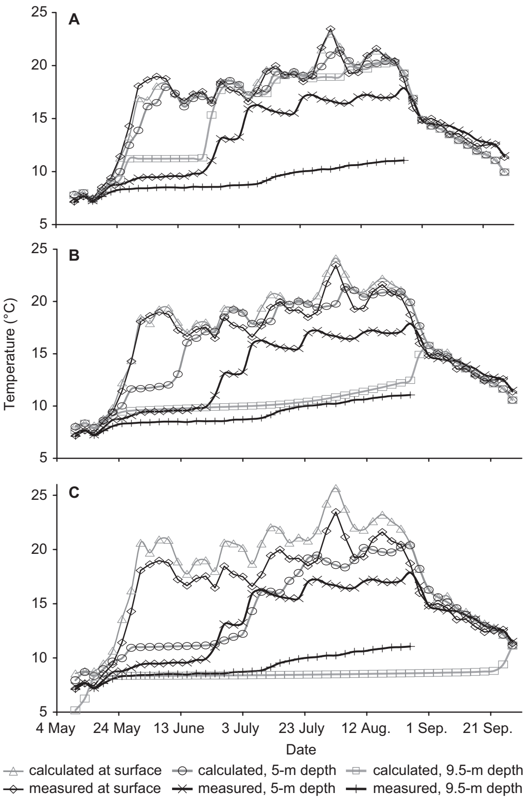

Fig. 7. Temperature development in Råksjö in summer 1995, The PROBE model calculations are compared with measurements averaged over three days. The term factor is used in order to reduce the measured wind from the lake to obtain effective net wind over the whole lake area: (**A**) no reduction of wind, (**B**) reduction by 20%, and (**C**) reduction by 40%.

energy input and warmed and cooled faster than the deeper one, and therefore water temperature maxima and minima were not always measured on same days in the both lakes. If mixing is not strong more heat is retained in the top layers, but then the fluxes upwards are larger due to the increased temperature. If the wind input was reduced to 60%, which generally increased the suitability of calculated temperature, surface temperature variations increased and the smaller peaks rose closer to the measured values, but the highest peaks were exaggerated.

The vertical temperature structure

The vertical temperature structure can be modeled only with the PROBE model; the SLAB model gives only one temperature, which represents that of the surface. Tämnaren was very homogenous over the vertical, with less than 0.5 °C difference over the vertical measured over 61 days. The calculated difference was smaller with the PROBE model, but if a wind reduction was applied, the difference increased and approached the measured difference.

The effects of a wind modification can be seen in time series of temperature on the surface and at the depths of 5 and 9.5 m for Råksjö (Fig. 7). The depth of 5 m represents approximately the mean depth and 9.5 m is rather close to the bottom. Results with no wind modification and with reductions to 80% and 60% are given in Fig. 7. Without wind modifications, the simulated lake remained stratified only for about one month at the beginning of summer. When wind speed was reduced, the surface temperature increased and the bottom stayed cooler. When wind was reduced to 80%, the temperature at both the surface and close to the bottom was successfully solved, but the middle layer remained too warm. When the wind was further reduced to the estimated optimum value of 60%, the lake temperature profile was more gentle and the temperature in the middle layer was closer to the measured temperature; the temperature at the surface was a little too high and the bottom remained a little too cool. This shows that the $k\varepsilon$-model cannot be totally adjusted to such a small lake. Nevertheless the PROBE model produced suitable results for the whole system throughout the whole summer period and the duration of stratification.

Equations 2–4 are bulk forms that can in principle be empirically calibrated for each lake, depending on lake-specific calibration factors. For the latent heat flux this also depends on the methods used to determine lake evaporation. Calibration also depends on modification of the wind, made as an average over that over the whole surface area, relative to the morphological features of the lake and its surroundings. In some cases, horizontal boundary effects were studied by adding mixing for deep lakes in the PROBE model (Elo 1994 and Elo *et al.* 1998): the term: $\rho_{\mathrm{ref}}A_s/N$ was added to turbulent viscosity. In the term, ρ_{ref} is the reference density

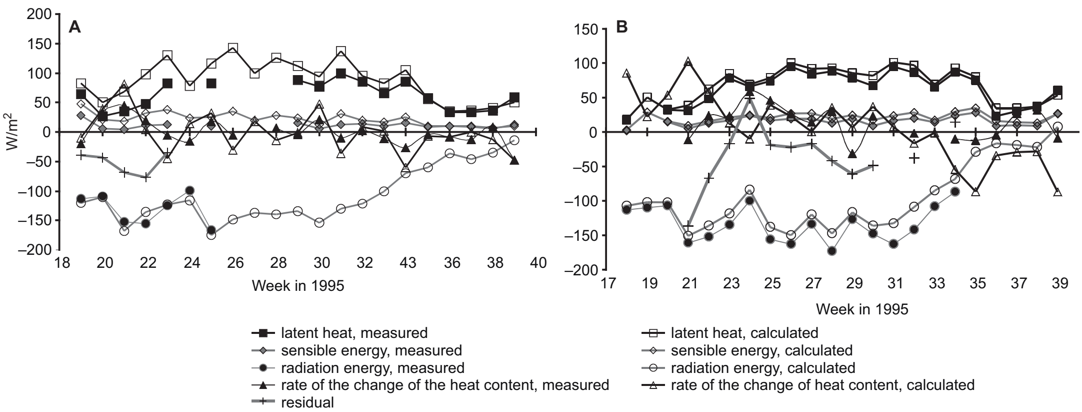

Fig. 8. Weekly heat balance for (**A**) Tämnaren and (**B**) Råksjö. Positive flux upward.

of 999.975 kg m^{-3}, A_s is a constant of 2×10^{-7}, and $N = [-(g\Delta\rho)/(\rho\Delta z)]^{0.5}$ is the Brunt-Väisälä frequency, g is acceleration by gravity. When the term was added, mixing was too strong and the results were unacceptable. The simulation of the surface temperature was still rather successful, because exchange fluxes have a strong influence on the surface layer conditions. This stresses that it is not enough to use the surface temperature to obtain a good overall model adjustment.

Heat balance

The values were calculated with the PROBE model using 80% wind for Tämnaren (Fig. 8A) and 60% wind for Råksjö (Fig. 8B). The measured values were determined using direct lake data recordings with no wind modification. The sum of the components was not zero, for Tämnaren the mean residual was –53 W m^{-2}, for Råksjö –42 W m^{-2}. The measured residuals were largest during the formation of stratification and again at the end of it during cooling. When the wind reductions used successfully for modelling were also applied to the measurements the residuals were on the average 0 W m^{-2} for Tämnaren and –1 W m^{-2} for Råksjö.

The values of surface fluxes obtained with the SLAB model were close to those obtained with the PROBE model: they were closely related to the surface temperature. However, the values of the surface fluxes were typically smaller with the SLAB due to smoothing. Because the calculated total balance was zero, the calculation differences were left in the terms of the changes of the heat contents, which were large. This again stresses that solving the surface temperature is not enough to ensure the successfulness of solving the temperature deeper in the lake.

Typically, the modelled lakes were not heated as much and as fast as observed. For Råksjö, the residual rose strongly during warming period in early summer. There were no large horizontal temperature variations in the water, but due to the volume, small temperature changes resulted in large differences in the heat stored. If wind was not reduced, the modelled surface temperature would be higher and the latent heat would be about 7% higher for Tämnaren and 15% higher Råksjö. The radiation balance has large absolute values but is very sensitive to surface temperature. With no wind speed reduction, the radiation balance would be about 4% larger for Tämnaren and about 9% larger for Råksjö.

Over longer periods the ratio of sensible heat to latent heat remained rather constant at about 1:4 when water was stratified. In the beginning of summer, sensible heat was almost as high as latent heat. The variations were much larger for Råksjö, where sensible heat was small. At the end of summer, when the water cooled, sensible heat was about 40% of latent heat for Råksjö. For Tämnaren sensible energy was smaller, about 20% of latent heat, and it decreased to 10% by the end of summer.

At the beginning of summer, the flux of latent heat over Tämnaren was about 50% larger than over Råksjö. Then it slowly decreased. When overturn occurred in Råksjö, for a short while its latent heat flux was 30% larger that it was over Tämnaren. Over the whole period, latent heat flux was on the average about 26% larger over Tämnaren. Sensible heat was on the average only 6% larger over Tämnaren than over Råksjö, however at the beginning of summer it was even twice as large, and at the end of summer fell close to half of what it was over Råksjö. The radiation balance was very much the same for both the lakes at the beginning of summer, but at mid-summer it fluctuated, being usually slightly larger over Tämnaren. At the end of summer during cooling, the absolute value of the radiation balance for Råksjö sometimes fell to less than half of that over Tämnaren.

Discussion

At mid-summer, lake water was usually stratified and the exchange was typically rather regular. Because of the close relationship between the atmosphere and the water surface, the water surface temperature fluctuates according to the air temperature, with strong warming caused by the sun. The routines can be adjusted to differences and errors in measuring surface temperature, including skin effects. This can be done on a small scale, but thermal inertia and advection make solving for temperature more difficult. For lakes, limited areal size effects and sheltering along the shore are most essential: turbulence is reduced because wind speeds are lower, and due to friction the motion approaches slow laminar motion.

Evaporation from lakes is not limited by the amount of available water. For this reason it is necessary to study how lakes affect areal evaporation or how lakes change due to evaporation. For practical reasons, lakes have not often been explicitly embedded in hydrological models, but such models have been using lake evaporation studies as a basis for determining evaporation. The mass balance method has determined the total evaporation of a lake as an average over the entire lake. Energy balance methods have eliminated some terms, and the Priestly-Taylor method has even eliminated the surface temperature. Gibson *et al*. (1996) compared several methods over a number of months with open water. The lake they studied, which was located in the tundra region, had a mean depth of only 0.65 m and they assumed fully adjusted boundary layer conditions with optimum fetch conditions. They also assumed that the lake evaporation was augmented by sensible heat from the surroundings. They found good correspondence between the methods, but the differences between the results could be as great as 20%. The subsurface heat flux also varied strongly. They found that the profile method overestimated evaporation. They also mentioned the empirically derived proportionality that evaporation from small lakes is to exponent of the surface area, $A^{-0.05}$, applied also to lakes as large as Råksjö and Tämnaren (Dingman 1994, based on studies in the southwestern United States and western Canada). This is not consistent with the results obtained by Venäläinen *et al*. (1998) and generally confirmed in this study. One possible explanation could be that the landscape around the two Swedish lakes is forested, and the evaporation from them is not intensified due to advection. In this study, as in the study by Venäläinen *et al*. (1998), the fluxes were determined with a method that does not even require a fully developed boundary layer and measurements from certain height, and the fluxes can be solved for each step as they are being measured.

In many studies of the relationship between the lake surface and the atmosphere, the focus has often been on the cooling period and the stability of the air: when the surface of water is warmer, air exchange is affected. In a study of autumnal cooling, Sahlberg (1983) showed that the PROBE model is able to describe mixing and heat flux and that it is suitable for lakes and brackish water with synoptical data. Strub and Powell (1987) focused on cooling with several evaporation formulations describing different stability situations. They suggested that heat and moisture are transported away from the lake and pointed out that it might be better to use the results from cooling ponds results than oceanic bulk formulas. They also noted that it might be possible to separate night and day processes properly. They studied an alpine lake in northern California, where the form of the surrounding landscape and climate might increase advection.

Lakes differ from the landscape, because surface temperature and related features are different in water. Temperature differences can also cause feedback effects, including advection of moisture into the surroundings. Depth is one of the most important morphological features in lakes. Related to volume and heat storage, its effects are often seen in the energy balance, which is typically used in different models and permits them to be related to each other. Many case-specific parameters in models introduce the problem of the role of calibration when models are connected to each other: parameters must be calibrated and too much calibration decreases the compatibility of the models and the reliability of the results obtained. That is why both the model and the data in this study were used with as few modifications as possible.

Conclusions

It was possible to model the summer temperature and energy balance of the two small lakes using one-dimensional lake models despite the limitations resulting from horizontal effects. It is relatively easy to solve the models for surface temperature due to the strong forcing by atmosphere, but it is much more difficult to model the vertical water temperature profile and the energy balance for the whole lake at the same time. The solutions for surface temperature in both models were quite similar because the connection with the atmosphere is very strong. In any case, it is important to remember that even if the surface temperature is at the correct level, the temperature below the surface may be quite wrong. Small changes in input have a great deal of impact on the solved entire temperature profile.

The SLAB model, the iso-thermal box model, can be used to solve for surface temperature if more detailed information is not needed and calculation resources are limited because it does much to even out the daily variations. The PROBE model with the turbulence model can also solve the vertical temperature profile, and it can give information on a finer scale. The daily temperature range can also be rather well described with the PROBE model.

This study shows that the PROBE model can be adjusted and applied even to extreme lakes: Tämnaren is very shallow and Råksjö is small and sheltered. For these lakes the effects caused by the shores are very important. It was possible to adjust the model succesfully by reducing the wind speed. The comparison was made with temperature profile measurements, and all the main features of the temperature development were considered in designing the model. If the shading by the shores and the consequent reduction of wind are not taken into account, mixing is far too strong and even stratification is soon lost. The calculated stratification was more abrupt than the actual measurement showed. Because the calculated profiles were more abrupt than the measured ones, adjusting was not easy. The measured thermocline was at a depth of about 6 m with a temperature of 13.7 °C, close to the middle depth drawn in Fig. 7, thus showing the effects of changing the wind velocity. With 80% wind the thermocline was a little over 1 m deeper with a temperature of slightly above 15 °C. With 60% wind, which was compatible with areal averaging, the thermocline was about 1.5 m higher with a temperature of 14.8 °C. These figures were calculated with the program developed by Juhani Virta to solve thermocline depth by using spline adjusting.

When the individual daily profiles were compared, with 80% wind it was possible for the water surface layer to be almost totally mixed and even about two meters too deep. With 60% it was somewhat too high and a little too much heat was left at the surface, as also shown in Fig. 7. The deep mixing routine, which has been able to smooth profiles for deep lakes (e.g. Elo 1994), was not effective because it made mixing too strong. Measurements of the absorption of light inside the water taken several times during the summer showed no significant changes. However, even small differences in temperature multiplied with large surface layer volumes give values which can be as large as the differences in the heat balance. It is very important to remember that adjusting the surface temperature is not enough to ensure that temperature is correct at a geater depth: typically, when the modelled surface temperature is correct, too much heat is transferred deep.

These results confirm the value of horizontal averaging of the meteorological fields over the lakes. With the same approach to averaging, it was possible to solve the energy balance of the lakes using the lake measurements, and over a longer period their average residuals approached zero. With the same wind reduction it was possible to use the turbulence model to solve the temperature structure even though the solved profiles were still too abrupt as compared with the measured ones. It is important to note that when measurements from a small lake are used, areal averaging needs to be taken into account when the lake measurements are interpreted to describe the entire lake.

For small lakes, areal averaging of meteorological input helps to adjust model results for deeper layers. The ability to model small lakes and their vertical temperature successfully would also benefit biological studies, because these are also strongly affected by temperature. One also has to keep in mind that although physical principles and mathematical formulae are the same everywhere, local conditions may differ and the local biology might have developed differently. The ability to model physical conditions may facilitate comparative studies of lakes in different locations.

Test should be conducted to study how the method for solving the stability and the corresponding turbulent surface flux exchange continuously according to the actual measured situation could be adapted for use with North American and Canadian lakes, where studies have given different results. As this method has been successfully applied to polynya near the Antarctic, it can be used to describe very cold conditions (Vihma 1995b). It could also be used to obtain information about the feedback from lakes to the atmospere.

The results of this study contribute to efforts to model and esitimate processes in lakes and their energy balances. They also provide insights into the use and transfer of data. Larger lakes and lake groups can affect their local climate in a remarkable way. Lake measurements have typically been needed to obtain data for lake studies. The results of this study shed light on how the data can be used and how data from distant stations can contribute to descriptions of lake conditions. Determinations of the heat balance based on measurements have often included a residual term. The energy balance method has frequently been used to solve for evaporation as the obtained residual. Such results can be used better when better methods have been developed to analyze the heat storage rate. The residual term can be rather large due to the large volume of water, even though the temperature difference is not large.

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