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Automated calculation of surface energy fluxes with high-frequency lake buoy data

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ABSTRACT

Lake Heat Flux Analyzer is a program used for calculating the surface energy fluxes in lakes according to established literature methodologies. The program was developed in MATLAB for the rapid analysis of high-frequency data from instrumented lake buoys in support of the emerging field of aquatic sensor network science. To calculate the surface energy fluxes, the program requires a number of input variables, such as air and water temperature, relative humidity, wind speed, and short-wave radiation. Available outputs for Lake Heat Flux Analyzer include the surface fluxes of momentum, sensible heat and latent heat and their corresponding transfer coefficients, incoming and outgoing long-wave radiation. Lake Heat Flux Analyzer is open source and can be used to process data from multiple lakes rapidly. It provides a means of calculating the surface fluxes using a consistent method, thereby facilitating global comparisons of high-frequency data from lake buoys.

Software availability

Lake Heat Flux Analyzer is written in MATLAB and is free to download (https://github.com/GLEON/HeatFluxAnalyzer). Users without access to MATLAB can use the web interface (heatfluxanalyzer.gleon.org) which runs Lake Heat Flux Analyzer on a remote server based on user input files and allows users to download results after completion.

1. Introduction

The dynamic coupling between lake and atmosphere depends on the transfer of momentum, heat and material, at the air–water interface. The magnitude of these fluxes influences physical processes within lakes which, in turn, have a major impact on lake ecology (George and Taylor, 1995; Winder and Schindler, 2004). In order to understand the functioning of lakes it is therefore imperative to have a detailed understanding of how different atmospheric forcing can affect the system. This is particularly true in the context of climate change (De Stasio et al., 1996; Desai et al., 2009) where interactions between the atmosphere and a lake are one of the major causes of alterations to lake ecology and biogeochemical fluxes.

Along with the exchange of radiant energy, the water surface turbulent fluxes play an integral part in the functioning of a lake. These fluxes, for example, produce sub-surface currents (Strub and Powell, 1986), influence ice-cover break-up dates (Anderson et al., 1996), and alter the strength and duration of thermal stratification. By influencing thermal stratification and mixing, surface energy fluxes can affect light availability to phytoplankton (MacIntyre, 1993), the metabolic cycles of primary producers (Staehr et al., 2010), and the rate of gas exchange between the lake and the atmosphere (MacIntyre et al., 2010). Surface energy fluxes are also often treated as upper boundary conditions for physical lake models (e.g. Peeters et al., 2002) and can be used to estimate the overall heat budget of lakes (Wetzel and Likens, 1991).

Direct measurements of turbulent fluxes at the water surface are expensive. A large amount of research has therefore focussed

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on the derivation of appropriate methods to estimate these fluxes from relatively well known and frequently measured variables (e.g. Garratt, 1977; Large and Pond, 1982; Fairall et al., 1996). These bulk aerodynamic parameterizations, however, require the use of transfer coefficients. Numerous bulk transfer coefficient schemes exist, which vary in complexity and sophistication (Renfrew et al., 2002). Simple approaches using constants or relationships with wind speed (e.g. Jones et al., 2005; Mackay et al., 2011; Vachon and Prairie, 2013) are easy to apply but have limited accuracy, while the technical complexity of the full calculations limits their usage.

Surface flux estimates are sensitive to the choice of algorithms used (Blanc, 1985; Zeng et al., 1998) especially when they have been developed for a limited range of wind speeds (e.g. Chang and Grossman, 1999). Despite recent efforts to develop these algorithms, no single method is consistently used to calculate the surface fluxes in lakes, and studies which compare different calculation approaches are uncommon. An additional source of uncertainty in comparing surface flux estimates across lakes results from comparing data measured at different heights above the water surface on different lakes. Standardization of methodology and cross-lake comparisons can be facilitated with easy-to-use and freely available software.

Recent advances in aquatic sensor technology have resulted in large numbers of instrumented lakes that have enabled multiple cross-site collaboration (e.g. Read et al., 2012; Solomon et al., 2013). Indeed, collaborative science in limnology on a global scale is fast becoming the norm (Hanson, 2007). In order to translate this present-day ‘flood’ of environmental data into reproducible science, the use and creation of shared analytical tools is critical (Porter et al., 2012). In the following, we introduce a program called “Lake Heat Flux Analyzer” which can be used to calculate surface energy fluxes from lake buoy data according to established methodologies available in the literature. We demonstrate the use of this program by calculating the surface energy fluxes for three lake datasets from the Global Lake Ecological Observatory Network (GLEON; http://www.gleon.org/).

2. Materials and methods

2.1. Site description

High-frequency observations of water temperature and meteorological drivers were collected from three lakes that range in surface area from 1.0 to 79.8 km^2. The study sites include one lake from the United Kingdom (Esthwaite Water), one lake from the United States of America (Lake Mendota) and one lake from New Zealand (Rotorua). Each lake is exposed to a temperate climate. They are seasonally stratified and none of the data series included occasions when the lakes were ice covered.

Surface water temperature and meteorological measurements from each lake were collected by several instruments and maintained by different organizations. Esthwaite Water is part of the United Kingdom Lake Ecological Observatory Network (UKLEON) and is maintained by the Centre for Ecology & Hydrology, United Kingdom. Air temperature and relative humidity were measured at a height of 2.14 m above the lake surface and wind speed was measured at a height of 2.85 m. The instrumented buoy on Lake Mendota is maintained by the North Temperate Lakes – Long Term Ecological Research (NTL-LTER) program, which includes lakes in northern and southern regions in the state of Wisconsin. Data were collected every minute and fifteen-minute averages were then computed from the high-frequency data. Air temperature, relative humidity and wind speed were measured at a height of 2 m above the lake surface. For Lake Mendota, hourly estimates of incoming long-wave radiation data were calculated from 15 min values observed at the nearby, Madison National Oceanic & Atmospheric Administration radiation monitoring site. The monitoring buoy in Rotorua is maintained by the Lake Ecosystem Restoration New Zealand (LERNZ) program which aims to restore indigenous biodiversity in New Zealand lakes. High-resolution temperature and meteorological data from Rotorua were measured at fifteen-minute intervals from July 2007 to July 2008. Air temperature, relative humidity and wind speed measurements were measured at a height of 1.5 m. Short-wave radiation was measured on each of the three lakes. Unlike the other meteorological variables measured, short-wave radiation does not vary with height above the lake surface, and thus is not height corrected in the Lake Heat Flux Analyzer program.

2.2. Bulk parameterization of surface fluxes

The following section describes the algorithms used to estimate the surface energy fluxes from lake buoy data. The calculated surface heat fluxes (W m^{-2}) are: the reflected short-wave radiation (Q_{sr}), the sensible (Q_h) and latent (Q_e) heat fluxes, the incoming long-wave (Q_{lin}) and the outgoing long-wave radiation (Q_{lout}), expressed in terms of the total surface heat flux (Q_{tot}) as:

$$Q_{tot} = Q_{sin} + Q_{lin} - Q_{sr} - Q_e - Q_h - Q_{lout}, \quad (1)$$

where Q_{sin} is the flux of short-wave radiation incident on the lake surface. To calculate these fluxes a variety of input variables are required: surface water temperature, air temperature, relative humidity, wind speed, and short-wave radiation. In addition, the measurement height of the sensors above the water surface is needed.

2.2.1. Incident and reflected short-wave radiation

The insolation (direct solar and diffuse sky radiation) reaching the lake surface is a large variable term in the heat budget of a lake and can be measured directly, using relatively inexpensive radiometers. Lake Heat Flux Analyzer does not compute short-wave radiation, but instead takes it as an input parameter. The reflected short-wave radiation, however, is rarely measured by instrumented lake buoys and must, therefore, be estimated from empirical relationships, the most common of which is in terms of the albedo, α_{sw}, as $Q_{sr} = \alpha_{sw} Q_{sin}$. Lake Heat Flux Analyzer calculates α_{sw} from Fresnel's Equation as:

$$\alpha_{sw} = \frac{1}{2}\left[\frac{\tan^2(Z-R)}{\tan^2(Z+R)} + \frac{\sin^2(Z-R)}{\sin^2(Z+R)}\right] \quad (2)$$

where R is the angle of refraction, calculated from Snell's law as:

$$R = \sin^{-1}(\sin(Z)/\eta), \quad (3)$$

where $\eta = 1.33$ is the index of refraction (Kirk, 1994) and Z is the solar zenith angle calculated as a function of latitude (φ), solar declination (δ) and the hour angle (H):

$$Z = \cos^{-1}\left(\sin\left(\frac{2\varphi\pi}{360}\right)\sin\left(\frac{2\delta\pi}{360}\right) + \cos\left(\frac{2\varphi\pi}{360}\right)\cos\left(\frac{2\delta\pi}{360}\right)\cos H\right), \quad (4)$$

$$\delta = \frac{180}{\pi}(0.006918 - 0.399912\cos\gamma + 0.070257\sin\gamma - 0.006758\cos2\gamma + 0.000907\sin2\gamma - 0.002697\cos3\gamma + 0.00148\sin3\gamma), \quad (5)$$

$$\gamma = \frac{2\pi(DOY-1)}{365}, \quad (6)$$

$$H = (\pi/12)(t_{noon} - t), \quad (7)$$

where DOY is the day of year (e.g. Jan 10 = 10), t_{noon} is the local solar noon and t is local solar time.

2.2.2. Net long-wave radiation

The net long-wave heat flux (Q_{lnet}) across the air–water interface comprises two main components: (i) incoming long-wave radiation (Q_{lin}) and (ii) outgoing long-wave radiation (Q_{lout}). The bulk formulae may be expressed as:

$$Q_{lnet} = Q_{lin} - Q_{lout}, \quad (8)$$

where in the absence of direct measurements, we estimate these terms from frequently measured variables. In Lake Heat Flux Analyzer, incoming long-wave radiation, Q_{lin}, is estimated following the methods of Crawford and Duchon (1999), as:

$$Q_{lin} = \left\{clf + (1-clf)\left(1.22 + 0.06\sin\left[(m+2)\frac{\pi}{6}\right]\right)\left(\frac{e_z}{T_{zK}}\right)^{1/7}\right\}\sigma T_{zK}^4, \quad (9)$$

where m is the numerical month (e.g. January = 1), T_{zK} is air temperature in Kelvin, e_z is the vapour pressure of the air (hPa) estimated based on the saturation vapour pressure of the air, and $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan–Boltzmann constant. The cloud cover fraction, clf, is estimated as $clf = 1 - s$, where s is the ratio of the measured short-wave radiation (i.e. Q_{sin}) to the estimated clear-sky short-wave radiation. Clear-sky short-wave radiation is estimated by Lake Heat Flux Analyzer following the methods of Meyers and Dale (1983) as shown in detail within the user manual of this program (see p.19 of the online user manual). However, as this calculation is based on the ratio of clear-sky and measured short-wave radiation, incoming long-wave radiation cannot be calculated at night. In this program, we estimate night-time incoming long-wave radiation based on the daytime averages of the cloud cover fraction. Therefore, the night-time incoming long-wave radiation is calculated as a function of air temperature, water vapour, and the daytime average cloud cover fraction. This adds an additional source of uncertainty in these estimates, but in comparison to other incoming long-wave