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Effects of spatial aggregation on the multi-scale estimation of evapotranspiration

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ABSTRACT

The influence of spatial resolution on the estimation of land surface heat fluxes from remote sensing is poorly understood. In this study, the effects of aggregation from fine (<100 m) to medium (approx. 1 km) scales are investigated using high resolution Landsat 5 overpasses. A temporal sequence of satellite imagery and needed meteorological data were collected over an agricultural region, capturing distinct variations in crop stage and phenology. Here, we investigate both the impact of aggregating the input forcing and of aggregating the derived latent heat flux. In the input aggregation scenario, the resolution of the Landsat based radiance data was increased incrementally from 120 m to 960 m, with the land surface temperature calculated at each specific resolution. Reflectance based land surface parameters such as vegetation height and leaf area index were first calculated at the native 30 m Landsat resolution and then aggregated to multiple spatial scales. Using these data and associated meteorological forcing, surface heat fluxes were calculated at each distinct resolution using the Surface Energy Balance System (SEBS) model. Results indicate that aggregation of input forcing using a simple averaging method has limited effect on the land surface temperature and available energy, but can reduce evapotranspiration estimates at the image scale by up to 15%, and at the pixel scale by up to 50%. It was determined that the predominant reason for the latent heat flux reduction in SEBS was a decrease in the aerodynamic resistance at coarser resolutions, which originates from a change in the roughness length parameters of the land surface due to the aggregation. In addition, the magnitude of errors in surface heat flux estimation due to input aggregation was observed to be a function of the heterogeneity of the land surface and evaporative elements. In examining the response of flux aggregation, fine resolution (120 m) heat fluxes were aggregated to coarser resolutions using a range of common spatial interpolation algorithms. Results illustrate that a simple averaging scheme provides the best choice for flux aggregation compared to other approaches such as nearest neighbour, bilinear interpolation or bicubic interpolation, as it not only preserves the spatial distribution of evapotranspiration, but most importantly also conserves the mass balance of evaporated water across pixel and image scales.

1. Introduction

Evapotranspiration (ET) is a complex process that incorporates interactions across a range of terrestrial and atmospheric variables, including the land surface temperature, air temperature, wind speed and humidity, as well as vegetation height and density (Brutsaert, 1982). As a consequence, evapotranspiration can be highly variable in space and time, particularly over heterogeneous surfaces. Given the importance of evapotranspiration in characterising aspects of the hydrological cycle, understanding the nature and degree of this variability has been an ongoing effort in the hydrological and related sciences (Anderson et al., 2003; Brunsell & Anderson, 2011; Entekhabi & Eagleson, 1989; McCabe & Wood, 2006; Settle & Drake, 1993). While there are established methods to estimate surface heat fluxes at the point scale (e.g. scintillometery and eddy covariance techniques), such local scale estimates cannot easily be extrapolated beyond the field to basin scales: although there are some approaches that attempt to do this (Jung et al., 2009). Given the spatial and temporal variability of the evapotranspiration process (McCabe et al., 2005), a practical method for the routine estimation of spatially distributed heat fluxes at both field and basin scales is through the use of remote sensing techniques (Allen et al., 2007a; Anderson et al., 2003; Bastiaanssen et al., 1998a; Norman et al., 1995; Su, 2002).

A number of remote sensing evapotranspiration models like SEBS (Su, 2002), SEBAL (Bastiaanssen et al., 1998a) and METRIC (Allen et al., 2007b) have been developed and validated at the patch scale using fine resolution satellite imagery (e.g. Landsat and ASTER) (Allen et al., 2007a; Bastiaanssen et al., 1998b; Choi et al., 2009; Tasumi & Allen, 2007; Timmermans et al., 2007; van der Kwast et al., 2009). However, there are cases when these methods are used with much coarser resolution data from sensors like AATSR (Advanced

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Along Track Scanning Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer) and AVHRR (Advanced Very High Resolution Radiometer) (Elhag et al., 2011; Gibson et al., 2011; Gokmen et al., 2012; Jia et al., 2003; Zwart & Bastiaanssen, 2007) in order to broaden the scope of their application. Unfortunately, the effects of subsequent changes in the spatial resolution on modelling performance and the implicit scaling influences that occur as a result of these are addressed in relatively few studies (Gebremichael et al., 2010; Hong et al., 2009; Long et al., 2011; McCabe & Wood, 2006; Tian et al., 2012).

Validation of turbulent heat fluxes using remote sensing algorithms can be significantly influenced by the spatial resolution of the data (Su et al., 1999). In particular, aggregation of the input forcing can have mixed influences on the evaluation of the resultant heat flux (Brunsell & Gillies, 2003; McCabe & Wood, 2006; Su et al., 1999). Likewise, validating coarse resolution measurements is generally more difficult due to the additional uncertainty introduced by the scale discrepancy between ground measurements and the coarse spatial resolution imagery (Gebremichael et al., 2010; Hong et al., 2009; Long et al., 2011). Furthermore, the mismatch between the variable being represented and the resolution at which it can be retrieved provides another level of uncertainty in the estimation process. For instance, the effects of spatial resolution of land surface temperature and roughness parameters on heat and vapour transfer are not well understood, particularly as the satellite resolution increases (Becker & Li, 1995; Brunsell & Anderson, 2011).

To address such issues, a number of studies have evaluated the aggregation (or up-scaling) effects on heat flux estimation (Brunsell & Gillies, 2003; Entekhabi & Eagleson, 1989; Famiglietti & Wood, 1994; Hong et al., 2009; Kustas & Norman, 2000; Kustas et al., 2004; McCabe & Wood, 2006; Nakaegawa et al., 2001; Su et al., 1999; Wang & Currit, 2011). In general, aggregation can be applied either on the input forcing of the evapotranspiration models, or it can be applied to the fluxes derived from fine resolution input fields (i.e. aggregate then calculate versus calculate then aggregate). To examine these different approaches further, the concepts of 'input aggregation' and 'flux aggregation' are explored.

Aggregation of the input forcing has an immediate influence on the representative heterogeneity of the surface and affects the land surface control on heat flux generation (Brunsell & Gillies, 2003). One of the underlying assumptions for most physically based evapotranspiration models is the requirement for homogeneous conditions across a pixel, including homogeneity in both land surface (vegetation type, roughness, temperature) and meteorological conditions. To date, the effect of spatio-temporal variability of surface and atmospheric fields on heat flux generation remains poorly explained and quantified (Brunsell et al., 2008).

In addition to the aggregation of input forcing, resultant surface heat fluxes may require subsequent aggregation for a range of purposes e.g. to allow spatially consistent comparison and evaluation of General Circulation Model (GCM) and Regional Climate Model (RCM) outputs (Jiménez et al., 2011; Mueller et al., 2011). Likewise, GCM and RCM models require input forcing with a coarse spatial resolution that is generally much larger than the spatial resolution of remote sensing sensors. Therefore, an aggregation procedure is used to bridge the scale gap between remote sensing derived fluxes and the input requirements for large scale models (Hong et al., 2009). Further, flux aggregation is useful (and sometimes necessary) in comparisons of heat fluxes derived from geostationary images and those from polar-orbiting satellites (Brunsell & Anderson, 2011).

Moran et al. (1997) evaluated the effect of radiance aggregation on temperature and consequently on the sensible heat flux over a semi-arid rangeland in Arizona, finding negligible change in the land surface temperature, but large errors (more than 50%) in the sensible heat flux across heterogeneous areas having small vegetation elements within the pixels. The authors indicated that the uncertainty in flux estimation by input aggregation was due mainly to the non-linearity of the relations between the sensor signals, estimated variables and fluxes, and the inherent heterogeneity of the landscape. Hong et al. (2009) examined the aggregation of radiance from Landsat ETM+ resolution (30 m) to MODIS resolution (250 m) using the SEBAL model (Bastiaanssen et al., 1998a) and found that the peak of the histogram of latent heat flux increased 10–25% due to input aggregation. In a related study, Gebremichael et al. (2010) found that both input and flux aggregation procedures produced similar spatial patterns in SEBAL. Recently, Long et al. (2011) found that input aggregation of Landsat data to MODIS resolutions resulted in similar spatial mean values of sensible heat flux but with smaller spatial standard deviations.

For studies examining flux aggregation, Moran et al. (1997) found that errors in the aggregation of turbulent fluxes were highly influenced by the heterogeneity of the site and due mainly to variations in atmospheric stability, aerodynamic roughness, and patchy vegetation structures. Separate to the underlying surface heterogeneity, Sridhar et al. (2003) evaluated the performance of the nearest neighbour, bilinear, and bicubic interpolation methods for aggregation of evapotranspiration, finding that nearest neighbour and bilinear methods provided better performance than bicubic interpolation. Hong et al. (2009) found that flux aggregation using simple averaging and nearest neighbour methods can preserve the mean value of the original image and that the nearest neighbour method performed better than simple averaging by preserving the spatial variability of the fluxes.

While the majority of previous aggregation studies have employed semi-empirical evapotranspiration methods (e.g. SEBAL), a physically-based approach is used here for simulation of the land surface interactions and heat flux estimation. Doing this provides an opportunity to directly quantify the effect of input aggregation on each of the contributing components of heat flux estimation, including the land surface temperature, roughness parameters, aerodynamic resistance, and available energy. Also, while flux aggregation techniques have been examined previously (see above), an evaluation of these approaches based on conservation of the evaporative mass balance has not been examined. Preservation of the evaporated water volume across scales provides a superior measure of performance of the flux aggregation than considering spatial statistical aspects of the aggregation alone.

In this research effort, we examine the following hypotheses: a) that the effect of aggregation on input variables and parameters is not equal and that the roughness parameters are more significantly influenced by aggregation than other input variables; b) that errors due to the input aggregation are a function of the land surface heterogeneity and the size of the evaporative elements; and c) that a simple averaging approach is the best candidate for flux aggregation based on preservation of the hydrological mass balance.

2. Description of study area and data sources

The focus of these investigations is a heterogeneous agricultural region located in a semi-arid environment in the south-east of Australia. The 10.8×10.8 km region is situated in the agriculturally rich and economically important Murrumbidgee catchment (a sub-catchment of the Murray Darling Basin), comprising natural drylands in the northern and eastern directions and active irrigation areas elsewhere. An irrigation canal passes through the study area from the south to the northeast (see Fig. 1).

2.1. Meteorological data

A meteorological station located in the centre of the study site provided the necessary meteorological forcing data. Observed variables included half-hourly air temperature, humidity, wind speed and atmospheric pressure, along with a Kipp and Zonen CNR1 four way net radiometer that provided detailed radiation budget components.