Journal of Hydrology 519 (2014) 1350–1361

Contents lists available at ScienceDirect

Journal of Hydrology

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

Impacts of elevated CO_2, climate change and their interactions on water budgets in four different catchments in Australia

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ARTICLE INFO

Article history:
Received 30 January 2014
Received in revised form 26 August 2014
Accepted 9 September 2014
Available online 4 October 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Venkat Lakshmi, Associate Editor

Keywords:
Elevated atmospheric CO_2 concentration
Carbon-water coupling relationship
Changing climate
Water balance
Physiological effects

SUMMARY

Future water availability is affected directly by climate change mainly through changes in precipitation and indirectly by the biological effects of climate change and elevated atmospheric CO_2 concentration (eCO_2) through changes in vegetation water use. Previous studies of climate change impact on hydrology have focused on the direct impact and little has been reported in the literature on catchment-scale the indirect impact. In this study, we calibrated an ecohydrological model (WAVES) and used this model to estimate the direct and indirect effects and the interactive effect between climate change and eCO_2 on water availability in four different catchments in Australia with contrasting climate regime and vegetation cover. These catchments were: a water-limited forest catchment and an energy-limited forest catchment, a water-limited grass catchment and an energy-limited grass catchment. The future meteorological forcing was projected from 12 GCMs representing a period centred on 2050s and future CO_2 concentration was set as 550 ppm. Modelling experiments show that impacts of eCO_2 and projected climate change on vegetation growth, evapotranspiration (ET) and runoff were in the same magnitude but opposite directions in all four catchments, except for the effects on runoff in the energy-limited grass catchment. Predicted responses of runoff to eCO_2 indicate that eCO_2 increased runoff in the energy-limited forest catchment by ~2% but decreased runoff in other three catchments from 1% to 18%. This study indicates that rising CO_2 increases ecosystem water use efficiency but it does not necessarily result in increased runoff because elevated CO_2 also stimulates vegetation growth and increases ET. Elevated CO_2 was proved to have greater impacts on runoff than climate change in the forest catchments. Modelling experiments also suggest that interactive effects between climate and CO_2 are important, especially for predicting leaf area index (LAI) and ET in grassland catchments or runoff in water-limited catchments, where interactive effects were 1–6%. It implies that the assumption that linear combination of individual effects in most of previous studies is not appropriate. This study highlights the importance of considering elevated CO_2 in assessing climate change impacts on catchment-scale water balance and failure to account for direct eCO_2 effect or its interactive effects can lead to large bias in the predictions of future water budgets, especially for the water-limited catchments in Australia.

1. Introduction

Climate change is predicted to shape new hydroclimatic regimes in many regions of the world (Ramanathan et al., 2001; Dore, 2005; Dai, 2013), and will have significant impacts on water availability (Milly et al., 2005; Bates et al., 2008; Milly et al., 2008). Recent observational studies have shown that elevated atmospheric CO_2 concentration (denoted as eCO_2) may have significant implications for water availability through its physiological effects on plant function associated with the increased water-use-efficiency (WUE) (Eamus, 1991; Field et al., 1995; O'Grady et al., 2011). Modelling results at both plot and global scales have shown that changes in WUE may lead to a discernible increase in water availability or runoff (Gedney et al., 2006; Betts et al., 2007; Cao et al., 2010; Warren et al., 2011). Potential increase in water availability under eCO_2 may be particularly important for water-limited regions (Wullschleger et al., 2002), such as Australia (Eamus et al., 2006). However, the physiological effects of eCO_2 on water budget at catchment scales have rarely been addressed (Bates et al., 2008).

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http://dx.doi.org/10.1016/j.jhydrol.2014.09.020
0022-1694/

At the leaf scale, eCO_2 trends to reduce stomatal conductance and consequently lower transpiration rate per unit leaf area. This is a water saving effect. Thus, if all other factors remain unchanged, eCO_2 should increase water availability. This leaf-scale effect has been observed in many experimental studies (Eamus and Jarvis, 1989; Norby et al., 1999; Medlyn et al., 2001; Ainsworth and Long, 2005). Several modelling studies showed that runoff increased significantly caused by this leaf-scale physiological effect of eCO_2 (e.g., Aston (1984), Gedney et al. (2006) and Cao et al. (2010)). At stand or regional scales, however, the physiological processes associated with eCO_2 can increase canopy leaf area index (LAI) via two mechanisms. One is via direct CO_2 fertilization effects (Field et al., 1995; Körner et al., 2007; De Kauwe et al., 2014); the other is indirectly via increased water availability resulting from reduced stomatal conductance (Wullschleger et al., 2002; Morgan et al., 2011). Increased LAI may offset the effect of the leaf-scale increased WUE on ecosystem water availability and result in little or no change in ecosystem water budgets (Levis et al., 2000). The net effect of eCO_2 on regional water budgets therefore depends on both responses of stomatal conductance and feedbacks of canopy LAI. The magnitude of the feedbacks of LAI is a key determinant of whether eCO_2 will increase runoff and by how much because leaves are the primary interface of among energy, water and carbon (Woodward, 1990; Cowling and Field, 2003; Piao et al., 2007; Bounoua et al., 2010; Norby and Zak, 2011). How the physiological effects of eCO_2 will manifest at catchment scale is poorly understood and likely to vary across different climate regimes and ecosystems (Ainsworth and Long, 2005; McMurtrie et al., 2008; Leakey et al., 2012).

Future changes in precipitation, temperature and evaporative demand (determined by radiation, humidity, wind speed and temperature) are direct drivers of catchment water yield (Bates et al., 2008). Increased evaporative demand can enhance regional evapotranspiration and decrease runoff. However, both evapotranspiration (ET) and runoff can increase if precipitation increases. Similarly, canopy LAI may be altered by climate change directly by the changes in meteorological forcing on growth (Cowling and Field, 2003) and indirectly through the influence of climate change on regional soil water availability (Knapp et al., 2002; Gerten et al., 2008a). Changes in canopy LAI induced by climate change can also exert indirect influences on regional water budgets through changes in partitioning of ecosystem transpiration and evaporation water use (Zhang et al., 2001; Puma et al., 2013). Future climate change is projected to vary spatio-temporally in both magnitude and direction (IPCC, 2007), thus sensitivities of both vegetation and water budget to climate change may be markedly different across space and time (Milly et al., 2005; Hyvönen et al., 2007; Bonan, 2008). In addition, complex interactions among the influences of both eCO_2 and climate change on canopy LAI and water budget can dampen or amplify the impacts of either individual factor (Cramer et al., 2001; Gerten et al., 2005), because physiological effects of eCO_2 at regional scale depend on both canopy LAI and meteorological conditions. However, the effects of the interactions between climate change and eCO_2 on canopy LAI and water budget have rarely been considered. In those studies that considered such effects, a linear combination of these effects caused by eCO_2 and other environmental drivers was routinely assumed (e.g., Betts et al. (1997), Gedney et al. (2006) and Piao et al. (2007)). Sellers et al. (1996) showed that nonlinear interactions between physiological and radiative effects of double CO_2 on plant growth were noticeable and differed across latitudinal gradients. Luo et al. (2008) demonstrated that interactions among changes in temperature, CO_2 and precipitation on carbon and water dynamics are not consistent among different ecosystems. However, whether nonlinear interactions between climate and CO_2 on plant growth and their impacts on the water availability are important has rarely been quantified across different ecosystems.

Quantifying the changes in future water yield due to either eCO_2 and climate change remains a challenge (Huntington, 2008; Luo et al., 2011), and whether interactive effects between eCO_2 and climate change on both canopy LAI and water budgets are negligible in different climatic and vegetation condition needs further investigation. Model simulations are a useful approach to elucidate and predict the physiological effects of eCO_2 and their interactions with climate change since physiological effects of eCO_2 at regional scale were poorly understood and atmospheric CO_2 content is projected to rise beyond our observation (Luo et al., 2011). General circulation models with sophisticated land surface models have been used to study the eCO_2 effects on water availability globally (e.g., Sellers et al. (1996), Betts et al. (1997), Gedney et al. (2006), Piao et al. (2007), Betts et al. (2007), Gerten et al. (2008b), Cao et al. (2010)), however the results of these studies are inconclusive due to their differences in modelling methodology including physiological processes of eCO_2, model structure and underlying assumptions (Gerten et al., 2008b; Bounoua et al., 2010; De Kauwe et al., 2013) and poor hydrological performances (Zhou et al., 2012). At catchment scales, previous modelling experiments have consistently predicted an increase in runoff in response to eCO_2 with a relative response ranging from less than 10% (Eckhardt and Ulbrich (2003), Kruijt et al. (2008), and Leuzinger and Körner (2010)) to about 90% (Aston, 1984). Many previous studies of eCO_2 at catchment scale suffer from two weaknesses. First, physiological processes and hydrological processes were loosely coupled in those models (e.g. Eckhardt and Ulbrich (2003)). As a result, interactions between canopy LAI and soil hydrology under eCO_2 cannot be studied systematically (Gerten et al., 2004; De Kauwe et al., 2013). Secondly, modelling was usually carried out for specific climate regime and vegetation cover. Thus results from those studies may not be applicable to other regions (Wullschleger et al., 2002; McMurtrie et al., 2008).

In this study, a coupled water-carbon ecohydrological model WAVES (WAter Vegetation Energy and Solute modelling, see Zhang et al. (1996)) was used to investigate the effects of eCO_2 and their interactions with future climate change on canopy LAI and the water budget. Four small catchments in Australia were selected with contrasting vegetation cover (i.e. forest versus grass) and climate regimes (i.e. water-limited versus energy-limited). Water-limited climate represents a dry climatic condition where mean annual precipitation is less than mean annual potential evaporation. While, energy-limited climate regime refers to a wet climatic condition where mean annual precipitation is larger than mean annual potential evaporation. The four selected catchments included a water-limited forest catchment and an energy-limited forest catchment as well as a water-limited grass catchment and an energy-limited grass catchment. The future meteorological forcing representing 2050s was projected from 12 GCMs of IPCC AR4 with emission scenario A2, and then downscaled to the study catchments. The future CO_2 concentration under emission scenario A2 (i.e., eCO_2) at 2050s is projected to be 550 ppm. In particular, this study has four objectives: (1) to demonstrate whether a water-carbon coupled model can capture the physiological impacts of both eCO_2 and climate change on canopy LAI and their hydrological impacts on catchment water budgets in different typical ecosystems; (2) to assess effects of eCO_2 on canopy LAI and catchment water yield under different climate regimes and vegetation cover in Australia; (3) to estimate whether impacts of eCO_2 on water budgets in vegetated catchments are small enough to be ignored in comparison to the impacts of future climate change; (4) to investigate whether the interactions between eCO_2 and changes in climate forcing are negligible in predicting future canopy LAI and water yield.