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Exploring the link between clouds, radiation, and canopy productivity of tropical savannas

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ABSTRACT

The control of clouds on the canopy gross primary productivity (GPP) was examined at Howard Springs, a tropical savanna site in the Northern Territory, Australia. It was demonstrated in this study that cloudiness can increase the initial canopy quantum efficiency (α), midday light use efficiency (LUE) and water use efficiency (WUE), but decrease GPP in savannas. Thick clouds (clearness index of 0–0.3 in the wet season produced much more diffuse fraction of Photosynthetically Active Radiation (fDPAR > 80%), which caused increases in α by 24% and 62% compared to thin clouds (fDPAR between 30% and 80%) and clear sky (fDPAR < 30%) conditions respectively. The influence of environmental conditions shows that under similar vapour pressure deficit, temperature and soil water content classes, α values were significantly higher under thick clouds compared to thin clouds or clear skies. This indicates the importance of diffuse radiation in enhancing LUE even within similar environmental conditions. However, the enhanced LUE under cloudy skies is insufficient to increase GPP due to the dramatic decline in total radiation. Therefore, it can be concluded that the quantity of solar radiation is more critical than the quality of radiation in savannas. However, savanna ecosystems appear to be well adapted to the environment where a 63% decrease in PAR only reduced GPP by 26%. These findings highlight the importance of clouds as a critical factor in determining savanna productivity that has implications for savannas carbon cycle.

1. Introduction

Generally, radiation and temperature do not limit savanna productivity because savannas receive high radiation due to their location near the tropics (Scholes and Walker, 1993). However, at local and regional scales, atmospheric aerosols from extensive burning in the dry season and high cloud cover in the wet season can affect savanna productivity by altering the amount and spectral composition of radiation reaching the surface (Kanniah et al., 2010a,b; Abbadie et al., 2006; Eck et al., 2003). These factors may influence the processes and interactions of savanna with the atmosphere. Aerosols and clouds can scatter the incoming solar radiation and produce much more diffuse radiation. Many terrestrial ecosystems in the northern hemisphere have been shown to respond to the partitioning of solar radiation by increasing or decreasing the GPP and/or NEE (net ecosystem exchange) depending on vegetation structure, canopy architecture and local environmental conditions (see review by Kanniah et al., 2012). On a global scale, Mercado et al. (2009) simulated net enhancement of the land carbon sink between 1960 and 1999 despite a significant reduction in total PAR as diffuse radiation overwhelms global dimming due to anthropogenic aerosols. Usually, the temporal and spatial variation in savannas' carbon fluxes is only related to rainfall, fire, grazing and land use patterns (see review by Kanniah et al., 2010a,b). The influence of clouds on biological productivity has not been explored. This is an area of uncertainty in savanna studies that needs to be addressed as it will aid in our understanding of how possible future changes in radiation due to changes in cloud cover may affect plant productivity.

Clouds can cause or be a consequence of changes in radiation, temperature and rainfall, which affect terrestrial productivity (Min and Wang, 2008). Clouds, depending on the size and water content interact with solar radiation and tend to affect the quantity and partitioning between diffuse and direct component of radiation (Min, 2005; Oliphant et al., 2011). Theoretically, enhanced diffuse radiation can affect ecosystem productivity by changing the light use efficiency (LUE) (Roderick et al., 2001), and observational evidence shows that GPP and/or NEE of terrestrial ecosystems is enhanced under a high proportion of diffuse radiation during cloudy days (Price and Black, 1990; Hollinger et al., 1994;

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Baldocchi, 1997; Gu et al., 1999; Urban et al., 2007, 2012; Still et al., 2009; Dengel and Grace, 2010; Jing et al., 2010; Zhang et al., 2011).

The interaction between clouds and solar radiation is complex because cloud particles not only scatter radiation but also absorb infra red radiation and reflect some of the radiation back to space (Ramanathan et al., 2001), resulting in decreased total PAR available for photosynthesis. Due to these counter acting effects, although clouds result in enhanced LUE under elevated diffuse light the reduction in total PAR can decrease the productivity (see review by Kanniah et al., 2012 for observational and modelling studies addressing this issue). This could have significant implications for terrestrial vegetation, notably light sensitive ecosystems such as the tropics, boreal plants and savanna ecosystems (Alton et al., 2007a,b; Alton, 2008). The long term formation and evolution of savannas are highly dependent on high irradiance and temperature (Bourliere, 1983). So, any changes in the intensity and duration of total available solar radiation can affect savanna growth.

The aim of this study is to investigate the role of clouds in modifying the surface radiation components (total, direct and diffuse radiation), and canopy gas exchange processes such as LUE, water use efficiency (WUE – carbon gain per unit of water loss) and gross primary productivity (GPP) at Howard Springs, a tropical savanna site in northern Australia. The influence of other environmental factors such as soil moisture, vapour pressure deficit (VPD) and temperature on GPP is also investigated. We used half hourly wet/growing season GPP and other meteorological data for different sky conditions in a woodland savanna forest. Briefly, this study will seek to answer if extensive cloud cover in the savannas during the wet season can increase the component of diffuse solar radiation reaching the surface and consequently increase GPP. The findings of this study will add to our knowledge of clouds; their effect on tropical savannas CO_2 exchange; provide data to calibrate dynamic vegetation models and contribute further insights into the carbon dynamics of this extensive tropical ecosystem.

2. Data and methodology

2.1. Study area

The impact of clouds on savanna GPP was examined using GPP derived from an eddy flux tower located at Howard Springs (12.425°S and 130.891°E, Northern Territory (NT), Australia (Fig. 1). Continuous measurements of NEE of carbon, latent and sensible heat fluxes have been measured at this site since August 2001 (Beringer et al., 2007). The site is classified as an open woodland savanna forest, with 50–60% canopy cover (Hutley et al., 2000). The over storey is co-dominated by evergreen tree species, *Eucalyptus miniata* and *Eucalyptus tetrodonta* with other species including *Erythrophleum chlorostachys* and *Terminalia ferdinandiana* (Hutley et al., 2011). The leaf area index (LAI) of over storey vegetation varies between 0.9 and 0.6 in the wet (December–April) and dry (May–September) seasons respectively. The under storey is covered by annual C_4 grasses (annual *Sorghum*) with a green LAI of 1.5 in the wet season which reduces to 0.2 in the dry season (O'grady et al., 2000). Soils at the site are red-earth sands (red kandosols) with cracking clay soils that limit woody plant growth (Hutley et al., 2011).

The study site is generally characterised by large seasonal changes in precipitation; hence soil water content but little seasonal variation in solar radiation and temperature (Hutley et al., 2011). The mean annual rainfall is 1675 mm and average temperature of 30 °C. During the dry season little or no rainfall is received due to the prevailing dry south east trade winds and the nocturnal temperatures range from 15 to 21 °C. Fire in this vegetation type typically occurs 2 in 3 years (Russell-Smith and Yates, 2007) and at this site, it occurs 1 in every 2 years on average with the fire line intensity of ranging from 0.9 to 3.6 MW m^{-1}.

2.2. Data sets

2.2.1. Gross primary productivity

GPP estimated from the flux tower at the Howard Springs site (Beringer et al., 2007) was used for this study. GPP was estimated to be equivalent to net ecosystem exchange (Fc) as measured by the eddy covariance system minus net ecosystem respiration (Re). Re was estimated from night time Fc observations that were measured under turbulent conditions (ustar filter of >0.15 m s^{-1}) and a model was developed using an Artificial Neural Network technique with soil moisture, soil temperature and air temperate as inputs to predict Re (Beringer et al., 2007). Re was then applied to daytime conditions to give a continuous time series. GPP was then taken as the difference between the modelled Re and observed Fc.

The effect of clouds on savanna GPP were analysed in the wet season. A total of 5 wet seasons spanned from December to March (2001–2002, 2002–2003, 2003–2004, 2004–2005 and 2005–2006) were considered in the study.

2.2.2. Cloud

Direct measurement of cloudiness, such as cloud thickness or cloud cover, was not available for Howard Springs. Therefore, a clearness index (CI) was used as a surrogate measure of cloudiness and was defined as the ratio of global solar radiation received above the canopy to the extraterrestrial solar radiation at a hypothetical horizontal surface at the top of the atmosphere (Gu et al., 1999). The CI has been used previously to investigate the effect of different sky conditions on NEE and GPP (Gu et al., 1999; Letts et al., 2005; Alton et al., 2007a,b; Alton, 2008).

Extra terrestrial radiation (Ex) was calculated in this study at 30 min interval using SOLPOS solar position online calculator Version 2.0 (http://www.nrel.gov/midc/solpos/solpos.html) distributed by the National Renewable Energy Laboratory, Centre for Renewable Energy Resources, United States Government. SOLPOS provides solar position estimates for periods from 1950 to 2050 with an accuracy of ±0.01° (http://www.nrel.gov/midc/solpos/). Shortwave radiation (0.3–2.8 μm) was measured above the canopy at Howard Springs using Kipp and Zonen thermopile pyranometers (model CM7b, Delft, The Netherlands).

2.2.3. Photosynthetically Active Radiation (PAR)

Photosynthetically Active Radiation (PAR) (0.4 and 0.7 μm) was also measured at the tower site with a Delta T BF-3 quantum sensor, but only for several months in 2006 (May to August). Hence, for periods with no PAR measurements (i.e. from December 2001 to March 2006) PAR was calculated by first estimating the ratio of PAR to SW. The ratio of PAR to SW (PAR:SW) changes with sky condition, with a higher ratio under cloudy conditions since clouds absorb some of the infra red radiation. PAR:SW can be described by a simple function of the clearness index (Finch et al., 2004; Tsubo and Walker, 2005). Therefore, a relationship was determined between CI and PAR:SW at 30 min intervals to obtain different ratios of PAR:SW under varying cloud conditions (Fig. 2a). The PAR:SW for each interval in CI of 0.1 was averaged and plotted against the values of PAR:SW ratio for the midpoint of the interval, following Tsubo and Walker (2005). The relationship between PAR:SW and CI were best fitted using a logarithmic function:

$$\mathrm{PAR:SW} = \sqrt{\frac{(a + b \times \ln(\mathrm{CI})}{\mathrm{CI}}} \quad (1)$$

where *a* and *b* are regression coefficients and CI is clearness index.