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Primary and secondary effects of climate variability on net ecosystem carbon exchange in an evergreen *Eucalyptus* forest

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ABSTRACT

To understand the dynamics of ecosystem carbon cycling more than 10 years of eddy covariance data, measured over an evergreen, temperate, wet sclerophyll forest, were analysed and related to climate drivers on time scales ranging from hours to years. On hourly timescales we find that incoming shortwave radiation is the major meteorological driver of net ecosystem carbon exchange (NEE). Light use efficiency is higher under diffuse light conditions and carbon uptake is further modulated by the effects of variable and suboptimal temperatures (optimal temperature $T_{opt} = 18\,^{\circ}\mathrm{C}$) as well as by water demand (critical vapour pressure deficit $VPD_{crit} = 12$ hPa). Incoming shortwave radiation is also the major driver on daily time scales. Effects of increased light use efficiency under diffuse conditions, however, are overcompensated by the increased carbon uptake with larger amounts of total incoming shortwave radiation under clear sky conditions. On synoptic time scales a low ratio of actual to potential incoming shortwave radiation is also related to a reduced carbon uptake, or carbon release, and associated with precipitation events. Overcast conditions during an extended wet period (2010–2011) led to lower than average carbon uptake as did extended dry periods during 2003 and 2006. The drought in 2003 triggered an insect attack which turned the ecosystem into a net source of carbon for almost one year. The annual average normalised difference vegetation index (NDVI) is highly correlated with NEE at this site and multiple linear regression shows that NDVI, incoming solar radiation and air temperature explain most of the variance in *NEE* ($r^2 = 0.87$, $p < 0.001$). Replacing air temperature with average spring air temperatures further increases the correlation ($r^2 = 0.91$, $p < 0.001$). Results demonstrate that carbon uptake in this ecosystem is highly dynamic, that wavelet analysis is a suitable tool to analyse the coherence between the carbon exchange and drivers seamlessly, and that long time series are needed to capture the variability.

1. Introduction

Forest ecosystems play a vital role in buffering the accumulation of carbon dioxide in the atmosphere by storing large amounts of carbon and by removing 3 billion tons of carbon every year through net uptake (e.g. Canadell and Raupach, 2008; Luyssaert et al., 2008). Forest carbon sinks, however, are vulnerable to disturbances, both human-induced and natural, that can lead to significant net transfers of carbon from the land to the atmosphere (e.g. Ciais et al., 2005; van der Werf et al., 2010; Zhao and Running, 2010).

Droughts impact a broad range of ecosystems across a range of spatial scales (van der Molen et al., 2011) and the area that is affected by droughts has increased strongly. IPCC-AR4 future climate projections predict more frequent and more intense droughts, particularly in mid-latitudes and over Africa, Australia and Latin America (Bates et al., 2008; Meehl et al., 2007). Drought – an intermittent disturbance of the water cycle – interacts with the carbon cycle by causing plants to respond physiologically and structurally to prevent excessive water loss (van der Molen et al., 2011). Physiological responses include decrease of stomatal conductance to

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prevent leaf water potential from reducing below a critical level. This also leads to a short term reduction in assimilation because stomatal closure reduces CO_2 diffusion into the leaf (Leuning, 1990). Structural responses include reduction of leaf area (Metcalfe et al., 1990), leaf area index due to increased senescence (Pook, 1986) and changes in leaf angle (Kull et al., 1999) and dynamic responses in the rooting system (Schymanski et al., 2008). These responses lead to a modification in carbon uptake. Carbon release is also modified through the effect of soil moisture on microbial activity and even more so through the supply of labile organic compounds produced by photosynthesis (Irvine et al., 2005). This explains an often observed joint reduction in carbon uptake and release. After a drought the disturbances in the reservoirs of soil moisture, organic matter and available nutrients lead to longer term effects in plant carbon cycling, to increased vulnerability to other disturbances such as insect, fire and wind throw, and potentially to mortality (van der Molen et al., 2011).

Insect attacks have an impact on the amount and the timing of leaf area (Clark et al., 2010). Increased leaf fall leads to changes in photosynthetically active biomass and increases in the litter layer. A species dependent reduction of tree growth and increased mortality has been observed (Keith et al., 2011). When integrated over time insect disturbances can impact long-term carbon storage in woody stems, forest floor, and soil, due in part to reduced litterfall production and stem increment, and increased tree mortality but there is little quantitative information on the effects of insect attacks on carbon uptake or release and water cycling in forest ecosystems. Rates of recovery of carbon exchanges following defoliation events are also largely unknown (Clark et al., 2010).

Both droughts and insect attacks are 'low frequency disturbances'. It is essential to understand the processes that regulate uptake and release of carbon and water on all relevant time scales under current climatic conditions. It is further critical to understand the consequences of a changing climate on the capacity of the biosphere to sequester carbon by using a certain amount of water and to understand the impact of disturbances on resilience and thresholds of the terrestrial biosphere.

In this manuscript we establish how climate drivers regulate carbon and water exchanges in a temperate wet sclerophyll ecosystem. We establish what the role of these drivers is on time scales ranging from days to multiple years. We present this in a concise framework that is provided through a wavelet coherence analysis (Torrence and Compo, 1998; Torrence and Webster, 1999; Schaefli et al., 2007).

To answer the question "What is the impact of climate variability on net ecosystem exchange of carbon in a temperate, evergreen, native Australian forest?" we address the following set of questions:

(i) How efficiently is light used for photosynthesis and how is this modulated by cloudiness, temperature and vapour pressure deficit?
(ii) How do extended dry and wet periods alter the exchanges of carbon and water?
(iii) Can we quantify or rank the impact of climate drivers on the exchanges of carbon and water on all relevant time scales? How does the importance of drivers change with time scales?

2. Methods and definitions

2.1. Micrometeorological approach

We use data collected at the 70 m tall Tumbarumba flux station from 2001 to 2011. An eddy covariance system is used to derive the net ecosystem exchanges of carbon (*NEE*), water (*LE*) and sensible heat (*H*). The turbulent fluxes are measured at tower top with a 3D-ultrasonic anemometer thermometer (Type HS, Gill Instruments, Ltd., Lymington, UK) to derive all wind components and virtual temperature at 20 Hz, and an open-path infrared gas analyzer (IRGA) for measuring carbon dioxide (CO_2) and water vapour (H_2O) (Li7500, Li-Cor Inc., Lincoln, NE, USA). To derive the rate of change in storage of CO_2 in the layer below the tower top, CO_2 concentrations were measured at nine heights (0.5, 4.6, 10.2, 18.1, 26.3, 34.4, 42.6, 54.4 and 70.1 m) using a closed path IRGA (Li6262, Li-Cor Inc.) and gas switching valves. Note that we implicitly assume that the rate of change of CO_2 in the control volume can be represented by a single profile where ideally it would be calculated from instantaneous profiles of space averaged concentrations (Finnigan, 2006). Advection is not routinely measured at our site, but an intensive field campaign in March 2005 showed that advection is significant below the canopy during light winds and stratification (Leuning et al., 2008). A follow up intensive campaign showed that measurements are also degraded when flows in and above the canopy are decoupled (van Gorsel et al., 2011). While we have developed a method to address these issues (van Gorsel et al., 2007, 2009) they involve heavy replacement of nighttime data by modelled respiration. This works well to quantify *NEE* and good agreement between eddy covariance and chamber methods has been reported (Keith et al., 2009) but is not ideal when driver–flux interactions are analysed. We have therefore used this approach when quantifying and ranking *NEE* (Figs. 6 and 7). We used a statistical look up table approach for gapfilling (Reichstein et al., 2005) when analyzing driver–flux relationships and used daytime fluxes only for timescales larger than diurnal.

Shortwave radiation was measured with a CM11-pyranometer from 2001 until February 2012 and a CM3 from then onwards (both instruments Kipp and Zonen, Inc., Delft, The Netherlands). Temperature and humidity were measured with a humitter (50Y, Vaisala Oyj, Helsinki, Finland). Rainfall was measured with tipping bucket rain gauges above the canopy and at ground level. Soil temperatures were recorded at 0.02 m depth with thermocouples manufactured in our laboratory. Measurements of three thermocouples were averaged at this depth. Soil moisture content was measured using time domain reflectometry (Satellite Pro, CSIRO) in four locations and four depths each. Measuring interval is 1 h. All other signals were sampled at either 1 or 0.1 Hz and averaged for 1 h.

2.2. Remote sensing data

Landsat 7 ETM+ imagery from 2001 to 2011 was downloaded from glovis (http://www.glovis.usgs.gov/) and atmospherically corrected using the dark object algorithm from Chavez (1988). The value for the dark object was taken from the minimum digital value of the histogram with at least 200 pixels. The values for atmospheric transmittance of the first 4 bands were taken from the original publication of Chavez (1996) while the values for the SWIR region were taken from Gilabert et al. (1994). The upwelling atmospheric transmittance and the diffuse irradiance were ignored. Spectra compared well with the spatially and spectrally resampled airborne hyperspectral data (not shown). The normalised difference vegetation index (NDVI) was calculated as NDVI = (band 4 − band 3)/(band 4 + band 3), where band 4 is the spectral band between 772 nm and 898 nm (near infrared) and band 3 is the spectral band between 0.631 nm and 692 nm (visible). NDVI was calculated for the area with a radius of 1 km around the tower as well as for the whole area within Bago State Forest that was classified as native Eucalyptus forest (305.05 km^2). Only images with less than 10% cloud presence and with no snow cover were selected. To avoid seasonal bias (strongly varying amount of