Appendix B. Additional methods: Calculation of heat fluxes.

As in Goudsmit et al. (2002) the heat budget considers heat fluxes due to short wave radiation H_S, long wave radiation from the atmosphere H_A, long wave radiation from the water surface H_W, evaporation H_E and conduction H_C. The net heat flux H is calculated as

$$H = H_S + H_A + H_W + H_E + H_C \qquad \text{(B.1)}$$

The heat fluxes are calculated from meteorological data and surface water temperatures obtained from the lake model using the bulk formulae of Livingstone and Imboden (1989) in case of H_W, H_E and H_C (see Goudsmit et al. 2002) and Izomon et al. (2003) in case of H_A. Data on short wave radiation S were available from the meteorological station and H_S was calculated by estimating reflection of short wave radiation according to Ollinger (1999) assuming a smooth water surface.

Meteorological and lake data required for the calculation of the heat fluxes

T_a: air temperature [°C]

T_w: surface water temperature [°C]

h: relative humidity [-]

S: solar radiation [Wm^{-2}]

Cl: cloud cover [-]

p_{air}: air pressure [hPa]

u_{10}: wind speed 10 m above ground [$m\ s^{-1}$]

Vapor pressure of water in the atmosphere VP_a and immediately at the lake surface VP_w were calculated after Gill (1982):

$VP_a = h\cdot (1.0+10^{-6}\cdot p_{air}\cdot (4.5+6\cdot 10^{-4}\cdot T_a\cdot T_a))\cdot 10^{(0.7859+0.03477\cdot Ta)/(1+0.00412\cdot Ta)}$ [hPa]

(B.2)

$VP_w = (1.0+10^{-6}\cdot p_{air}\cdot (4.5+6\cdot 10^{-4}\cdot T_w\cdot T_w))\cdot 10^{(0.7859+0.03477\cdot Tw)/(1+0.00412\cdot Tw)}$ [hPa] (B.3)

Bulk formulae for the heat fluxes

All heat fluxes are defined positive for heat fluxes directed from the atmosphere to the lake.

Heat flux due to long wave radiation from the atmosphere based on Iziomon et al. (2003)

$H_A = p_1 \cdot (1-r_a) \cdot R_A$ (B.4)

$R_A = 5.67e\text{-}8\cdot (273.15+T_a)^4\,(1+0.0035\cdot Cl\cdot Cl\cdot 64)\cdot (1-0.35\cdot e^{(-10\cdot VPa/(Ta+273.15))})$ (B.5)

long wave radiation from the atmosphere (Iziomon et al. 2003)

$r_a = 0.03$ ratio of reflected long-wave irradiance

$p_1 = 0.99527$ calibration parameter (see also Goudsmit et al. 2002)

Heat flux due to short wave irradiance (Ollinger 1999)

$H_S = (1-r_{dir})\cdot S_{dir} + (1-r_{diff})\cdot S_{diff}$ (B.6)

$S_{dir} = (0.8 - 0.8\,Cl)\cdot S$ direct solar radiation

(B.7)

$S_{diff} = (0.2 + 0.8\,Cl)\cdot S$ diffuse short wave radiation (B.8)

r_{dir} : fraction of reflected direct solar radiation, which is calculated from the Fresnel equations and an 1.33 as index of refraction. r_{dir} depends on the angle of the incident light and therefore varies with time.

$r_{diff} = (Cl \cdot 0.05 + (1-Cl) \cdot r_{diff,c})$ fraction of reflection diffusive (B.9)

short wave radiation

$r_{diff,c}$: fraction of reflected diffusive short wave radiation for clear sky conditions based on Dirmhirn (1964). r_{diff} depends on the zenith angle and therefore varies with time.

Heat flux due to long-wave radiation from the water surface (Livingstone and Imboden 1989)

$$H_W = -\,0.97 \cdot 5.67 \cdot 10^{-8} \cdot (T_w + 273.15)^4 \qquad \text{(B.10)}$$

Heat flux due to evaporation (Latent heat flux) (Livingstone and Imboden 1989)

$$H_E = -\,f_u^{*} \cdot (VP_W - VP_A) \qquad \text{(B.11)}$$

$$f_u = 4.4 + 1.82 \cdot u_{10} + 0.26 \cdot (T_w - T_a) \qquad \text{(B.12)}$$

$p_2 = 0.97521$ calibration parameter (see also Livingstone and Imboden 1989 and Goudsmit et al. 2002)

$$f_u^{*} = p_2 \cdot f_u \qquad \text{(B.13)}$$

Sensible heat flux (Livingstone and Imboden 1989)

$$H_C = -\,f_u^{*} \cdot B0 \cdot (T_w - T_a) \qquad \text{(B.14)}$$

$B0 = 0.61$ Bowen constant

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