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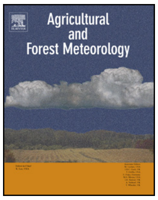

Sensitivities of the Australian terrestrial water and carbon balances to climate change and variability☆

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ABSTRACT

To assess both past and future responses of the coupled terrestrial water and carbon cycles to climate change and variability, it is important to characterise the sensitivities of water and carbon fluxes and stores to long-term changes in drivers such as precipitation (P), temperature (T) and CO_2 concentration. Here we quantify observed sensitivities using a well-calibrated terrestrial biosphere model and data for the Australian continent, and thereby infer likely changes to the water and carbon cycles under specified scenarios for future changes in the drivers. We find: (1) evapotranspiration (ET) has a large positive sensitivity to P, a positive sensitivity to T, and a negative sensitivity to CO_2 through increased plant water use efficiency with rising CO_2. Consequently, likely changes in T and CO_2 over the next half century will have opposite and nearly cancelling effects on ET. (2) Runoff has a large sensitivity to P (positive) and significant sensitivities to T (negative) and CO_2 (positive). These sensitivities are largest in cool temperate regions, where major contributors to likely long-term changes in runoff are decreased P (where a 5% rainfall reduction would lead to a 12% decrease in runoff), increased T (with a warming of 1.5 K leading to an additional 6% decrease in runoff), and response to CO_2 (with an increase of 100 ppm causing an offsetting 6% increase in runoff). (3) Sensitivities of soil moisture to P, T and CO_2 have similar signs and spatial patterns to those for runoff, but are smaller in magnitude by a factor of 5–10. (4) In the terrestrial carbon cycle, net ecosystem production (NEP) is increased by rising CO_2 but simultaneously reduced (and nearly cancelled in likely scenarios) by warming.

1. Introduction

The terrestrial water and carbon cycles respond to climate change and variability through a set of coupled physical and physiological processes. Prominent among these are (1) the joint control of transpiration and CO_2 assimilation by plant stomata (Wang and Leuning, 1998; Leuning et al., 1998; Tuzet et al., 2003); (2) feedbacks between surface temperature, evaporation and CO_2 assimilation (Raupach, 1998); (3) effects of temperature and moisture on soil evaporation (Haverd and Cuntz, 2010); and (4) effects of temperature and moisture on soil respiration of CO_2 (Lloyd and Taylor, 1994). The main physical drivers of these interacting processes – precipitation, light, temperature, humidity and CO_2 concentration – are all affected by climate change, leading to a range of coupled responses in water and carbon cycles.

For the terrestrial water cycle, a major hypothesised response to anthropogenic climate change is an increase in runoff, caused both by a global intensification of the water cycle in response to warming (Labat et al., 2004) and also by local-scale increases in plant water use efficiency in response to rising CO_2 (Gedney et al., 2006; Betts et al., 2007). While there is observational evidence for such an increase in globally aggregated terrestrial runoff (Labat et al., 2004), regional changes in runoff are expected to be strongly heterogeneous because of regional differences in precipitation changes. In particular, drying trends are both expected and observed in subtropical regions such as Southern Australia (Larsen and Nicholls, 2009; Ummenhofer et al., 2011), leading to runoff reductions (Chiew et al., 2009b).

For the terrestrial carbon cycle, a major response to anthropogenic forcing is the existence of a global terrestrial carbon sink that removes over a quarter of total anthropogenic CO_2 emissions from the atmosphere (with the oceans removing another quarter) (Le Quéré et al., 2009). Among several mechanisms, a major contributor in all attributions is CO_2 fertilisation, the effect of rising CO_2 on terrestrial gross primary production (GPP) and net primary production (NPP = GPP − plant respiration). Heterotrophic soil respiration (RH) is also affected by climate change through both soil temperature and moisture, leading to complex regional patterns for net

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ecosystem production (NEP = NPP − RH) and net biome production (NBP = NEP − disturbance fluxes).

In the past, it has been usual to undertake separate assessments of the responses of the terrestrial water and carbon cycles to climate change and variability, respectively in the hydrological literature (for instance, Chiew et al., 2009b) and biogeochemical literature (for instance, Friedlingstein et al., 2006; Sitch et al., 2008). However, there are both modelling and observational reasons for considering the water and carbon cycles together. From a modelling perspective, numerous process interactions between the water and carbon cycles must be considered in order to model either cycle reliably, as sketched in the opening paragraph. From an observational perspective, these interactions mean that observations of each cycle constrain the other, with the aid of model-data fusion approaches (Raupach et al., 2005; Haverd et al., 2013a).

In this paper we undertake such a coupled investigation of the sensitivities of the major fluxes and stores in the terrestrial water and carbon cycles to driving variables, primarily precipitation (P), temperature (T) and CO_2 concentration (CO_2), but also solar irradiance and wind speed, together with leaf area index (LAI), an endogenous variable that is directly observable.

The study is motivated by four related questions:

1. There is controversy over whether warming leads to increased ET in southeast Australia, as maintained by some on simple heuristic grounds (Karoly et al., 2003; Nicholls, 2004) but disputed elsewhere (Lockart et al., 2009). What is the sign and space–time pattern of the sensitivity of ET to temperature, and how does this sensitivity compare with the sensitivity of ET to other major drivers, including precipitation and CO_2?
2. It is already well known that runoff is highly sensitive to precipitation and that projected declines in precipitation in southeast Australia will proportionally reduce runoff by about three times as much as the decline in precipitation (Chiew et al., 2009b), an effect that has been termed the "rainfall-runoff amplifier" (Raupach, 2010). How much do other drivers (especially but not only temperature and CO_2) affect the gain of the amplifier?
3. What are the effects of changes in all drivers on soil moisture? In particular, how much does warming exacerbate soil-moisture-related drought – substantially (Dai et al., 2004) or insignificantly (Sheffield et al., 2012)?
4. How do the major climatic drivers affect NEP and its component fluxes, NPP and RH, across the Australian continent (and by extension in similar semi-arid regions elsewhere), and what are the consequences for rates of carbon accumulation in the Australian biosphere?

The first three of these questions focus on the water cycle, respectively through evapotranspiration (ET), runoff and soil moisture. The last focuses on the carbon cycle, through NEP and the total terrestrial carbon store.

The paper is structured as follows: after this introduction, Section 2 outlines theory and the model and observations used here. Sections 3 and 4 respectively present results for the water cycle, with foci on ET, runoff and soil moisture, and for the carbon cycle, with foci on NEP and the soil carbon store. Sections 5 and 6 respectively discuss results and summarise conclusions.

2. Theory, model and data

2.1. Mass balances for water and carbon

A simplified mass balance for terrestrial water is

$$\frac{dw}{dt} = p - e - q = p - (e_{\text{Trans}} + e_{\text{Soil}}) - q \qquad (1)$$

where w is total column soil moisture store, and p, e and q are respectively the water fluxes due to precipitation, total evaporation or evapotranspiration (ET), and total runoff or outflow from the soil column. Total runoff includes surface runoff, deep drainage to groundwater, and the divergence of lateral water flows in the soil. ET is the sum $e = e_{\text{Trans}} + e_{\text{Soil}}$ of transpiration and soil evaporation. All stores and fluxes are functions of space and time, resolving landscape heterogeneity and the diurnal cycle. Throughout, lower-case letters denote space–time-resolved variables; corresponding upper-case letters will later denote temporal and spatial averages.

At a similar simplified level, the mass balance for terrestrial carbon is

$$\frac{d(c_{\text{Plant}} + c_{\text{Soil}})}{dt} = f_{\text{NPP}} - f_{\text{RH}} - f_{\text{Disturb}} = f_{\text{NEP}} - f_{\text{Disturb}} = f_{\text{NBP}} \qquad (2)$$

where the total terrestrial carbon store is the sum $(c_{\text{Plant}} + c_{\text{Soil}})$ of plant and soil C stores, and carbon fluxes (denoted by f) arise from net primary production (NPP), heterotrophic respiration (RH) and disturbance, with net ecosystem production NEP = NPP − RH and net biome production NBP = NEP − disturbance. Disturbance fluxes include fire, harvest offtakes, waterborne and windborne transport flux divergences, and fluxes from land use change.

2.2. Model and data

The fluxes and stores in the coupled carbon and water cycles, Eqs. (1) and (2), were simulated using a modified version of the CABLE land surface model in the BIOS2 modelling environment, following Haverd et al. (2013a,b) where full details are given. BIOS2 is an offline environment for modelling the coupled energy, water and carbon balances of the Australian continent, at fine spatial (0.05°, ~5 km) and temporal (hourly) resolutions. The land surface model in BIOS2 is CABLE v1.4 (Wang et al., 2011), modified by replacement of the default CABLE soil and carbon modules (Wang et al., 2011) by the SLI soil model (Haverd and Cuntz, 2010) and the CASA-CNP biogeochemical model (Wang et al., 2010). Only the carbon dynamics in CASA-CNP are used in this work; nutrient (N and P) dynamics are not considered. CABLE includes vertical resolution of soil heat and water stores into multiple layers to depth 10 m and CASA-CNP resolves three carbon stores that differ by turnover time; for simplicity, Eqs. (1) and (2) aggregate these stores into total soil-column stores. The BIOS2 environment provides CABLE with (1) efficient infrastructure for the treatment of inputs (gridded vegetation data, meteorological data and parameters) and outputs at fine space–time resolution, based on developments for the Australian Water Availability Project (AWAP) (Raupach et al., 2009); (2) a weather generator for downscaling of daily meteorological data to the hourly model time step; and (3) model-data fusion capability.

Model parameters were estimated by constraints from multiple data sets on fluxes and stores in both the water and carbon cycles (Haverd et al., 2013a): (1) streamflow from 416 gauged catchments; (2) measurements of ET and NEP from 12 eddy-flux sites; (3) litterfall data, and (4) data on carbon pools. This use of multiple constraints provides safeguards against bias from any single data type. With parameters estimated in this way, evaluation of BIOS2 against a wide range of data on water and carbon fluxes and stores (extending far beyond the data sets used for parameter estimation) yields satisfactory model-measurement agreement (Haverd et al., 2013a).

The reference run of BIOS2 for this work is a 213-year run from 1799 to 2011, at full spatial and temporal resolution, as in Haverd et al. (2013b). Specifically:

- Forcing meteorological data for precipitation (p), temperature (τ) and solar radiation (s) were from AWAP (Jones et al., 2009), with downscaling from daily to hourly (see above). Observed p and