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Seasonal and inter-annual variability of soil moisture stress function in dryland wheat field, Australia

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ABSTRACT

It is assumed that the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) is mostly controlled by the soil water content available for ET. This control is formulated using the soil moisture stress function (SSF), where the evaporative fraction (EF) or the fraction of the AET to PET (fPET) is assumed to be either a linear or a non-linear function of soil moisture. We examine the effectiveness of the soil moisture stress function to quantify soil moisture control on EF or fPET over a dryland wheat field in Victoria, Australia. Micrometeorological observations from two cropping seasons were used for the analysis. The efficacy of a root-density-weighted soil moisture estimate in predicting EF and fPET was investigated as against the commonly assumed fixed-depth root zone soil moisture. However, results indicate a strong relationship between EF and available soil water fraction (AWF) in the root zone only when solar radiation is higher than 5 MJ/m^2/day. As the rooting depth increases with vegetation growth, SSF exhibits the strongest correlation with AWF for increasing soil profile depth. In the early and harvesting crop growth stages, ET is constrained mostly by surface soil moisture (0–5 cm). In the mid-growth stages, ET is strongly influenced by soil moisture in the root zone (0–60 cm). The shape of SSF, however, changes significantly between the two years (2012 and 2013). It is inferred that different temporal rainfall patterns between the years caused wheat's different response to water stress.

1. Introduction

Water shortage is one of the significant issues currently being experienced throughout the developing world. Ensuring freshwater availability to meet the needs of urban, rural and agricultural activities is already a challenge in many parts of the world (Godfray et al., 2010; Hamdy et al., 2003). Nearly seventy-five percent of global freshwater is used for agriculture annually (Wallace, 2000) and a majority of the water consumed in agriculture returns to the atmosphere via evapotranspiration (ET). Consequently, an accurate estimation of ET over agricultural fields can provide critical information about their water use across various scales and, in turn, crop water productivity.

ET is also one of the most important components of terrestrial water balance contributing to hydrological and biophysical systems modelling and applications. ET is controlled by various environmental conditions such as available energy, vegetation condition and available soil moisture (Detto et al., 2006; Ryu et al., 2008; Vivoni et al., 2008; Wetzel and Chang, 1987). However, for a given PET or a reference ET estimated using solar radiation, air temperature, wind speed, and relative humidity, it is generally assumed that AET is mainly constrained by soil moisture (Jung et al., 2010; Teuling et al., 2006). A typical approach to characterize ET is to calculate potential evapotranspiration (PET) and then employ a function accounting for the constraint by soil moisture (Akuraju et al., 2013; Lai and Katul 1999; Mahfouf et al., 1996).

The correlation between AET-to-PET ratio (denoted by fPET hereafter) or the evaporative fraction (EF), represented by soil moisture stress function (SSF) and soil moisture is a potential way of estimating root zone soil moisture (RZSM) over large vegetative regions using remote sensing and data assimilation methods (Crow et al., 2006; Hain et al., 2012; Norman et al., 1995; Wang et al., 1980). Therefore, an accurate representation of ET vs. SM is critical to enable regional to global scale RZSM estimation.

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Several studies have examined the sensitivity of fPET to SM, and the influence of meteorological conditions on the relationship. For example, relative transpiration rate has been formulated as a function of SM and PET (Denmead and Shaw, 1962). Some studies propose that the sensitivity of fPET to SM also constrained by crop growth stages (Fischer and Kohn, 1966; Vivoni et al., 2008; Wei et al., 2014). A large number of agronomic studies have reported or assumed a linear correlation between ET or fPET and SM in wheat crops (Baier, 1969; Eagleman and Decker, 1965; Liu et al., 2002; Nan et al., 2011; Vivoni et al., 2008; Wetzel and Chang, 1987).

Recent advances in remote sensing demonstrate the potential use of EF or fPET, surface temperature, and normalized difference vegetation index (NDVI) in estimating SM. For example, satellite-derived NDVI and surface skin temperature have been shown to have a significant correlation with SM (Carlson et al., 1981; Wang et al., 2007). The combined use of surface temperature and NDVI (Ts/NDVI) based on their non-linear relationship satisfactorily estimated surface SM information (Komatsu, 2003; Merlin et al., 2010, 2008; Noilhan and Planton, 1989). In a series of novel attempts, the surface thermal infrared (TIR) data or surface soil moisture derived from soil latent heat flux was assimilated into land surface models to predict soil moisture (Anderson et al., 2007; Crow et al., 2006; Das and Mohanty, 2006; Hain et al., 2011, 2009; Li et al., 2010; Scott et al., 2003). Most remote sensing approaches assume a simple and constant linear or non-linear relationship between EF/fPET and SM over each site (Akuraju et al., 2013; Hain et al., 2009; Scott et al., 2003).

Furthermore, seasonal and inter-annual variability of EF/fPET to RZSM has not been rigorously examined due to the lack of continuous observations such as optical and thermal infrared data and SM measurements. Also, the effect of net radiation, vegetation biomass (represented by NDVI), crop physiology and rainfall pattern (temporal) on the ET vs. RZSM relationship has not been thoroughly examined yet. Since transpiration is driven by 'plant available water' in the root zone (Albergel et al., 2008; Lai and Katul, 1999; Li et al., 1999; Molz and Remson, 1970), EF and fPET derived from vegetated land surfaces may vary with plant growth and phenological stage. The studies mentioned above did not evaluate the relationship between EF (or fPET) and RZSM at various crop growth stages.

In this study, EF derived from field observations were used for SSF to obtain the available water fraction (AWF) on the surface and at various layers of the root zone. AWF is the plant available water between field capacity and wilting point, which can be used as a proxy for SM at different depths. The root zone soil moisture, especially in remote sensing methods, is defined as the arithmetic average of soil moisture at different depths, which disregards the importance of dynamic root distribution at different crop phenological stages. However, in practice, it is very difficult to measure actual root distribution. In order to estimate plant root distribution, we employed a field-proven cropping system simulation model, Agricultural Production Systems sIMulator (APSIM) (www.apsim.info), which was later used to calculate the root-density-weighted AWF in the root zone.

The objectives of this study are to: (1) examine the seasonal and interannual variability of SSF, vegetation biomass and net radiation in two cropping seasons; (2) investigate how surface or root zone soil moisture control on EF varies with net radiation, soil wetness and season; and (3) determine the meteorological and biophysical factors controlling the relationship between EF and RZSM in a wheat field site. Continuous measurements of hydrometeorological variables such as evapotranspiration, net radiation, vegetation phenology and biomass, and profile soil moisture content collected from the wheat site were used to examine the relationship between EF and surface or root zone soil moisture.

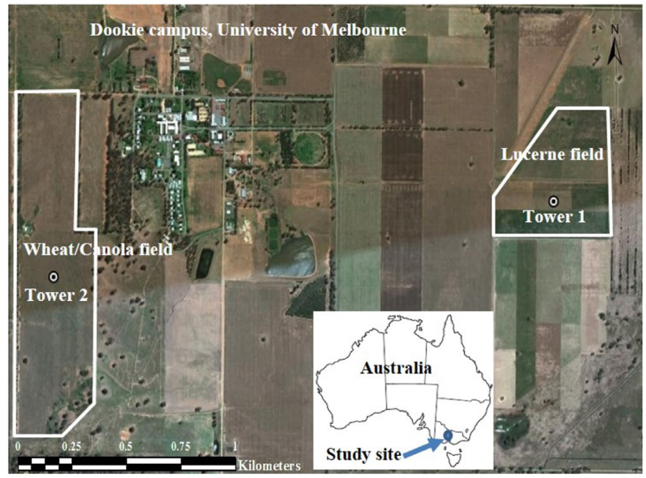

Fig. 1. Location of study sites at Dookie, Victoria, Australia.

2. Materials and methods

2.1. Description of the study site

The study was conducted at the agricultural research farm of the Dookie Agriculture farm, The University of Melbourne, located 220 km northeast of Melbourne (36°37′S, 145°70′E, at 185 m altitude), Victoria, Australia. Fig. 1 shows the geographical location of the study site. The climate is Mediterranean semi-arid with hot/dry summers and cold/wet winters (Bell et al., 2012). Relative humidity is on average 10% in January–February and 90% in July–August. The average annual rainfall of the study area typically varies between 450 mm and 770 mm (BOM, 2015).

The overall study consisted of two field sites. Site 1 was a pastureland with forage lucerne rotationally grazed by sheep. Site 2 was cultivated with wheat in 2012–2013. Each site was instrumented with automated meteorological sensors, which consisted of meteorological sensors and profile soil moisture and temperature sensors (refer to Table 1 for details). The soil moisture and temperature sensors recorded measurements over the top 1.2-m soil profile at five intervals. This paper presents the data collected from Site 2 grown to wheat. Fig. 1 shows the study sites.

2.2. Data collection

Turbulent fluxes, surface reflectance, and soil moisture were measured using a suite of tower-based sensors. Eddy covariance system consisting of a sonic anemometer with an open path IRGA gas analyser (LI-7500, LI-COR, Inc., USA) was installed 2.6 m above ground level to estimate latent heat (LE) and sensible heat flux (H). A CNR1 net radiometer (KIPP & ZONEN, The Netherlands) was installed at 5.7 m height to measure net radiation.

Ground-based surface reflectance was measure using SKR-1850 and SKR-1870A radiometers (Skye Instruments Ltd, UK) which were installed at 5.7 m height at six channels with wavelengths 527–537, 565–575, 620–670, 837–877, 1228–1248, and 2110–2148 nm. Surface reflectance allows the calculation of vegetation indices such as NDVI (Normalized Difference Vegetation Index) to represent vegetation dynamics. Soil and vegetation surface temperatures were measured using an infrared radiation sensor. Five capacitance soil moisture probes (CS616) were installed vertically to measure soil moisture at average depths of 0–5 cm, 0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm.

Air temperature and relative humidity were measured using a HMP45C probe (Campbell Scientific). Barometric pressure was