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Modelling sub-daily latent heat fluxes from a small reservoir

Ryan McGloin [a,*], Hamish McGowan [a], David McJannet [b], Stewart Burn [c]

[a] Climate Research Group, School of Geography, Planning and Environmental Management, The University of Queensland, Brisbane 4072, Australia
[b] CSIRO Land and Water, 41 Boggo Road, Dutton Park, QLD 4102, Australia
[c] CSIRO Land and Water, 37 Graham Road, Highett, VIC 3190, Australia

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SUMMARY

Accurate methods of latent heat flux quantification are essential for water management and for use in hydrological and meteorological models. Currently the effect of small lakes in most numerical weather prediction modelling systems is either entirely ignored or crudely parameterized. In order to test methods for modelling hourly latent heat flux from small water bodies, this study compares results from several modelling approaches to values measured by the eddy covariance method at an agricultural reservoir in southeast Queensland, Australia. Mass transfer estimates of *LE* calculated using the theoretical mass transfer model and using the Tanny et al. (2008) and Sacks et al. (1994) bulk transfer coefficients showed the best relationship with measured values under a range of meteorological conditions. The theoretical model showed the strongest correlation with measured values, while the Tanny et al. (2008) and Sacks et al. (1994) models had regression equation slopes with the closest proximity to 1. Latent heat fluxes estimated using the Granger and Hedstrom (2011) evaporation model, that was specifically developed for use at small reservoirs, showed a poor relationship with measured values, particularly in stable atmospheric conditions. The 1-dimensional hydrodynamics model, DYRESM, was used to obtain predictions of hourly latent heat flux without the use of water surface temperature measurements. DYRESM estimates of latent heat flux showed a slightly worse relationship with measured values than those predicted using the traditional mass transfer models (which used measurements of water surface temperature). However, DYRESM performed considerably better than the Granger and Hedstrom (2011) model.

1. Introduction

Inland water bodies can vary greatly in spatial scale, from small irrigation reservoirs on farms to large lakes. According to Downing et al. (2006), 50% of the total global continental surface area covered by water consists of small lakes and reservoirs (<1 km^2). Global estimates of the number of small reservoirs and lakes is in the order of 300 million, with a total surface area of approximately 2.3 million km^2 (approximately 1.5% of the Earth's continental surface area) (Downing et al., 2006). Despite the large number and importance of small lakes and reservoirs throughout the world, studies of water surface–atmosphere exchanges tend to be biased towards larger bodies of water (Rosenberry et al., 2007). Energy exchanges between the atmosphere and inland water bodies in the form of latent (*LE*) and sensible (*H*) heat fluxes can be ecologically and climatologically important at regional and global scales (Rouse et al., 2005; Long et al., 2007). However, the environmental factors that determine these exchanges, such as wind speed (u), humidity and atmospheric turbulence, can be substantially different over small water bodies than over larger lakes (Assouline et al., 2008; Granger and Hedstrom, 2011).

There have been occasional studies that have analysed direct measurements of *LE* from small reservoirs using the state of the art Eddy Covariance (EC) technique (e.g. Tanny et al., 2008, 2011; Nordbo et al., 2011; McGloin et al., 2014a), while other studies have analysed estimates of *LE* derived using the scintillometry method (McJannet et al., 2011, 2013b). Although these methods are essential in understanding the processes controlling *LE*, their use is limited due to the expensive and complex nature of their operation, therefore effective modelling approaches are required. There have been some studies that have evaluated the performance of evaporation models at small reservoirs (i.e. Rosenberry et al., 2007; Tanny et al., 2008; McJannet et al., 2013a). However, most approaches have been limited to quantifying daily (or greater) estimates of evaporation. Reliable estimates of surface heat fluxes are often necessary to correctly represent the effect that different surface types have on the regional climate (Chen and

* Corresponding author.
E-mail addresses: r.mcgloin@uq.edu.au (R. McGloin), h.mcgowan@uq.edu.au (H. McGowan), David.McJannet@csiro.au (D. McJannet), Stewart.Burn@csiro.au (S. Burn).

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Dudhia, 2001). In order to accurately model processes such as diurnal variability in Atmospheric Boundary Layer (ABL) height and associated cloud and precipitation processes, it is essential that surface processes are simulated frequently enough to capture their influence on the ABL (i.e. time-steps in the order of one hour) (Chen and Dudhia, 2001; Pielke, 2001; Pitman, 2003).

Understanding the relationship between small lakes and the local climate is of particular interest for regions where there is a high density of such lakes (e.g. in permafrost, periglacial, and riverine landscapes) (MacKay et al., 2009). In these environments small water bodies can represent up to 10% of the local land surface area (MacKay et al., 2009; Nordbo et al., 2011; Bouin et al., 2012). Although few studies have focused specifically on analysing the impact of small lakes on regional climates, authors such as MacKay et al. (2009), Balsamo et al. (2012) and Martynov et al. (2012) have indicated the potential importance of these water bodies in modifying the local climates of regions where they are abundant. Currently, the effect of small to medium size lakes in most numerical weather prediction (NWP) and climate modelling systems is either entirely ignored or crudely parameterized (Mironov et al., 2010). However, with continuing improvements in the horizontal resolution of NWP systems such as the Weather Research and Forecasting model (WRF), it is likely that in the near future there will be the potential to effectively model the effects of small lakes on regional weather. However, this will require accurate parameterisations of water surface–atmosphere exchanges at sub-daily timesteps.

In this study three models were selected according to their potential to accurately model sub-daily estimates of *LE* from a small reservoir. Model selection was limited by the need to use sub-daily inputs. For example, widely used methods like the energy balance or combination methods (such as the Priestly–Taylor (Priestly and Taylor, 1972) and Penman–Monteith (Monteith, 1965) methods) were not considered for use in this study because they require an estimate of the change in water body heat storage, which is notoriously difficult to quantify accurately at short timesteps. In addition, in order to allow researchers to replicate this study's methodology in locations where available input data may be limited, it was decided to keep model complexity to a minimum.

Each of the selected modelling techniques used in this study are based on the mass transfer model principle, where *LE* is determined as a function of u and the difference in humidity between the water surface and overlying air (Stull, 1988). The first of the selected modelling techniques in this study is the traditional mass transfer model, which simply determines *LE* using the $u(q_s - q_a)$ function (where $(q_s - q_a)$ is the difference between the specific humidities of the water surface and air) and a bulk transfer coefficient (C_E). The second technique is a model developed by Granger and Hedstrom (2011) for the specific purpose of estimating sub-daily evaporation from small reservoirs. Both the traditional mass transfer and Granger and Hedstrom (2011) models require site-specific meteorological measurements and measurements of water surface temperature (T_s). However, in many cases over-water meteorological measurements and T_s measurements are unlikely to be available. Therefore, the third model tested was the one-dimensional hydrodynamics model known as DYRESM (Dynamic Reservoir Simulation Model) (Imberger and Patterson, 1981; Imerito, 2010a), which does not require user specification of T_s. DYRESM is used to predict the vertical distribution of temperature in water bodies at daily and sub-daily time-steps. It has been used at a wide variety of water bodies with different morphologies and climates (e.g. Gal et al., 2003; Perroud et al., 2009; Weinberger and Vetter, 2012). However, most applications of the model have been related to water body ecology or water quality rather than for the specific purpose of *LE* quantification.

This study explores the potential to accurately model *LE* at hourly time steps from a small agricultural reservoir in southeast Queensland, Australia. Latent heat flux predictions made by the traditional mass transfer, Granger and Hedstrom (2011) and DYRESM models are assessed through comparison with measurements made on site using an EC system. Explanations for differences between measured and modelled results are provided and periods where model performance varied with changes in the ambient meteorological conditions are identified.

2. Methods

2.1. Study site

Field measurements were conducted at Logan's Dam (27°34′25.93″S; 152°20′27.45″E; altitude 88 m), located approximately 75 km west of Brisbane in southeast Queensland, Australia. Note that "Logan's Dam" refers to the water storage reservoir used in this study (in Australia it is common to refer to man-made reservoirs as "dams"). The reservoir wall is constructed of compacted earth and is roughly rectangular in shape with dimensions of approximately 480 m × 350 m. The reservoir has an approximate surface area of 0.17 km^2, a storage capacity of 0.7 GL and a maximum depth of 6 m. The terrain surrounding Logan's Dam is complex with the water body, forested areas (to the north, south and west), the reservoir wall and farm land all within a short distance of one another. For an image of Logan's Dam and the location of some of the equipment described in the following sections see Fig. 1 in McGloin et al. (2014a). Note that previous micrometeorological studies at Logan's Dam (i.e. McJannet et al., 2011; McJannet et al., 2013a,b; McGloin et al., 2014a,b) focused on analysing surface heat flux measurements and did not present any analysis involving methods for modelling sub-daily *LE*.

A 47-year time series (1965–2011) of archived meteorological data from the nearest available Bureau of Meteorology (BOM) weather station (Gatton 040082), located approximately 3 km north of Logan's Dam, was used to provide a long-term summary of the climatic conditions in the region. The mean maximum and minimum air temperatures (T_a), vapour pressure (e_a) and u over the 47 year record were 26.8 °C, 13.2 °C, 1.64 kPa and 2.74 m s^{-1}, respectively, while the mean annual rainfall was 781 mm. The region experiences a seasonal subtropical climate (Bureau of Meteorology, 2005) with the warmest and wettest weather during summer and the coolest and driest weather in winter. Two types of meteorological conditions characterise the climate of the study site. Moist easterly winds dominate for the majority of the year (especially in summer) and comparatively dry westerly winds dominate in winter, with transitional periods between.

2.2. Equipment and measurements

2.2.1. Eddy covariance

The EC technique involves determination of surface heat fluxes using high frequency measurements of vertical wind velocity by a sonic anemometer and the density of scalars by an infrared gas analyser. For this study a full year of EC data, from 1 March 2010 to 28 February 2011, was selected for analysis. The EC system setup included a sonic anemometer (CSAT-3, Campbell Scientific, Utah, USA) installed at a height of 2.4 m, an open-path H_2O and CO_2 infrared gas analyser (CS7500, LiCor, Lincoln, USA) installed at a height of 2.4 m and a net radiometer (CNR1, Kipp & Zonen, Delft, Netherlands) installed at a height of 1.4 m. The EC unit was located on a pontoon near the centre of the reservoir and supplied with power from mounted solar panels. The pontoon consisted of a square platform that had an approximate surface area of