ARTICLE IN PRESS

Agricultural and Forest Meteorology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Within-field advection enhances evaporation and transpiration in a vineyard in an arid environment

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ARTICLE INFO

Keywords:
Within field advection
Local advection
Irrigated vineyard
Arid environment
Transpiration
Evaporation

ABSTRACT

Advection of hot air from a warmer to a cooler surface is known to enhance evaporation through additional supply of energy, provided that water is readily available. This study investigated advection in an isolated irrigated vineyard in the Negev desert, over a period of several months under changing plant cover and environmental conditions, and for different degrees of water availability. Field, canopy, and soil energy balance fluxes were assessed, as well as likely indicators of advection such as wind speed, VPD, vertical temperature gradients between the soil, the canopy air space, and the air, and lateral temperature gradients between the vineyard and the surrounding desert. It was found that for a period from May to July, advection enhanced transpiration by 8%, where diurnal patterns suggested that most of the advection originated from within the field. At times, soil-to-canopy advection enhanced transpiration by as much as 30–40%. Wet irrigated strips likewise experienced soil-to-soil advection from drier soil, but to a much lesser degree. A surprisingly large difference was observed in the contribution of advection to transpiration between June (2%) and July (11%), which had almost identical environmental conditions. This indicates that small changes in the agro-system such as row-width and leaf area could have a large impact on within-field advection, and that row crops could potentially be managed to reduce or enhance advection.

1. Introduction

Water use in arid environments is dictated by evapotranspiration, including evaporation from the soil and plant transpiration. Evapotranspiration and its partitioning determines plant growth, ecosystem functioning, and weather patterns; and better quantification of its drivers can help improve irrigation practices, prevent desertification, and improve climate models. Net radiation (R_n) is the primary source of energy for evapotranspiration, or latent heat flux (LE), but advection of heat energy can also be a major contributor under certain conditions.

In applied meteorology, this type of advection is defined as net horizontal transport of sensible heat (H) between a field and its surroundings; where horizontal transport generally occurs in a downwind direction, through wind sweeping over and through a field (McNaughton and Jarvis, 1983; Oke, 1987; Prueger et al., 1996; Hillel, 1998). Advected sensible heat adds available energy to a field when the field is cooler than its surrounding, as is often the case for irrigated areas or oases (Tolk et al., 2006; Díaz-Espejo et al., 2008). This additional energy can enhance LE when available energy is the limiting factor for evapotranspiration, either because of high demand, i.e. when soil water supply and evaporative demand are high and plants are physically capable of transpiring more (McNaughton and Jarvis, 1983; Oke, 1987; Yunusa et al., 2004); or because of low available energy, e.g. at night, when advection can cause night time transpiration (Hanks et al., 1971). Other types of advection, such as the advection of vapor pressure deficit (VPD) or 'dry air', which may enhance evaporation and affect the energy balance by horizontal transport of latent heat (Slatyer and McIlroy, 1961; McNaughton, 1976; Monteith, 1981). The primary focus of this paper is sensible heat advection; thus, unless otherwise specified, advection in this paper refers to conditions where advected H enhances LE.

Advection can be quantified as $-H$, or $LE - R_n - G < 0$, where R_n is net radiation, G is soil heat flux, and defining R_n as positive towards the surface and LE, H, and G as positive away from the surface. This approach may underestimate advection, as studies have shown that advection can sometimes be larger than the downwelling heat flux, due to the importance of turbulence in transporting energy fluxes (Zermeño-Gonzalez and Hipps, 1997; Prueger et al., 2012). While this is the most common way to quantify advection (Ham et al., 1991; Heilman et al., 1994; Prueger et al., 1996; Daamen, 1997; Lund and

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http://dx.doi.org/10.1016/j.agrformet.2017.10.018
Received 11 January 2017; Received in revised form 28 September 2017; Accepted 14 October 2017

Please cite this article as: Kool, D., Agricultural and Forest Meteorology (2017), http://dx.doi.org/10.1016/j.agrformet.2017.10.018

Soegaard, 2003; Alfieri et al., 2012), alternative ways include comparing *LE* to equilibrium *LE* (LE_{eq}), defined as the equilibrium evaporation rate over a saturated surface (Priestley and Taylor, 1972), formulated as:

$$LE_{\text{eq.}} = \frac{s(R_n - G)}{s + \gamma} \tag{1}$$

where *s* is the slope of saturated vapor pressure vs. temperature and γ is the psychrometric constant. The ratio $LE/LE_{\text{eq.}}$, known as the Priestley-Taylor coefficient (α_{PT}; Priestley and Taylor, 1972), equals one if both the surface and the air are saturated. However, in the absence of advection, α_{PT} typically equals approximately 1.26 (Eichinger et al., 1996). Thus, advection over wet surfaces has also been defined as $\alpha_{PT} > 1.26$ (Diaz-Espejo et al., 2005). However, in some cases *H* does not turn negative until α_{PT} reaches 1.4 or 1.5 (Diaz-Espejo et al., 2005; Li and Yu, 2007). The first difficulty with defining advection as $\alpha_{PT} > 1.26$ is that this threshold is only valid for well-watered conditions, while advection may also occur under drier conditions so long as energy is limiting evaporation. Secondly, the 1.26 value, though reported to be valid under a range of conditions, is empirical and somewhat arbitrary. It appears therefore that $-H$ is the most straightforward way to quantify advection, with the understanding that advection might be larger than $-H$, while the more empirical $\alpha_{PT} > 1.26$ can serve as an indicator of advection under well-watered conditions.

Advection is commonly specified to be "regional" or "local" referring to the assumed source of advected *H* (Brakke et al., 1978; Tolk et al., 2006). Regional advection is thought to occur on a scale > 1 km (Prueger et al., 2012), or even > 100 km (Ringgaard et al., 2014), and will affect an entire irrigated area. Local advection originates from adjacent drier and warmer areas and will most strongly enhance evaporation in the upwind section of the field, with declining influence on evaporation as the horizontally moving air comes into equilibrium with the surface (Brakke et al., 1978; Tolk et al., 2006). Thus, regional and local advection are often distinguished using measurements of *H* close to the edge and in the middle of a large field, where the contribution of regional advection is equal to $-H$ in the middle of the field and local advection is considered the source for any additional $-H$ near the edge (Brakke et al., 1978). However, Zermeño-Gonzalez and Hipps (1997) postulated that the assumed decline of the influence of local advection on *H* in a downwind direction may not always be correct for vegetated surfaces. The increase in transpiration in the upwind section of the field may decrease the vapor pressure deficit further downwind. This could reduce stomatal resistance in the downwind area, enhancing transpiration indirectly. Prueger et al. (2012) noted that spectral analysis of the turbulence structure in the surface boundary layer during advective conditions may shed some light on the origins of advection, e.g. the variance in temperature caused by larger eddies are likely to originate from further away. However, much of the turbulent processes during advective conditions are still not fully understood. Determining whether advection is regional or local and quantifying advection in general is therefore not straight-forward.

In addition to regional and local advection, in ecosystems with partial canopy cover, such as row-crops, orchards, or shrublands, distinct dry and wet zones within a field can cause within-field advection, occurring at a much smaller scale. Unlike regional or local advection, within-field advection is not driven by wind. Rather, free convection from a dry (warmer) surface is drawn in circular motions to wet (cooler) surfaces (Graser et al., 1987). Within-field advection tends to occur in semi-arid and arid environments, where temperature gradients between drier and wetter surfaces are more pronounced (Lund and Soegaard, 2003). The most common form of within-field advection is from a dry exposed soil surface to a wetter vegetated surface (soil-to-canopy advection). This type of advection has been referred to as within-canopy advection (Hanks et al., 1971), inter- or within row advection (Graser et al., 1987; McGowan et al., 1991; Heilman et al., 1994; Lund and Soegaard, 2003), convection (Figuerola and Berliner, 2006) or simply horizontal heat flux between the soil and the plant (Blyth and Harding, 1995). Advection from a dry canopy to a wet soil (canopy-to-soil advection) can occur when soil water evaporation is the main component of evapotranspiration, and has also been referred to as within row advection (Ham et al., 1991). A third form of within-field advection is heat transfer below the canopy, from drier to wetter parts of the soil surface (soil-to-soil advection). This type of advection has been referred to as micro or micro-scale advection and has been studied in drip-irrigated fields (Bonachela et al., 2001; Yuge et al., 2005, 2014; Figuerola et al., 2013).

For canopies with partial cover, not only is within-field advection more likely to occur, but there is also a decreased likelihood of local advection, because hot dry surfaces within the field decrease the temperature gradient between the field and its surroundings (Stoughton et al., 2002). In irrigated cotton, for example, it was observed that local advection was minimal at early stages of canopy growth, but increased as the canopy increased (Alfieri et al., 2012). Under within-field advective conditions, *H* from a wet surface within the field is negative but the average *H* for the field (H_{field}) can be positive or negative. Negative H_{field} and canopy *H* (H_c) were observed in sprinkler irrigated cotton in Texas, where negative H_{field} was considered local advection, and the remaining negative H_c was considered within-field advection, accounting for 21% and 12% of transpiration respectively (Ham et al., 1991). In a flood irrigated vineyard in Texas 17–36% of transpiration was attributed to advection, and, as no negative H_{field} was observed, all advection was assumed to have been generated within the field (Heilman et al., 1994). A different strategy has been applied to determine within-field advection from dry to wet soil, where advection was estimated as the surplus of *LE* from a wet soil surface within a field with intermittent wet and dry surfaces relative to the theoretical *LE* of a homogeneously wetted soil surface (Bonachela et al., 2001).

A better understanding of both the magnitude and the source of advection is required to measure or model evapotranspiration components in semi-arid and arid regions. Depending on the source of advection, energy balance models have to allow energy exchange between wetter and drier surfaces within the field or consider sources outside the field may contribute to available energy. There is also evidence that advection decreases the efficiency of plant carbon uptake per unit of water used (McGowan et al., 1991; Li and Yu, 2007). Specifically within-field advection was found to negatively affect water use in a field, where plants growing in widely spaced rows transpired more water per unit ground cover while producing less dry biomass than their narrow row counterparts (McGowan et al., 1991). A better understanding of advection may help determine if management strategies such as row spacing could be adapted to reduce these negative effects.

Great advancements have been made in studying different kinds of advection, including detailed measurements of a grid of irrigated and dry lysimeters (Diaz-Espejo et al., 2005), and comprehensive short-term measurements in the field (e.g. Ham et al., 1991). The limitations of these short-term measurements is that they neither incorporate changes in advective conditions as a function of evaporative demand and plant cover (Diaz-Espejo et al., 2005; Bonachela et al., 2012), nor account for effects of irrigation and plant drought stress (Ham et al., 1991; Gutiérrez and Meinzer, 1994). Seasonal studies have used combined measurement and modeling efforts (e.g. Lund and Soegaard, 2003) but we are unaware of any seasonal assessment of advection using independent estimation of soil and plant energy balance components.

The aim of this study is to assess the contribution of advection to soil and plant energy balance components in a drip-irrigated vineyard in an arid environment, and evaluate changes in advective conditions with canopy growth, evaporative demand, and irrigation.