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Estimation of wet surface evaporation from sensible heat flux measurements

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[1] A new method is proposed to estimate wet surface evaporation by means of measurements of sensible heat flux and of air temperature, relative humidity, and wind speed at one level only. This formulation is made possible by the linearization of the Bowen ratio, a common assumption in other methods, such as Penman's model and its derivatives. The method will be useful in those cases where the sensible heat flux is more reliably acquired at field scales than the net radiation and the ground heat flux, which are needed in many operational methods because of energy budget considerations. Indeed, the ground heat flux is a notoriously difficult variable to measure on wet surfaces, such as lakes or wetlands, especially at the appropriate length scales, whereas sensible heat flux can be obtained from standard temperature variance methods or other instruments such as scintillometers. The proposed method was tested with field experimental data taken over Lake Geneva in Switzerland, where it showed excellent agreement with evaporation rates measured using eddy covariance techniques.

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1. Introduction

[2] Accurate estimates of evaporation are crucial to project future water availability [*Rind et al.*, 1997; *Bou-Zeid*, 2002; *Kustas*, 1990; *Ortega-Farias et al.*, 1995] and to study the potential effects of climate change on ecosystems [*Szilagyi et al.*, 2001; *ter Heerdt*, 2007]. In regional hydrological systems, open water bodies such as lakes or wetlands are often important components of the landscape. Therefore, methods to estimate evaporation from wet surfaces are essential. Moreover, this type of evaporation, also known as potential evaporation, is used in many operational methods as a basic component in the estimation of evaporation from nonwet surfaces [*Brutsaert*, 1982; *Stagnitti et al.*, 1989].

[3] A widely used approach to estimate evaporation, including evaporation from wet or other surfaces where the water vapor concentration at the surface can be presumed to be at saturation, is based on energy budget considerations [*Brutsaert*, 2005; *Priestley and Taylor*, 1972; *Shuttleworth*, 2007; *Parlange and Katul*, 1992; *Rosenberry et al.*, 2007]. The energy available for evaporation can be written as $Q_n = R_n - G$, where R_n is the net radiation and G is the downward positive surface or ground heat flux (consisting of conductive, convective and radiative heating of the water body and the underlying bed). The flux G is sometimes neglected in the available energy flux density, such that $Q_n = R_n$ is assumed. Nevertheless, the contribution of this term for water bodies can be considerable [*Tanny et al.*, 2008]. Its omission from Q_n was already pointed out almost 50 years ago as an important source of error by *Tanner and Pelton* [1960]. Measurements of G are thus necessary in energy balance methods to accurately estimate evaporation from any surface. But, even when available, the use of measurements of G has also been shown to be a large potential source of error in lake evaporation calculations [*Stannard and Rosenberry*, 1991].

[4] Another problem that arises with the application and verification of energy budget related methods is that the individual footprints of the necessary measurements can be very different and often mutually incompatible. For example, a typical radiometer will have a footprint area located directly underneath the instrument on the order of 10 m^2; ground heat flux measurements (G) will be very local with a footprint on the order of 0.1 m^2; and air properties (temperature, humidity, ...) will represent upstream surface conditions of several square kilometers [*Albertson and Parlange*, 1999; *Brutsaert*, 1998; *Parlange et al.*, 1995; *Eichinger et al.*, 1996; *Bou-Zeid et al.*, 2004]. Thus, when these measurements are combined to compute evaporation with formulations such as Penman's model, the footprint of the resulting evaporation rate will be ambiguous. In addition, when the model is verified against direct eddy covariance measurements of evaporation (with a variable footprint that can be on the order of several kilometers for unstable atmospheric stability conditions with strong winds), the discrepancy in the footprints of the various measurements will cause differences between the measured and modeled evaporation rates that cannot be distinguished from the differences caused by instrument and model errors.

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[5] In light of the limitations inherent in methods using the energy budget with net radiation R_n and surface heat flux G, it is the purpose of this paper to present an alternative approach using measures of the turbulent sensible heat flux H. The derivation of the proposed formulation relies on an approximation of the Bowen ratio used in *Penman*'s (1948) model, which has been shown to be accurate in many studies in the past [e.g., *Stannard and Rosenberry*, 1991; *Katul and Parlange*, 1992]. By using estimates of H, discrepancies between footprint scales of the different measurements can be greatly reduced, if not totally avoided. Moreover, even when no such discrepancies exist, measurements of G and R_n are not always easy; in contrast, measurements of the H from the surface into the atmosphere have become more ubiquitous through rapid advances in suitable instrumentation, such as for example, sonic anemometers and, more recently, scintillometers [*Andreas*, 1991; *Kleissl et al.*, 2008; *Meijninger et al.*, 2006, and references therein]. Estimates of H have been reliably obtained among others from a free convective second-order model [*Tillman*, 1972; *Kader and Yaglom*, 1990; *Albertson et al.*, 1995; *Weaver*, 1990; *Assouline et al.*, 2008] using very simple high-frequency measurements of the air temperature alone. In what follows, the proposed method will be presented and tested with experimental data obtained over Lake Geneva, Switzerland, and will be shown to produce results that are at least as accurate as other methods currently available.

2. Formulation of the Method

[6] The derivation starts with an estimate of the Bowen ratio,

$$Bo = \frac{H}{LeE}, \tag{1}$$

where E is the rate of evaporation from the surface and L_e the latent heat of vaporization of water. If the turbulent transfer coefficients of heat and water vapor are assumed equal above a wet surface (e.g., lake surface, well irrigated field, and surface after precipitation), this ratio can be estimated as

$$Bo_P = \gamma \frac{T_s - T_a}{e_s^* - e_a}, \tag{2}$$

where T_s is the surface temperature (K), $e_s^* = e^*(T_s)$ the surface water vapor pressure (hPa) (i.e., saturation value at the temperature T_s), the asterisk denotes saturation values, the subscript a denotes the same variables in the air, at the measurement level,

$$\gamma = \frac{c_p p}{0.622 L_e}$$

is the psychometric constant, where c_p is the specific heat of air at constant pressure (J kg^{-1} K^{-1}), p is the pressure (hPa). At 20°C and atmospheric pressure at sea level, $L_e = 2.453 \times 10^6$ J kg^{-1} and γ = 67 hPa K^{-1}. The subscript P in (2) denotes that this Bowen ratio estimate is derived from a profile method.

[7] Note with Penman that $\Delta = (e_s^* - e_a^*)/(T_s - T_a)$ can be used to estimate the slope of the saturation vapor pressure curve $\Delta = de^*/dT$ at air temperature. For the wet surface under consideration, (2) then can be rewritten as

$$Bo_L = \frac{\gamma}{\Delta}\left(1 - \frac{e_a^* - e_a}{e_s^* - e_a}\right), \tag{3}$$

where the subscript L indicates that this ratio is a linearized approximation.

[8] The ratio $(e_a^* - e_a)/(e_s^* - e_a)$ in (3) can be readily determined, after Penman, by use of a bulk transfer equation for evaporation $E = f(u)(e_s^* - e_a)$ and by defining a drying power of the air, $E_A = f(u)(e_a^* - e_a)$, where $f(u)$ is a function of the wind speed u (m s^{-1}). Thus, one can write

$$\frac{e_a^* - e_a}{e_s^* - e_a} = \frac{E_A}{E}, \tag{4}$$

which, by virtue of (1) yields immediately from (3) the final result

$$E = \frac{\Delta}{\gamma}\frac{H}{L_e} + E_A. \tag{5}$$

In practice, the slope of the saturation vapor pressure curve Δ can be readily estimated from the air temperature using available equations of e^* versus T such as, for example, the polynomial derived by *Lowe* [1977]. Equation (5) thus needs only measurements of H, the mean wind speed u, the vapor pressure of water in the air e_a and the air temperature T_a, all of which will have very similar footprints if measured at the same height. No measurements of surface temperature, net radiation, or surface heat flux are needed.

[9] The simplest form of the wind function is an empirical formulation of the type $f(u) = a + bu$, where a (s/m) and b (s^2/m^2) are dimensional constants; in practical applications over land surfaces, $f(u)$ as proposed by *Doorenbos and Pruitt* [1975] can be used or it can be determined on the basis of similarity or by calibration [*Brutsaert*, 2005]. For reasons to be explained below, in the present study dealing with Lake Geneva, we used the formulation $f(u) = 1.25.10^{-8}u$, (with $a = 0$) in which all the variables are in SI units. Note in the case of a water surface, that as wind speed increases, waves may start to have an important effect on the fluxes [see *Veron et al.*, 2008] that is not taken into account in this particular $f(u)$ formulation; therefore the wind function used here is valid only for small to moderate wind speeds. Note also that if H in (5) is replaced by (R_n− G − L_eE) one obtains exactly the formulation first derived by Penman,

$$E = \frac{\Delta}{\Delta + \gamma}\frac{Q_n}{L_e} + \frac{\gamma}{\Delta + \gamma}E_A. \tag{6}$$

3. Experimental Data

[10] The proposed formulation was tested with data collected during the Lake-Atmosphere Turbulent Exchange (LATEX) field campaign (August–October, 2006) over

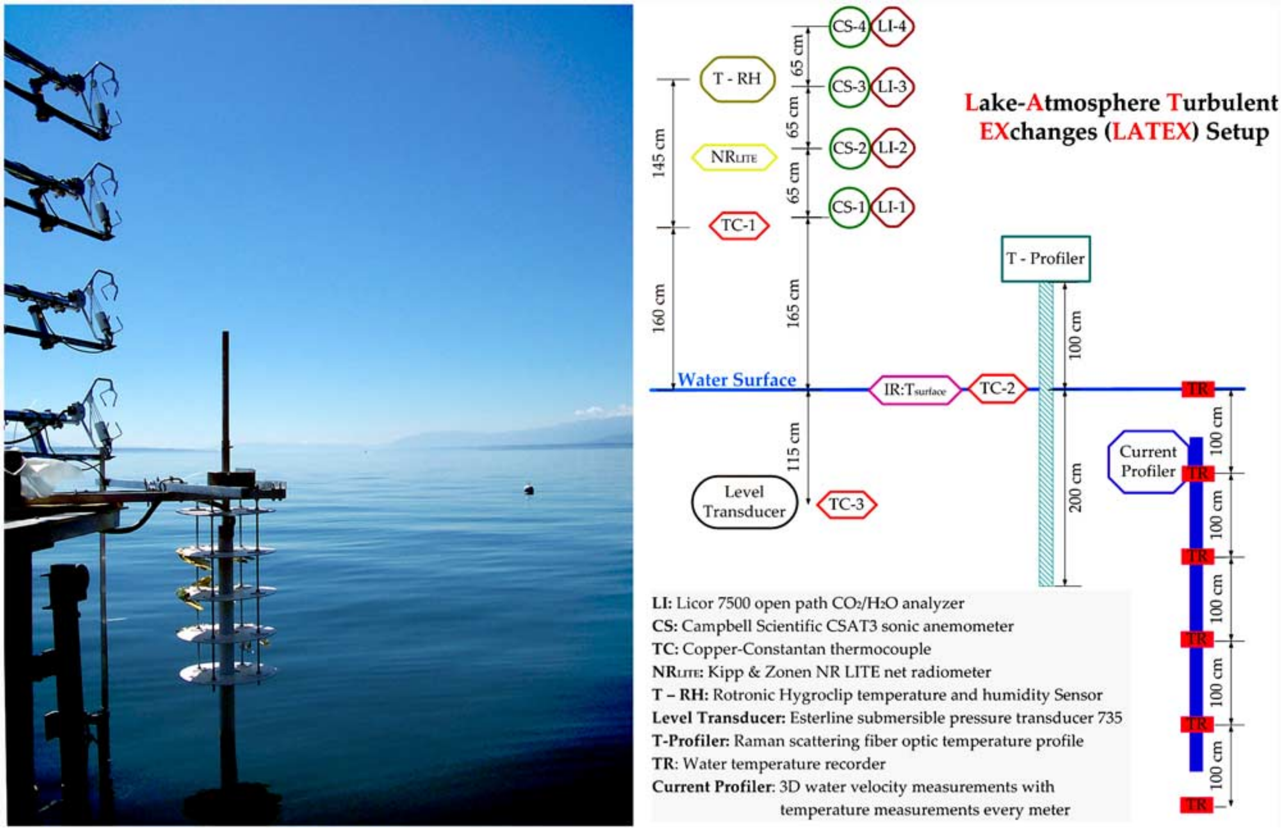

Figure 1. Setup of the vertical array over Lake Geneva during LATEX [from *Vercauteren et al.*, 2008] (with kind permission from Springer Science + Business Media).

Lake Geneva, Switzerland. Wind velocity, temperature and humidity profiles were measured at 20 Hz using a 5 m tower with a vertical array of four sonic anemometers (Campbell Scientific CSAT3) and open path gas analyzers (LICOR-7500). The heights of the four measurement levels above the lake surface were 1.65 m, 2.3 m, 2.95 m and 3.6 m, but only measurements at 2.95 m were used in the following results. The analysis was actually done for the four heights, giving very similar results (the average of the root-mean-square differences between the heat flux measurements from the four sonics was only about 1 W m^{-2}). For the benefit of later tests the water surface temperature was also measured by two independent systems (though these measurements are not needed in the formulation proposed). One was a thermocouple that was placed just below the average water surface, rigidly attached to the tower structure. The second system consisted of an Apogee Instruments IRTS-P infrared temperature sensor. Note that all subsequent comparative analyses requiring surface temperature made use of the thermocouple.

[11] The area of the lake is 582 km^2, and the measurement site was located 100 m from the northern shore of the lake. Only data collected with the wind coming from over the lake (southwest) were used, ensuring a minimal fetch of 10 km, with the measurements fully within the internal equilibrium layer of the lake. The wind speed never exceeded 10 m s^{-1} and waves rarely exceeded 20 cm. The details of the experiment are presented by *Vercauteren et al.* [2008] and by *Bou-Zeid et al.* [2008], and the setup is depicted in Figure 1.

[12] Sensible and latent heat fluxes during LATEX were also obtained using eddy covariance measurements, following

$$H = \rho c_p \overline{w'T'} \tag{7}$$

$$E = \rho \overline{w'q'}, \tag{8}$$

where the prime represents the fluctuating (turbulent) component for the vertical wind (w) and temperature (T) and the specific humidity (q); ρ is the mean density of the air, and the overbar denotes Reynolds averaging, which was performed in time over data records of 30 min. The evaporative flux obtained by eddy correlation was used to test the evaporation formulation (5) proposed in this paper.

4. Results

[13] The assumptions made in the proposed formulation (and also in the Penman model) are embedded partially in the approximation of the Bowen ratio. The first one, used in (2), states that the transfer coefficients of heat and water vapor are equal. The subsequent estimate of the Bowen ratio (Bo_P, equation (2)) is shown in Figure 2, and compared to the measured Bowen ratio (1) computed using the eddy covariance measurements for H and L_eE as described above. The correlation between the two is 76%, but the root-mean-square error is 109% because of the presence of a bias due to difficulties in measuring surface temperature which is

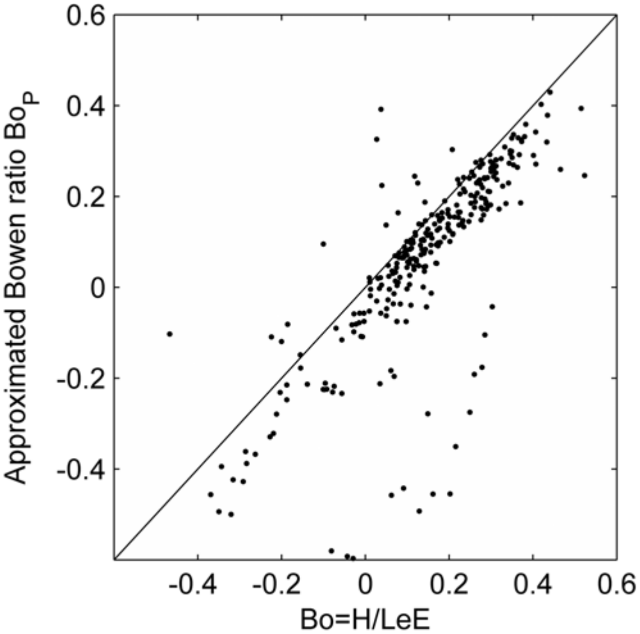

Figure 2. Approximated Bowen ratio (equation (2)) assuming equal heat and water vapor transfer coefficients versus Bowen ratio estimated by eddy covariance measurements.

discussed in more detail at the end of the paper. The second assumption used in the proposed formulation appears in (3) and states that the Bowen ratio can be computed using the linearized slope of the saturation vapor pressure curve (in addition to the equal turbulent transfer coefficients assumption). The quality of this estimate (Bo_L of equation (3)) can be judged in Figure 3, where it is tested again versus the measured Bowen ratio computed using the eddy covariance flux measurements. The correlation coefficient is 77%, and the root-mean-square error is 113%, again because of a bias. The averaging period used for the results is 30 min. Since the measurements used to compute Bo_L and Bo_P are the same, the fact that both have practically the same correlation and error may suggest that the assumptions underlying (2) and (3) are nearly equally valid, and that the errors result primarily from the measurements themselves. Actually, this should be no surprise, because both assumptions have already been validated in numerous studies in the past.

[14] Beside the Bowen ratio approximation, the other assumption used in (5), as well as in the Penman model, states that the evaporation can also be expressed as a bulk transfer equation, namely as a wind function multiplied by the difference between the water vapor pressures at two heights. As can be seen in (4), this leads to the second term in the equation with the drying power of the air. The wind function used here is the one mentioned above, i.e., $f(u) = 1.25.10^{-8}u$, which was obtained by using (5) together with the eddy correlation measurements of H and E. Note that this is thus derived on the basis of the drying power of the air and not from the mass transfer equation. One could determine $f(u)$ on the basis of similarity [*Brutsaert*, 1982; *Katul and Parlange*, 1992] but for simplicity we rely on the simple wind function as it can be more easily applied in field applications. Finally note that this wind function is similar to the original form given by Penman.

[15] After describing the different steps and separate components of the derivation, the proposed model performance can be directly tested by comparing the evaporation obtained with (5) with the evaporation measured using the eddy covariance technique. The results are shown in Figure 4, and the correlation coefficient is 95%, with a root-mean-square error of 23%. Thus the method certainly appears quite promising for regular applications. It is interesting to observe that evaporation values derived with the Bowen ratio (3) combined with the eddy covariance technique is much less reliable. The correlation of the measured evaporation and the evaporation obtained from

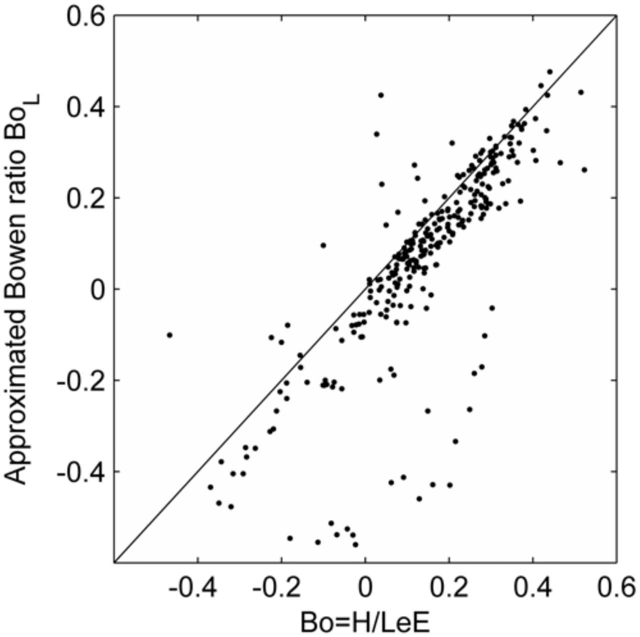

Figure 3. Linearized Bowen ratio (equation (3)) versus Bowen ratio estimated by eddy covariance measurements.

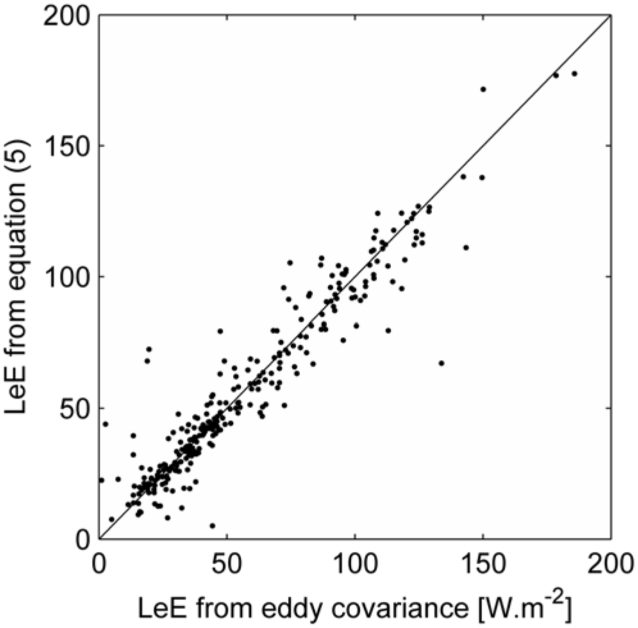

Figure 4. Evaporation from the proposed formulation (5) versus measured evaporation.

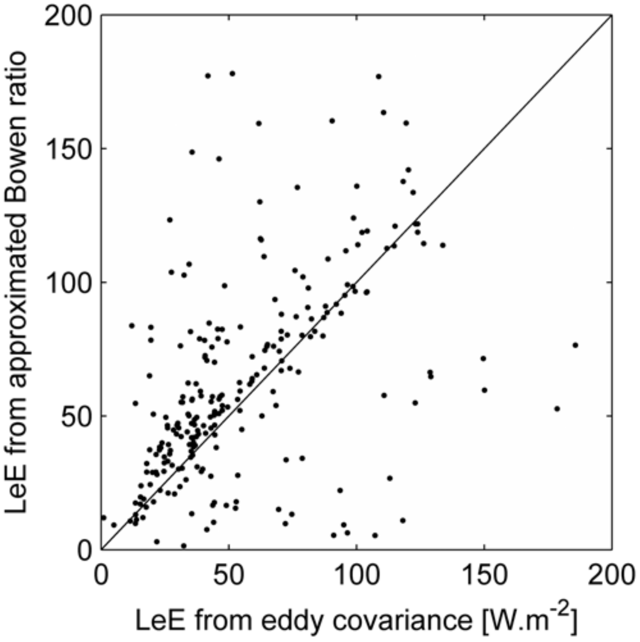

Figure 5. Evaporation from the Bowen ratio (equation (1)) (with (3) and (7)) versus measured evaporation.

a pure Bowen ratio model (namely, (1) with (3) and (7), or $L_eE = \rho c_p \overline{w'T'}/Bo_L$) can be inspected in Figure 5. This comparison shows significant scatter, with a correlation coefficient of 50% and root-mean-square error of 67%. This difference in performance may be explained as follows. In the computation of the estimated Bowen ratios Bo_P and Bo_L, the measured water surface temperature is needed to determine the difference between air and water properties (temperature and water vapor pressure). This is likely to include significant measurement errors when different temperature sensors are used. In addition, water surface temperature is not a straightforward variable to measure. Recall that during LATEX, two independent measurements of water surface temperature were made: one using a thermocouple that was kept as much as possible at most just a few centimeters below the surface (attempts to mount it on a float were not successful) and the other using the Apogee Instruments IRTS-P infrared temperature sensor. The two instruments did not agree all the time (see Figure 6). The thermocouple measurements were almost always higher. The thermocouple could have had errors related to its immersion or to radiative heating. The IR surface temperature measurements tend to have errors associated with the sensor body temperature correction needed and recommended by the manufacturer [*Bugbee et al.*, 1998] and with the IR transmissivity of liquid water (although liquid water is largely opaque to the wavelengths used by the Apogee instrument: 6–14 μm corresponding to frequencies of 275–715 cm^{-1}). With the significant errors in measuring the water surface temperature, and with the higher-order dependence of e^* on temperature T which will amplify any errors, the computations of the differences between T_a and T_s and e_a and e_s in (2) and (3) to estimate the Bowen ratios can be expected to produce significant errors. Hence the relatively low correlation between the measured and modeled Bowen ratios is not unexpected. On the other hand, when (1) and (4) are combined to yield (5), the parameters related to the water surface are canceled out (approximated by the linearized Δ) and the measurement errors related to water surface temperature are removed in the estimation of the surface evaporation.

[16] The important difference of performance between the Bowen ratio estimated evaporation and the one obtained via (5) can partly be explained by the difference of error propagation in each method. The propagation of errors is very different in the Bowen ratio estimation and in our proposed evaporation estimation method. Errors in the measurements of the vapor pressure of water and temperature in the air and at the surface will appear directly in the Bowen ratio estimate from (3), whereas measurement errors in air temperature and vapor pressure of water in the air will be balanced and somehow buffered by the first term in (5). A discussion about error propagation for Bowen ratio evaporation estimations can be found in [*Cragoa and Brutsaert*, 1996]. However, the difference of performance is probably mostly due to the use of the error-prone surface temperature measurement in the Bowen ratio approximation. The above analysis reveals one of the main strengths of the new approach proposed here: no surface measurements are needed so that the model will hence not suffer from the errors associated with such measurements.

5. Conclusions

[17] A method to estimate evaporation from wet surfaces, requiring estimation of the sensible heat flux and standard atmospheric variables (temperature, humidity and wind speed), is derived following the method of linearization of the Bowen ratio in the manner of *Penman* [1948]. The new approach does not require measurements of the ground heat flux and the net radiation and is especially useful where measurements of the sensible heat flux are more easily and cheaply available. This is often the case, since such data can

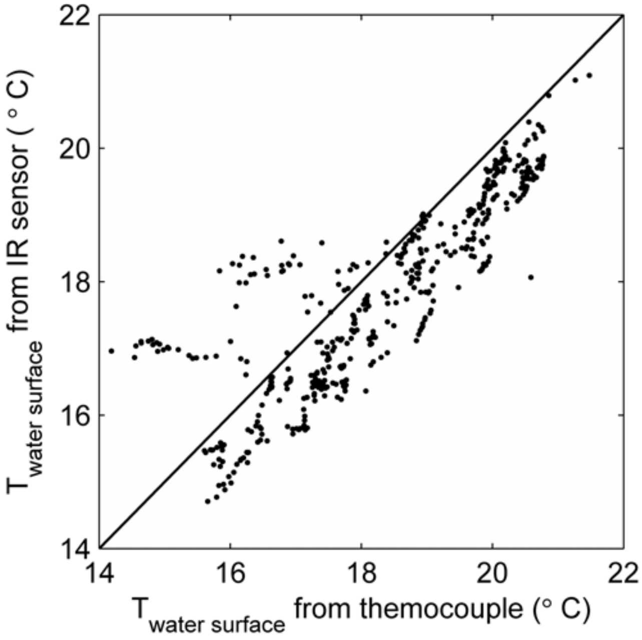

Figure 6. Comparison of water surface temperature measurements with two different instruments.

be obtained, for example, by measurements relying on flux variance relations using fine-wire thermocouples [*Albertson et al.*, 1995] or from estimates of the average rate of dissipation of the temperature fluctuations among other approaches [*Albertson et al.*, 1995; *De Bruin et al.*, 1993; *Katul et al.*, 1994; *Kiely et al.*, 1996]. Also, other methods based on optical scintillometers, direct eddy covariance measurements from a sonic anemometer can be used. Though often not discussed, evaporation methods that require measurements of heat flux both into a water body and into a moist land surface involve many challenges [*Tanny et al.*, 2008]. The proposed method could also be useful in applications with satellite remote sensing products that allow the estimation of the sensible heat flux. The performance of the proposed formulation (5) was assessed using data from the Lake-Atmosphere Turbulent Exchange (LATEX) experiment over Lake Geneva, Switzerland, and excellent agreement was obtained between predicted and measured evaporation rates.

[18] Formulations like the one proposed here, which are based on assumptions that allow the use of measurements at one level only instead of two, actually appear to improve the model performance. This is due to the typically large errors involved in measuring temperature and humidity differences between two or more levels over wet surfaces (especially surface temperatures). Finally, in any model of evaporation requiring variables measured with different types of instruments, the characteristic spatial scales of all observed variables and the upwind fetches, that is the footprints captured by the instruments, should ideally be mutually compatible. The proposed formulation also satisfies this requirement. Indeed, the air properties (e.g., wind speed, humidity, and temperature) and sensible heat flux measurements that are needed in (5) will have roughly the same footprint, and the resulting evaporation estimate will consequently have the same footprint as well. It is suggested then that the next generation weather stations for hydrologic applications (including wireless weather sensor networks [e.g., *Ingelrest et al.*, 2009]) include simple extensions to estimate sensible heat flux.

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