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Micrometeorological measurements and vapour pressure deficit relations under in-field rainwater harvesting

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ABSTRACT

In a cropped field, microclimate and thermal stability conditions depend on the canopy structures and the prevailing weather. The main aim of the study therefore was to characterize the vertical profiles of weather variables within and above a maize (*Zea mays* L.) canopy and to describe the water vapour pressure deficit (VPD) under different atmospheric and soil surface conditions for both wide and narrow runoff strips with the in-field rainwater harvesting (IRWH) system. Micrometeorological measurements of wind, temperature and relative humidity were performed at eight levels, within canopy (1.8 and 2.1 m), and just above the canopy (2.4, 2.7, 3.0, and 3.3 m) up to reference levels (3.9 and 4.5 m) when the maize reached a maximum height of 2.2 m. Under incomplete canopy cover of the IRWH system, two important factors complicated evapotranspiration estimation, namely the local advection and high temperatures of the bare soil between adjacent plant rows. Diurnal variations of water vapour related to turbulence at each locality and its position in the thermal internal boundary layers. Generally, advection was more pronounced in wide runoff strips than narrow strips. On wide runoff strips the wind was more effective in replacing the air between the rows and maintained a higher driving force for evaporation. The maximum VPD over the narrow strips was observed at reference level during a dry day, at about 2.2 kPa in the afternoon, while wet day VPD reached a maximum of 1.8 kPa. The VPD of the wide runoff strips correlated negatively with wind speed, but showed a fairly positive correlation with some scattered values on wet days after rain. Therefore, profile characteristics within and above plant canopies played a key role in determining the VPD and consequently, could help to explain transpiration rates of crops. Hence, VPD relations enhanced the understanding of the heat energy exchange processes under the heterogeneous nature of maize canopy of the IRWH tillage system.

1. Introduction

In semi-arid areas of South Africa, maize (*Zea mays* L.) yield variations mainly characterized due to the influence in fluctuating seasonal weather parameters at a canopy microclimatic level. Water deficit is ubiquitous in many maize production areas (Gholipoor et al., 2013) and interpreted as transpiration response on the atmospheric vapour pressure deficit is frequently severe enough to result in significant yield decreases in semi-arid areas. In a cropped field, microclimate and thermal stability conditions depend on the canopy structures and the prevailing weather variables. Understanding of the momentum and heat transfer inside and above the canopy is an essential step to quantify and evaluate heat and water vapour exchange processes. The assumptions underlying the theory of one dimensional energy exchange can be challenged in a number of circumstances, which are of agricultural interest and include the various tillage systems (Stigter, 2010). For instance, in the system of in-field rainwater harvesting (IRWH) with different arrangements of runoff and basin area, various small-scale processes occur within and above the crop canopy. A maize canopy under IRWH acts as a source and/or a sink of heat energy and water vapour. The air surrounding the crop is always in turbulent motion, which causes efficient mixing and exchanges of heat and water vapour, with the crop surface. Therefore, an understanding of the effects of the vertical profiles of heat and water

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vapour at canopy level indicate fluxes that needed to estimate evapotranspiration (ET).

Both crop yield and ET are influenced by a variety of factors, such as the crop type, atmospheric variables, tillage practices, and soil conditions. Yield is linearly related to transpiration (Hanks, 1974) and consequently to atmospheric water vapour pressure deficit (VPD) (Ben-Asher et al., 2013). Tanner and Sinclair (1983) as well as Zangvil et al. (2004) described yield and water use in a wet humid climate as greater than a dry arid climate. However, due to diurnal variations, fluctuations of weather variables and canopy water conductance (Vialet-Chabrand et al., 2013) in a cropped field, it is difficult to determine the relationship between crop stomatal response and atmospheric water vapour. However the stomatal response to water VPD is a case sensitive according the plants in the way optimizing dry matter production by balancing photosynthesis and transpiration processes (Streck, 2013). The greater VPD the more water transpiring out of the leaf but obviously if the diffusion increases up to rate that cannot be supplied the entire plant would be experience water stress situation. Therefore not surprising stomata have to regulate their opening to avoid dehydration at high VPD and this varies when the plants invests on vegetative surface and reproductive organs. Streck (2013) concluded that high VPD can cause water stress and it would be reasonable to assume that stomata respond to VPD and linearly related to transpiration. Soil water status also is one of the factors confound the stomatal response to VPD. Campbell and Norman (1998), Buckley et al. (2003) and Wang et al. (2009) generally showed that stomatal closure occurred as VPD and transpiration increased. Comparing dry and wet conditions Ben-Asher et al. (2013) concluded that a positive response of maize to high water vapour indicates that under dry conditions where available water is limited, water use would be less efficient, compared to wet conditions where water vapour is high and water is abundant. Thus, micrometeorological research in atmospheric vertical profile studies can be strengthened by considering the driving forces of VPD in a maize canopy planted under an IRWH tillage system.

Various experimental measurements have confirmed that horizontal wind speed is strongly sheared at canopy height and attenuates quickly within the canopy (Rosenberg et al., 1983; Allen et al., 1998). The canopy effects are felt from the ground up to canopy height, which is described as the roughness sub-layer (Garratt, 1992). A good understanding of vertical profile of horizontal wind speed within and above a plant community is a prerequisite to understanding turbulent transport of water vapour as well as temperature fluctuations within a crop canopy (Arya, 2001; Figuerola and Berliner, 2006). Over time, the mean horizontal wind speed will vary rapidly with height above the ground through the roughness sub-layer, particularly within the plant canopy, due to the effects of drag exerted by the underlying surface (Raupach et al., 1991; Kroon and Bink, 1996). Water vapour and heat fluxes are some of the most important constituents of the atmosphere, which also have great biological importance (Ray et al., 2002). The bulk rates of exchange between the canopy and the air flowing over it can be determined by measuring vertical fluxes in that part of the boundary layer.

Within the plant canopy, turbulence is generated by several sources. In the IRWH system, the bare area (runoff strips) between the planting zone (basin) and the next basin dries out due to a high solar radiative load and can generate plumes of hot air (Figuerola and Berliner, 2006). These plumes may therefore enhance a strong lack of horizontal homogeneity due to the arrangement of basin area and runoff sections in IRWH. Within the canopy layers in the basin area, however, an increase in temperature occurs near the level of maximum leaf area where most of the solar radiation is absorbed. Generally the highest temperature is observed in the lower and middle lower portion of the canopy for narrow and wide strips, respectively (Tesfuhuney et al., 2013). Thus, the source of semi-homogenous characteristics within the maize canopy under IRWH system is a balance between the processes of energy input by radiation and its redistribution by convection; the details of these profiles have not been measured before. Although the typical IRWH field might not represent the ideal conditions for an ideal micrometeorological study it is the focus of this research, therefore the vertical profile of weather variables both within and above a maize canopy were measured. These micrometeorological measurements could then be used to express the heat exchange processes for wet and dry surfaces and air passing over it. The main objective of the study therefore was to characterize the vertical profiles of climatic variables within and above a maize canopy and to describe the VPD under different atmospheric and soil surface conditions for both wide and narrow runoff strips.

2. Materials and methods

2.1. Experimental layout

A field experiment with maize (hybrid, DKC 80-30R, medium maturing variety) under IRWH was conducted during the 2008/09 growing season at the Kenilworth Experimental Farm (Latitude 29°01′S, Longitude 26°09′E, Altitude 1354 m above sea level) of the University of the Free State near Bloemfontein in the Free State, South Africa. The experimental site is characterized by a high annual evaporative demand, with a relatively low and erratic rainfall (528 mm), resulting in a semi-arid climate classification on the aridity index (Middleton and Thomas, 1992). The mean annual minimum and maximum temperatures on Kenilworth are 11.0 °C and 25.5 °C, respectively. Topographically, the experimental plots are located in an area with <1% slope falling Northward. The soil is 2 m deep reddish brown in colour with a fine sandy loam texture and is classified as a Bainsvlei form according to the Soil Classification Working Group (1991).

The 1 ha maize field under IRWH was designed in to four replicate blocks with each main plot consisting of four IRWH runoff strip length (RSL) treatments with rows extending the entire length of the field in the East-West (E–W) direction. Each of the four RSL treatments included 1 m wide basin area with 1, 1.5, 2 and 3 m lengths of runoff strips. The 1 m wide basin of 0.4 m depth was positioned in between the plant rows of 1.1 m. In this study, two RSL treatments were selected, *viz.* 3 m and 1.5 m representations for a wide and a narrow RSL, respectively. To meet adequate upwind fetch the south-eastern block was selected for the micrometeorological measurements. The resulting minimum fetch was approximately 150 m with a 2.2 m high maize crop in an adjacent field. Thus, the fetch requirement is partially fulfilled; if one assumes a fetch to height-above-surface ratio of 100: 1 as a rule of thumb (Rosenberg et al., 1983).

Profiles of temperature, humidity, and wind speed measurements were continually performed within and above the maize canopy, when the crop was in the reproductive stage during the last part of cropping season from 16 April – 12 May, 2009 (DOY 106–132). The focus of the analysis was on the vertical profiles of the potential virtual temperature (θv), water vapour pressure (ea) and wind speed (u) from measurements taken at eight heights within and above maize canopy on both wide (3 m) and narrow (1.5 m) runoff strips.

2.2. Measurements and research approach

The micrometeorology observations were taken over the wide RSL treatment from day of year (DOY) 106–121 (first period) and