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A new empirical procedure for estimating intra-annual heat storage changes in lakes and reservoirs: Review and analysis of 22 lakes

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ABSTRACT

Evaporation is an important component of the water and energy balance of lakes and reservoirs. The energy balance combination method for estimating evaporation requires the heat storage changes (Q_t) to be known. The lack of data on water temperature profiles and water depth fluctuations hinders routine computations of Q_t. Following successful estimation of the soil heat flux density of land surfaces (G) and heat storage change of urban areas and wetlands from net all wave radiation (Rn), we investigated in this paper whether a similar generic Q_t(Rn) empirical relationship can be developed for lakes and reservoirs. A comprehensive literature survey was conducted and experimental datasets for 22 lakes with different characteristics were collected. A linear Q_t(Rn) model with a hysteresis function to describe seasonal warming and cooling effects was developed ($Q_t = a * \mathrm{Rn} + b + c * \mathrm{dRn/dt}$) that fits the 22 independently gathered datasets satisfactory (R^2 of 0.83 and RMSE of 22 W m^{-2}) for bi-weekly and monthly time scales. Predictive models for the coefficients *a*, *b* and *c* were also developed, using Rn and water surface temperature measurements that can be retrieved from routine earth observation measurements. The average R^2 between measured and modeled Q_t was 0.84 and the RMSE was 37 W m^{-2} if predictive models were used for the assessment of lake specific Q_t(Rn) functions. Two independent satellite-derived products were explored: the ARC-Lake (ATSR Reprocessing for Climate) product for water surface temperature using the ATSR (Along Track Scanning Radiometer) series data, and the CM SAF (Satellite Application Facility on Climate Monitoring) product for solar radiation Rs based on the AVHRR (Advanced Very High Resolution Radiometer) data. The proposed procedure using purely satellite-derived data as inputs resulted in comparably good Q_t estimates as those using in-situ measurements. The new Q_t hysteresis model can thus be applied together with satellite measurements for supporting the computation of evaporation from open water bodies based on energy balance equations.

1. Introduction

Lakes and reservoirs store fresh water, and make valuable water resources available to domestic, industrial, irrigation, hydropower, wetlands, recreational and environmental water use sectors, among others, during dry periods. Reservoirs buffer the peak discharge after rain storms, which prevents flooding of deltas and other downstream areas. Evaporation is an important component of the water and energy balance of lakes and reservoirs, and considered as a consumptive use of water for the services that this water provides. Mekonnen and Hoekstra (2012) for instance showed that the world wide reservoir evaporation behind dams for generating hydropower adds up to 90 km^3/year. Direct measurements of evaporation from water bodies for operational purposes are difficult (e.g. Rimmer, Samuels, & Lechinsky, 2009), and usually only done during dedicated, short duration scientific studies. Most evaporation measurements with eddy covariance techniques relate to limited periods and a few selected lakes only (e.g. Blanken et al., 2000; Panin, Nasonov, Foken, & Lohse, 2006). For applications in hydrology and water management, lake evaporation needs to be computed using indirect methods, such as the water balance methods, mass transfer methods and energy balance methods. Reviews of computational methods for estimating lake evaporation are given by for instance Brutsaert (1982), Singh and Xu (1997), Xu and Singh (2000, 2001), Finch and Calver (2008) and Jensen (2010). The performances of various methods have been evaluated and compared for several specific lakes (e.g. Delclaux, Coudrain, & Condom, 2007; Rosenberry, Winter, Buso, & Likens, 2007).

Given the lack of direct measurements of evaporation from water bodies, the energy balance method is generally considered as an accurate method for assessing open water evaporation if other components can be measured or estimated with sufficient accuracy (e.g. Assouline & Mahrer, 1993; Finch & Calver, 2008; Gianniou & Antonopoulos, 2007; Rosenberry et al., 2007). Evaporation estimates as the residual from other known energy balance components, contains however cumulative errors from the other components (Croley Ii, 1989). By assuming other energy fluxes to be small and negligible, the surface energy

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balance equation for open water surfaces can be written as (Gallego-Elvira, Baille, Martin-Gorriz, & Martinez-Alvarez, 2010):

$$\mathrm{Rn} = \mathrm{H} + \lambda\mathrm{E} + \mathrm{Q_t} \tag{1}$$

where Rn is the net all wave radiation, H is the sensible heat flux density, λE is the latent heat flux density, and Q_t is the water heat flux density at the water–atmosphere interface. Q_t is often considered equal to the heat storage changes in the water body. The signs of H, λE are positive if directed away from the water–atmosphere interface. The sign of Q_t is positive when water body is storing energy while negative when the stored energy is released as a heat flux density from the water body into the atmosphere. Q_t is not only controlled by conduction and solar radiation, but is also governed by all heat convective flows inside the water body. Most energy balance combination equations require the explicit determination of Q_t and Rn (e.g. Blanken et al., 2000; McJannet, Cook, & Burn, 2013; Rosenberry et al., 2007).

Generally, Q_t is computed from the change in water temperature for the time step over which the energy balance method is conducted. The equation is described as (e.g. Gianniou & Antonopoulos, 2007; Rodriguez-Rodriguez, Moreno-Ostos, De Vicente, Cruz-Pizarro, & Da Silva, 2004):

$$\mathrm{Q_t} = \frac{\rho_w c_w}{A_s}\frac{d}{dt}\int_0^{z_m} A(z,t)T(z,t)dz \tag{2}$$

where ρ_w is the density of water (kg m^{-3}) which is also a function of water temperature; c_w is the specific heat of water (J kg^{-1} $°C^{-1}$); A_s is the surface area of the lake (m^2); A(z,t) is the horizontal area of the lake as a function of depth z and time t; z_m is the maximum depth (m); T(z,t) is the water temperature as a function of depth z and time t. The solution of Eq. (2) requires detailed vertical water temperature profiles T(z,t) and bathymetric information for A(z,t) and A_s. Sensors for measuring T(z,t) profiles need to be installed at various depths inside the water body. These measurements are rarely available for the vast majority of lakes around the world (Kirillin et al., 2011). The point-based temperature measurements are not representative of influences over a larger horizontal area. Furthermore, the bathymetric information is also not easily accessible. The A(z,t) relationship can be solved from altimeter satellite measurements combined with optical satellite imagery that provides the area for a given lake (e.g. Duan & Bastiaanssen, 2013a). For some cases, the A(z,t) may not change very much and thus the area terms A_s and A(z,t) can be removed from Eq. (2) (e.g. Gallego-Elvira et al., 2010).

Because of the measurement problems described above, many studies simply ignore Q_t for lake evaporation estimations (e.g. Benzaghta, Mohammed, Ghazali, & Soom, 2011; Keskin & Terzi, 2006; Vallet-Coulomb, Legesse, Gasse, Travi, & Chernet, 2001). Considering the relatively large magnitude of Q_t (Gentine, Entekhabi, & Heusinkveld, 2012; Rodriguez-Rodriguez et al., 2004), the neglect of Q_t will inevitably introduce a large uncertainty in estimating evaporation for periods of one month and shorter (e.g. Finch, 2001; Gallego-Elvira et al., 2010). Allen and Tasumi (2005) showed on a monthly time scale, that Q_t could account for 50–70% of Rn for the American Falls Reservoir (AFR, U.S.A.). When Rn reaches minimum values in winter, the magnitude of Q_t could be even more than ten times the value of Rn (see Fig. 1 as an example for Lake Vegoritis, Greece). Hence, any energy balance or combination model requires an accurate quantification of the annual cycle of Q_t that controls the heat storage changes in water bodies.

Although various numerical heat storage models for lakes have been developed to simulate temperature profiles (T(z,t)) using routine weather data and several lake-specific characteristics (e.g. depths, optical transparency), calibration using measured water temperature profiles is necessary for most applications (e.g. Antonopoulos & Gianniou, 2003; Momii & Ito, 2008). Several studies assume a lake to be well-mixed. The "equilibrium temperature method" (ETM) developed by Edinger, Duttweiler, and Geyer (1968) has been used in numerous evaporation studies of shallow lakes to account for Q_t (De Bruin, 1982; Finch, 2001; McJannet et al., 2013). The assumption of well-mixed water temperatures may hold true for shallow lakes, but not for deep lakes where thermal stratification occurs due to many complex convective mixing processes. Finch and Hall (2001) mentioned that a lake with depth of up to 10 m may be reasonably assumed to have no thermal stratification. Thus, the accuracy of ETM method could not be warranted for lakes with a depth exceeding 10 m because of its fundamental assumption becomes invalid (Finch & Hall, 2001). The thermal stratification in lakes can be caused and affected by many factors such as change of water density, the heat exchanges with the atmosphere, and wind speed (Churchill & Kerfoot, 2007), inflow from rivers, besides interactions with the deeper underground, including geothermal processes.

An alternative solution for estimating Q_t is to explore the available energy from shortwave and longwave radiation at the water–atmosphere interface. The annual radiation cycle is namely regarded as the general key driver of Q_t variability and Q_t has to be a certain fraction of Rn. Some studies (Choudhury, Idso, & Reginato, 1987; Clothier et al., 1986; Verhoef, 2004) observed strong relationship between the soil heat flux density (G) and Rn for land surfaces (the energy balance equation for land surface is described as Rn = H + λE + G). Since then, empirical procedures have been developed to estimate G from Rn (e.g. Allen, Tasumi, & Trezza, 2007; Bastiaanssen, Menenti, Feddes, & Holtslag, 1998; Su, 2002). Similarly, heat storage in urban environments has also been found to be strongly related to Rn. Methods based on

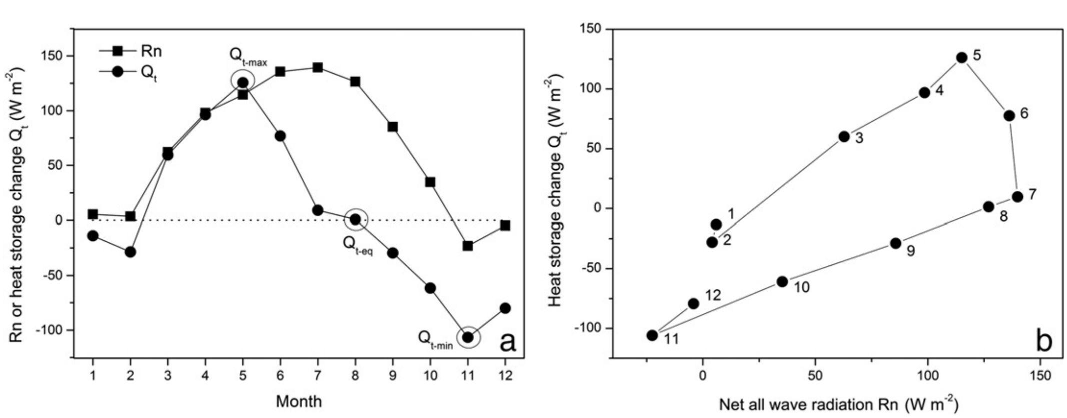

Fig. 1. (a) The annual cycle of monthly averaged net all wave radiation Rn and net change in heat storage Q_t, and (b) the scatterplot of Q_t against Rn (the number for each point refers to the month) for Lake Vegoritis, Greece (Table 1). The $Q_{t\text{-max}}$ and $Q_{t\text{-min}}$ refer to the maximum and minimum of Q_t, respectively. The $Q_{t\text{-eq}}$ means the assumed equilibrium point $Q_t = 0$ W m^{-2}, see Section 4.3.3 for details.