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A Sensitivity Analysis of a Temperature Model of a Lake Examining Components of the Heat Balance

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Abstract

A one-dimensional mathematical model was used to simulate thermal development in a lake during two summers. Monthly values of the components of the heat balance equation, temperatures from the surface and from a depth of 2.5 m, as well as the depth of the thermocline were calculated and compared to earlier predictions and measured values. The PROBE lake temperature model uses the turbulent surface fluxes at the surface of the lake. The sensitivity of the lake model to differences of surface forcing was studied so that first the usual flux routine (with bulk formulae by Friehe and Schmitt) was used. Secondly, latent heat flux was calculated with a bulk form formula, the parameters of which have been obtained with the water budget method describing the particular lake. Finally, a detailed iteration routine for all of the turbulent surface fluxes was used. Sensitivity of the model was examined with the mentioned indicators. Effects of some differences and errors in the input data are also considered. Although the model seems to be rather sensitive and some tuning might be required to get very accurate results of all the indicators, the model can give, for example, a good areal estimate of lake evaporation. This information is useful in studies connected to climate change.

1. *Introduction*

There are several numerical models that can be used to calculate the distribution of temperature in a lake and its time development. Often these are one dimensional and only one vertical profile is calculated to represent temperatures in the whole lake. These vertical models ignore horizontal differences in lake temperatures and climatological conditions along the lake. One vertical model for the prediction of the thermal structure of the ocean and lakes was introduced by *Svensson* (1978). Lake applications are studied further for example by *Sahlberg* (1983). The differential equation solver program PROBE (PROgram for Boundary Layers in the Environment) by *Svensson* (1986) is used in calculations. PROBE embodies a two equation turbulence model, the k-ε model. The lake temperature model is usually used with synoptical input data from nearest suitable station. Short wave radiation is calculated theoretically and corrected for observed cloudiness. The model

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calculates fluxes of latent heat and sensible heat and they are used with long wave net radiation as a boundary value for the temperature equation in the lake. The short wave radiation is the dominant heat flux (during spring and summer), and it was added as a source term for the temperature equation (*Sahlberg*, 1983).

The PROBE program has been used in lake and ocean studies (see for example *Omstedt et al.* (1983)). Its turbulence model is used also in some studies about rivers and other flows. Some studies are listed in *Svensson* (1986). The PROBE temperature model of a lake is used in connection with SILMU, the Finnish Research Programme on Climate Change, e.g. *Huttula et al.* (1992) when studying effects on lakes. To make reliable estimates of the effects of climate changes one has to have information about the sensitivity of the model. It is also important to verify how well one dimensional models can describe a whole lake area. Another SILMU project includes measurements at lake Pääjärvi, as described in *Virta et al.* (1992), and is studying also these things.

Simulated surface temperatures and vertical temperature profiles can be compared with corresponding measurements to verify the models accuracy. In this study, predictions are made of the heat balance components for different months, the corresponding monthly mean water temperatures at the surface and at a depth of 2.5 m depth, and thermocline depths (for July and August). In addition, time series of predicted daily surface temperatures are presented to give general idea about their features. All the predictions are compared to measured data and earlier predictions.

The sensitivity of the lake temperature model to surface forcing was studied. The models usual calculation routine uses a bulk form formula and parameters by *Friehe and Schmitt* (1976). Secondly, parameters found by *Virta* (1981) for the particular lake were used for the calculation of latent heat flux. He connected the water budget method with a bulk form formula. Also a sophisticated iteration routine by *Launiainen and Vihma* (1990) was used. It calculates all the surface fluxes, the latent heat, the sensible heat, and the momentum flux. The first and the last of these methods describe areas with unlimited fetch, the second represents evaporation from the particular lake. No calibration was done in these three simulations, only corrections according to measurement heights were done. The versions of the submodels were as basic as possible to see the effects more clearly.

The lake model can be calibrated by adjusting wind data to produce temperatures and thermocline depths that resemble the measurements (that is done for example by *Huttula et al.*, 1992). Often wind data over the lake are not available and the shores and sheltering by the terrain might affect the lake temperatures calculated with the lake model considerably. The wind was increased and decreased by 10 % to see how the calculated indicators changed using the usual routine (with bulk formulas by Friehe and Schmitt). This can also be thought to describe the effects of errors in the wind data. Effects of some errors (mainly in air temperature) in the data can also be seen in the results.

2. *Heat balance*

Elomaa (1977) studied the heat balance at lake Pääjärvi based on measured climatological data (*Elomaa,* 1976). In 1969 and 1970, for the periods between June and the end of October, he gave monthly values of the heat balance components in eq. (1). *Virta* (1981) investigated evaporation in those periods.

The heat balance equation per unit surface area of the lake can be written as

$$R + H + LE + Q = 0 \tag{1}$$

where R is the net radiation, H is the flux of sensible heat, LE is the flux of latent heat (these are positive when directed up) and Q is approximated as the rate of change of the heat storage in the lake. Other energy terms, for example advection and conduction through the bottom, are assumed to be insignificant. The significance of possible terms to be added in eq. (1) has been examined in various studies (*Elomaa*, 1977).

The terms in eq. (1) are connected to each other in many complicated ways. The most important connecting factor may be the temperature of water surface. It influences directly all the terms. The term Q behaves differently in water than in ground. Global (short wave) radiation is absorbed in water and the heat is conducted downwards more through turbulent mixing than through diffusion.

3. *Lake Pääjärvi and the data*

Pääjärvi lies in southern Finland about 100 km north of Helsinki. The maximum depth is about 80 m and the surface area is 13.4 km^2. Its longest dimension is approximately 9.4 km and is oriented in the SW-NE direction. The longest dimension perpendicular to this is 3.4 km. Measurements were carried out at the lake during years 1991-1993 to get the data needed by the model. Wind speed, global radiation, air temperature and relative humidity of air were measured on the lake. Temperature and humidity are also used to calculate long wave radiation from the sky. A correction to the calculated long wave radiation to account for cloud cover was made using measured global radiation. The correction method, based on work reported by *Uden* (1982), was developed by *Virta et al.* (1992) for this purpose. Measurements made in 1991 were used to describe how data from a nearby synoptical station can be used to describe conditions on the lake. These comparisons took into account seasonal and diurnal variations. A meteorological station in Lahti (ϕ=60°58'N, λ=25°38'E) was used to generate data on lake Pääjärvi (ϕ=61°04'N, λ=25°08'E) for the same periods that Elomaa studied in 1969 and 1970. The velocity of wind was further corrected according to the measurements on the lake so that long term averages were the same as what was measured on the lake. The generated lake data were compared with measured values by Elomaa. The comparison is presented in Tables 1 and 2.

Table 1. Monthly means of data generated and used for the simulations and the corresponding values by Elomaa (in parenthesis) on lake Pääjärvi in 1969 and 1970. A: temperature of air (°C), B: relative humidity (%), C: global radiation (Wm^{-2}) and D: velocity of wind (m/s, only generated data, with correction on the periods).

Month	A	B	C	D
1969				
July	16.3 (15.9)	71 (74)	240 (230)	3.2
August	16.1 (15.6)	74 (74)	215 (202)	2.5
September	9.6 (9.5)	87 (85)	94 (90)	4.8
October	4.6 (5.6)	91 (88)	33 (48)	4.7
1970				
July	16.0 (16.2)	75 (79)	190 (194)	3.5
August	15.2 (15.1)	80 (79)	164 (173)	3.0
September	9.5 (9.6)	88 (87)	76 (83)	4.7
October	3.6 (5.6)	91 (84)	28 (33)	5.3

Table 2. Ratios of the mean net radiations to the mean global radiation on lake Pääjärvi in 1969 and 1970. Monthly means of net radiation (from Tables 3 and 4) are simulated with the PROBE lake temperature model (A, B and C) and earlier determined values in column D by *Elomaa* (1977). Values in column A are calculated with normal bulk formulae, *Friehe and Schmitt* (1976). In column B values are calculated so that flux of latent heat in the lake model is calculated with parameters defined for Pääjärvi by *Virta* (1981). Values in column C are calculated when the lake model includes the surface flux iteration algorithm by *Launiainen and Vihma* (1990).

Month	A	B	C	D
1969				
July	0.70	0.70	0.68	0.61
August	0.53	0.57	0.52	0.52
September	0.31	0.33	0.27	0.34
October	-0.82	-0.81	-0.87	-0.12
1970				
July	0.68	0.70	0.67	0.67
August	0.56	0.58	0.54	0.55
September	0.27	0.28	0.24	0.35
October	-0.89	-0.90	-1.00	0.003

4. *Calculation of fluxes at the atmosphere-water boundary*

In the usual flux routine sensible heat, H, and latent heat (moisture), LE, are calculated with bulk aerodynamic formulas and parameters by *Friehe and Schmitt* (1976):

$$H = \rho_a c_{pa}(C_1+C_H)u_z\Delta T \tag{2}$$

$$LE = \rho_a L_E C_E u_z(q_w-q_a) \tag{3}$$

where ρ_a is the density of air, c_{pa} its specific heat capacity and u_z is the wind velocity at height z. ΔT is the temperature difference between the surface of the water and height z, L_E is the latent heat of evaporation, q is specific humidity and indeces w and a refer to the surface of the water and the air. Parameters C_1 and C_H are determined according to stability, the product $u_z \Delta T$. When it is less than zero, the situation is stable and C_1=0.0026 and C_H=0.00086. When the product is positive, but less than 25 °C m/s, the situation is unstable and C_1=0.002 and C_H=0.00097. Otherwise, the situation is very unstable and C_1=0.0 and C_H=0.00146. Parameter C_E=1.36C_H. The reference height is 10 m. The actual surface temperature should be the so-called skin temperature, but, according to the original article, the measured temperature at a 1 m depth was often used.

The flux of latent heat was alternatively calculated by using parameters estimated for Pääjärvi by *Virta* (1981) with the water budget. According to his work, the evaporation E from lake Pääjärvi can be calculated (measurements at the height of 2 m) with the formula

$$E=C'u_z(e_w-e_a), \tag{4}$$

where C'=1.27 10^{-6} m (day Pa m/s)$^{-1}$, and e_w and e_a are the water vapour pressures on the water surface and at the 2 m height.This formula describes a neutral situation. Virta took stability into account with the bulk Richardson number R_{iv}:

$$R_{iv} = \left(\theta_z - \theta_o + 0.61T\,(q_z - q_o)\frac{C}{C_H}\right)\frac{gz}{(T_v\,u_z^2)} \;.. \tag{5}$$

T_v is the virtual absolute temperature, which may be replaced by the absolute temperature, T, without significant error. θ_z and θ_o are the potential temperatures at height z and at the surface, respectively. C_H is the bulk coefficient of sensible heat. In the unstable region the non dimensional Dalton number, C, is approximately equal to C_H. With eq. (5) (z=2 m) *Virta* (1981) gave the formula

$$C'=(1.00-3.67\,R_{iv})\alpha \tag{6}$$

where =1.19 10^{-6} m (day Pa m/s)$^{-1}$.

With both these ways to calculate the flux of latent heat, the flux of sensible heat was calculated with eq. (2). Wind stress τ_a was calculated in both these cases with the formula

$$\tau_a=0.00169\,\mathbf{u}_z^{\,2} \tag{7}$$

(τ_a and u_z are vectors).

The turbulent fluxes of momentum, sensible heat, and latent heat between the atmosphere and the water surface were also solved with iterative algorithms by *Launiainen* *and Vihma* (1990). The effect of stratification is included in universal functions that describe the profiles of wind speed, temperature, and specific humidity according to the Monin-Obukhov similarity theory. This iteration procedure includes new knowledge about these profiles. The iteration procedure calculates roughnesses, which are affected by wind and waves. The height of the measurements can be arbitrary. When it is used, the effects of stability should be described physically correctly. This routine also describes oceans, areas with unlimited fetch.

The iteration routine used was translated (into fortran) by the author from the original (basic) one by Launiainen and Vihma. The values it calculates were compared with the ones the original routine calculates. No further testing was made with the translated version (the article by *Launiainen and Vihma* (1990) includes testing).

5. *Simulations*

The generated lake data were used for the model, and the thermal development in the lake was simulated for both years using all three methods described in the previous chapter. Also various other simulations have been made to study the model's sensitivity to some errors.

When each of the simulations was done, the components of the heat balance eq. (1) were calculated as mean values of the months for the years 1969 and 1970. The results are shown for the two years in Tables 3 and 4. There are also earlier values defined by Elomaa and Virta (these values are not necessarily based on whole months). The simulated rate of the change of the heat storage, Q, was also calculated with values of the solved temperature profiles. *Elomaa* (1977) gives his values of Q as residuals of eq. (1). All the flux values are positive when directed upwards. When the heat balance components in eq. (1) were added, the result did not exceed 2 Wm^{-2} in any of the simulations. The results and their general accuracy are discussed in the following paragraphs. The estimates of the accuracy here are largely based on different sensitivity estimates from various simulations and the earlier calculated values available. Also the errors in data must be taken into account.

This kind of overall seasonal behavior is rather well described. *Elomaa* (1970) has also given shorter time mean values (e.g. about latent heat flux), but these averages are affected much by the way averages are actually calculated (*Elomaa*, 1977). It was also not possible to know, for example, exactly the times of averaging. When the average from simulated values is calculated (for a period of about one week), it is sensitive to, for example, the time of day the averaging is started. Still, one could see similar peaks in the simulated and Elomaa's time series of latent and sensible heat fluxes.

Table 3. Components of the heat balance computed for lake Pääjärvi in 1969. Monthly means are simulated with the PROBE lake temperature model (columns A, B and C). Earlier calculated values in column D are by *Elomaa* (1977) (and by *Virta* (1981) in parenthesis, first, for the neutral situation, then with stability effects). Values in column A are calculated with normal bulk formulae, *Friehe and Schmitt* (1976). Values in column B are calculated so that flux of latent heat in the lake model is calculated with the parameters defined for Pääjärvi by *Virta* (1981). Values in column C are calculated when the lake model includes the surface flux iteration algorithm by *Launiainen and Vihma* (1990). Units are Wm^{-2}, positive direction is upwards, and Q is positive, when the water warms up.

Month	A	B	C	D
LE				
July	90	110	88	126 (111, 116)
August	108	123	100	100 (110, 115)
September	83	81	74	85 (84, 86)
October	41	41	35	42 (35, 38)
H				
July	15	11	16	26
August	24	15	25	35
September	35	27	35	33
October	25	20	24	21
R				
July	-168	-170	-164	-140
August	-115	-123	-112	-105
September	-29	-31	-25	-31
October	27	27	29	6
Q				
July	62	49	59	-13
August	-17	-14	-13	-30
September	-88	-76	-83	-87
October	-91	-87	-86	-69

The surface temperature used was the temperature of the uppermost vertical grid point at the depth of about 20 cm. Its monthly mean value, as well as the mean value of the temperature from the depth of 2.5 m, were also calculated. In many test runs the 12 °C isotherm was seen as a good description of the thermocline. Means of this isotherm depth were calculated from hourly temperature profiles (July's and August's). These values are given for the year 1969 in Table 5 and for the year 1970 in Table 6. There are also corresponding values defined according to measurements that were carried out at the lake in those years. Temperature measurements at the lake were rather sparse, so the values based on them are not very accurate. The sensitivity of the simulated temperatures and depths are discussed later as well. More detailed analysis will be done in future with more developed models, examining the years 1991 to 1993. There are much more data about temperatures in the lake in those years and their accuracy is better.

Table 4. Components of the heat balance computed for lake Pääjärvi in 1970. Monthly means are simulated with the PROBE lake temperature model (columns A, B and C). Earlier calculated values in column D are by *Elomaa* (1977) (and by *Virta* (1981) in parenthesis, first, for the neutral situation, then with stability effects.). Values in column A are calculated with normal bulk formulae, *Friehe and Schmitt* (1976). Values in column B are calculated so that flux of latent heat in the lake model is calculated with parameters defined for Pääjärvi by *Virta* (1981). Values in column C are calculated when the lake model includes the surface flux iteration algorithm by *Launiainen and Vihma* (1990). Units are Wm^{-2}, positive direction is upwards, and Q is positive, when the water warms up.

Month	A	B	C	D
LE				
July	91	101	86	88 (88, 85)
August	80	86	74	92 (91, 92)
September	81	76	68	79 (72, 72)
October	40	41	36	47 (43, 44)
H				
July	18	12	18	13
August	20	15	21	27
September	38	30	36	40
October	24	21	25	22
R				
July	-130	-133	-127	128
August	-92	-95	-89	-95
September	-20	-21	-18	-29
October	26	26	28	0.1
Q				
July	21	20	22	27
August	-8	-6	-6	-24
September	-97	-84	-85	-90
October	-88	-87	-88	-69

Preliminary simulations, (*Virta et al.*, 1994), have shown that caution must be exercised when generalizing results directly from one year to another. Wind data is very important for the model, and the results are easily affected by the corrections to the wind velocity.

6. *Fluxes of latent and sensible heat*

Edges of the lake affect the profile of wind. Wind also affects the momentum flux and the mixing of the lake, and is very important for temperature development in a lake. Nevertheless, lake Pääjärvi should be large enough that no stress reduction factors are needed and formulas describing areas with unlimited fetch can be used when the temperature model of a lake is used. When the iteration routine is used, latent heat fluxes are 5 to 15 % smaller than when the usual bulk routine is used. The difference is smaller in summer.

Table 5. Simulated and measured temperatures and thermocline depths in lake Pääjärvi in 1969. Monthly means are simulated with the PROBE lake temperature model (columns A, B and C) and measured (in column D). Values in column A are calculated with normal bulk formulae, *Friehe and Schmitt* (1976). In column B values are calculated so that flux of latent heat in the lake model is calculated with parameters defined for Pääjärvi by *Virta* (1981). Values in column C are calculated when the lake model includes the surface flux iteration algorithm by *Launiainen and Vihma* (1990). Units are °C for temperatures and m for depths.

Month	A	B	C	D
Surface temperature				
July	19.3	18.9	20.0	18.4
August	22.7	21.3	23.3	19.5
September	13.7	13.4	14.5	12.6
October	7.4	7.4	7.8	7.3
Temperature at 2.5 m depth				
July	19.2	18.8	19.9	18.5
August	22.5	21.1	23.1	19.5
September	13.8	13.4	14.5	12.8
October	7.5	7.4	7.9	7.5
Depth of thermocline				
July	6.9	4.6	5.1	7.2
August	10.0	7.9	8.8	8.0

Table 6. Simulated and measured temperatures and thermocline depths in lake Pääjärvi in 1970. Monthly means are simulated with the PROBE lake temperature model (columns A, B and C) and measured (in column D). Values in column A are calculated with normal bulk formulae, *Friehe and Schmitt* (1976). In column B values are calculated so that flux of latent heat in the lake model is calculated with parameters defined for Pääjärvi by *Virta* (1981). Values in column C are calculated when the lake model includes the surface flux iteration algorithm by *Launiainen and Vihma* (1990). Units are °C for temperatures and m for depths.

Month	A	B	C	D
Surface temperature				
July	18.9	18.4	19.5	17.2
August	19.1	18.6	19.8	17.6
September	12.7	12.6	13.3	12.3
October	6.4	6.5	7.0	7.0
Temperature at 2.5 m depth				
July	18.8	18.2	19.4	17.9
August	19.0	18.5	19.6	17.6
September	12.7	12.6	13.3	13.1
October	6.4	6.5	7.0	-
Depth of thermocline				
July	9.7	7.4	8.0	6.9
August	12.3	10.5	11.3	10.1

Synoptical data give air temperature values at a 2 m height. This is also the height of the measurements. The transfer coefficients usually used are determined for a 10 m height. The wind profile was corrected by assuming the profile to be logarithmic. The usual routine contains an easy correction for water vapour pressure (about 10 %). If this correction is not done, temperatures are slightly smaller (0.0 to 0.4 °C),the depth of the thermocline is about the same, negative values of the radiation balance decrease few Wm^{-2}, the changes in the heat storage term are relatively small, summer evaporation is slightly bigger and sensible heat flux is slightly smaller.

With some exceptions the calculated fluxes of latent heat are close to the earlier calculated values, although they are not quite comparable. Earlier values by *Elomaa* (1977) are determined in one place in the middle of the lake and it is possible that they do not directly give the areal value from the entire lake. *Elomaa* (1977) also mentions that, due to differences in the surface temperature along the lake surface, there might be 10 % uncertainty in his numbers. When parameters for a bulk form formula are obtained with the water budget method the results are representative of the whole lake. Using the formula and parameters by *Virta* (1981), the calculated values agree with his values with an accuracy of 7 % (except July 1970). This method gives bigger values for latent heat flux in summer than the two other methods.

The values of the sensible heat flux are also small compared to other components and their uncertainties. The temperature profile is not corrected and the surface temperature seems to be rather sensitive. Errors in air temperatures also affect the values of sensible energy in 1969, which is also seen in the radiation balance.

7. *Radiation balances*

Radiation balances (net radiations) were relatively stable in different simulations. For 1969, the differences between measured and calculated values were bigger. This may be explained by errors in the data (Table 1). Air temperatures are higher (this also influences the long wave radiation from the sky) and global radiation is bigger than those measured on the lake. The measurements by Elomaa were taken in one point over water with an estimated accuracy of 5 %. There may be areal variation in the surface temperatures and the the long wave radiation, too ($\propto T^4$, T is the absolute temperature). The calculated ratios of net radiation to the global radiation over water (Table 2) are rather close to Elomaa's values for 1970 and August, 1969. The values from October and September are smaller and more sensitive to errors, and they are different from Elomaa's values.

8. *Heat storage terms and temperatures*

The calculated values of the monthly means of the heat storage terms Q differ more from the earlier ones by Elomaa. There has to be differences in some other components of the balance. Usually this is seen more clearly in the radiation balance and differences in the long wave radiation emitted from water ($\propto T^4$, T is the absolute temperature). Fluxes of latent heat and sensible energy are also affected, but not as much. There are also differences in the measured and calculated water temperatures. According to the simulations, there can be differences of 1 to 2 ^oC when different methods are used. There were also differences in the depth of the thermocline, as large as 2 to 3 m. Still, all the simulations gave changes in heat storage terms closer to each other than the earlier values by Elomaa that were calculated as residuals of eq. (1). The lake model calculation with the iteration routine (also the stresses are calculated with iteratively corrected wind profiles) usually gave higher temperatures than other two methods, but its prediction of the depth of the isotherm was between the depths obtained with other two methods.

Time series of daily values of measured and calculated surface temperatures are presented in figures 1 and 2. Generally, peaks and valleys can be seen in all of the series at the same points. Usually at the end of summer, differences between the predicted and measured series are bigger: the measured values are smaller than those calculated. When the lake temperature model uses parameters defined for the lake, the values are closest.

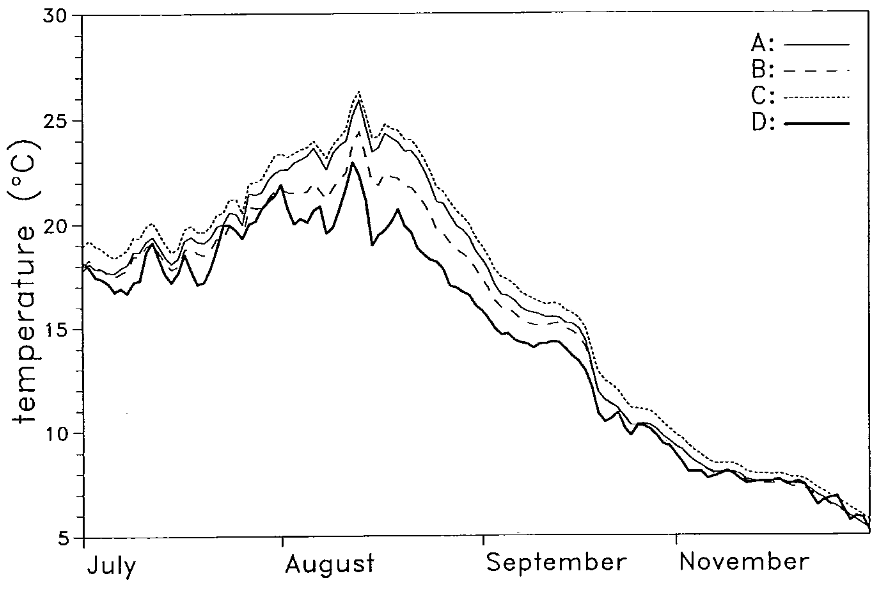

Fig. 1. Daily values of measured and simulated water surface temperatures in lake Pääjärvi in 1969. Simulations are done with the PROBE lake temperature model (lines A, B and C) and measured (line D). Line A is calculated with normal bulk formulae, *Friehe and Schmitt* (1976). Line B is calculated so that flux of latent heat in the lake model is calculated with parameters defined for Pääjärvi by *Virta* (1981). Line C is calculated when the lake model includes the surface flux iteration algorithm by *Launiainen and Vihma* (1990).

9. *Sensitivity to wind velocity*

The model can be calibrated by multiplying the wind with a suitable factor and by controlling the changes in temperatures. Comparison runs with the usual bulk formulae and parameters by *Friehe and Schmitt* (1976) were performed to see the changes in calculated values, when the wind velocity was increased or decreased by 10 %. Increasing wind caused only slighly increased evaporation (less than 4 Wm^{-2}), and the depth of thermocline (about 2 m). Values of sensible heat flux stayed almost the same. At the same time, temperatures decreased less than about 0.5 °C. Changes in the heat storage terms were from about 3 Wm^{-2} in July to -5 Wm^{-2} in October. Decreasing wind velocity had about the opposite effect: the changes of the indicator values had about the same values but opposite signs. Although simulated values of temperatures, depth of the thermocline, and the latent heat flux got values closer to the measured and earlier values, at the same time the values of the radiation balance had values further from earlier measured values. Still, adjusting the wind data helped to describe temperatures in the lake as was expected.

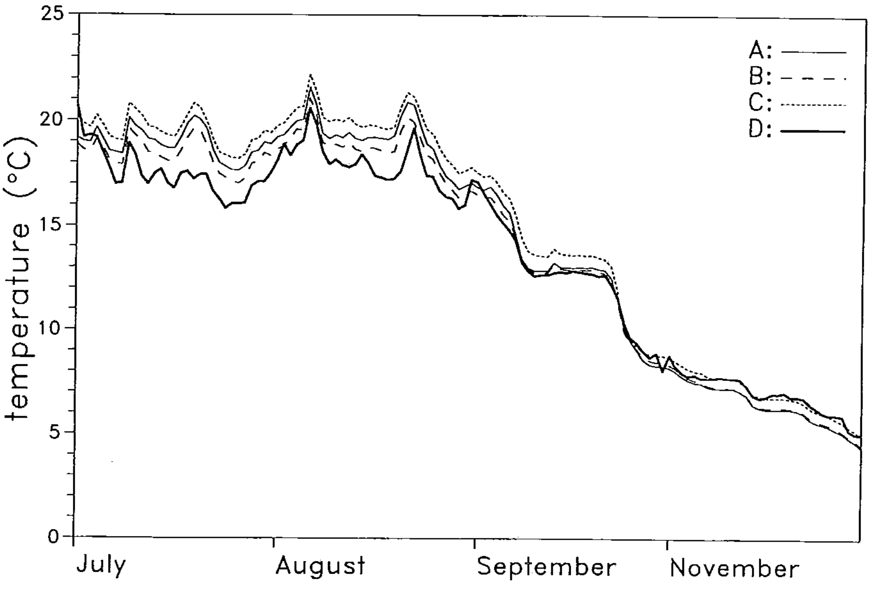

Fig. 2. Daily values of measured and simulated water surface temperatures in lake Pääjärvi in 1970. Simulations are done with the PROBE lake temperature model (lines A, B and C) and measured (line D). Line A is calculated with normal bulk formulae, *Friehe and Schmitt* (1976). Line B is calculated so that flux of latent heat in the lake model is calculated with parameters defined for Pääjärvi by *Virta* (1981). Line C is calculated when the lake model includes the surface flux iteration algorithm by *Launiainen and Vihma* (1990).

10. Stability

The usual routine for the surface flux calculation takes stability effects into account using different parameter values in different stability situations, as described above. In the simulations, a little less than 20 % of the time situation was classified as stable, a little over 60 % as unstable and a little over 20 % as very unstable.

When parameters by Virta were used, eq. (6) was used about 80 % of the time. It is actually determined for the range: R_{iv}=-0.14 to 0.00. About 25 % of bulk Richardson's numbers were smaller, but eq. (6) was still used. Introducing them gave only marginal changes to the indicators given. So, essentially, the values in columns B in Tables 3 to 6 also represent the neutral situation.

11. Conclusions

Results of areal estimates of the heat balance components of the lake calculated using the PROBE lake temperature model are very encouraging. One can calculate the lake evaporation well. Still, if very accurate result are required and all the components of the heat balance must be described well at the same time, it seems that the model needs some kind of tuning: in the two years simulated in this study, either the flux of the latent heat component, or the radiation balance component was generally well described, but not the both at the same time.

The model can be calibrated by multiplying the wind velocity by a suitable factor. Increasing the wind speed gives better values for the temperatures and the thermocline depth. Then, the values of the latent heat flux correspond better to earlier calculations. At the same time, the radiation balance gets values further from the measurements. This also indicates that some tuning might be needed.

The temperature of the water and the depth of the thermocline are sensitive to forcing at the surface. Therefore it is worth studying forcing routines further. The accuracy of lake temperatures was difficult to estimate in this study, because there were not many water temperature measurements in a month for those years. Further studies can use more accurate temperature data.

The results cannot show that one flux routine is better than the others when used as a part of the PROBE temperature model of a lake. Further analyses are needed together with a lot of measured information. Together with some other preliminary simulations, one can say that it is still not possible to directly generalize these results to other years. One cannot even exclude some systematic difference between 1969 to 1970 and 1991: at least 1991 was warmer and less windy. The importance of appropriate corrections to the wind velocity has clearly been shown.

When the temperature model is used with the bulk formula parameters obtained with the water budget method (concerning latent heat flux), the results are generally closest to the measured values. It also should best represent the lake area as a whole. Parameters for the bulk formula should anyway be estimated for the particular lake and situation. This needs a lot of measurements on the lake. Calculation of other fluxes should also perhaps be changed. This was not yet studied.

Adjustments of the wind and use of parameters defined for the particular lake give results that are closer to earlier determinations and measurements. This also indicates that it is useful to pay attention to the calculation of the surface forcing. The conditions over the lake differ from those over an area with unlimited fetch.

The iteration routine by *Launiainen and Vihma* (1990) is already capable of handling different measuring heights and can calculate all the fluxes easily. When it was used, the results were generally close to the values obtained with the usual routine with bulk formula and parameters by *Friehe and Schmitt* (1976). These two methods actually describe areas with unlimited fetch. When the lake model was used with the iteration routine, the latent heat fluxes were smaller and the water temperature higher, meanwhile the ratios of net to global radiation were closer to the measured values. The depth of the thermocline was usually well described. It is well worth trying to tune the iteration routine to describe lake conditions better.

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References

Elomaa, E., 1976: Pääjärvi Representative Basin in Finland: Comparative studies of climatological conditions over a lake and the surrounding land areas in 1969-1970, *Fennia*, **146.**

Elomaa, E., 1977: Pääjärvi representative basin Finland: heat balance of a lake, *Fennia*, **149**.

Friehe, C. and Schmitt, K., 1976: Parametrization of Air-Sea Interface Fluxes of Sensible Heat and Moisture by Bulk Aerodynamic Formulas, *Journal of Physical Oceanography*, **6**, 801-809.

Huttula, T., Peltonen, A., Bilatetdin, Ä. and Saura, M., 1992: The effects of climatic changes on lake and water temperature, *Aqua Fennica*, **Vol. 22**, 2, 129-142.

Launiainen , J. and Vihma, T., 1990: Derivation of Turbulent Surface Fluxes - An Iterative Flux-Profile Method Allowing Arbitrary Observing Heights, *Environmental Software*, **Vol. 5**, No. 3, 113-124.

Sahlberg, J., 1983: A Hydrodynamical Model for calculating the Vertical Temperature Profile in Lakes During Cooling, *Nordic Hydrology*, 239-254.

Svensson, U., 1978: Examination of the Summer Stratification. *Nordic Hydrology*, **9**, 105-120.

Svensson, U., 1986: PROBE An Instruction Manual, *SMHI rapporter Oceanografi*, Nr 10.

Omstedt, A., Sahlberg, J. and Svensson, U.,1983: Measured and numerically-simulated autumn cooling in the Bay of Bothnia. *Tellus*, **35A**, 231-240.

Unden, P., 1982: The Swedish Limited Area Model, Swedish Meteorological and Hydrological Institute, RMK **35**.

Virta, J., 1981: Estimating the Effect of Atmospheric Stability on Lake Evaporation with the Water Budget Method, *Geophysica* **17**:1-2, 123-131.

Virta, J., Elo, A.-R., Pulkkinen, K., 1992: Effect of climatic change on the temperature of lakes, The Finnish Research Programme on Climate Change, Progress Report, Publications of the Academy of Finland 3/92, 109-114.

Virta, J., Elo, A.-R., Pulkkinen, K., 1994: Application of lake temperature model for predicting the effect of climatic change, The Finnish Research Programme on Climate Change, Second Progress Report, Publications of the Academy of Finland 1/94, 134-139.