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LETTER

Vegetation plays an important role in mediating future water resources

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Abstract

Future environmental change is expected to modify the global hydrological cycle, with consequences for the regional distribution of freshwater supplies. Regional precipitation projections, however, differ largely between models, making future water resource projections highly uncertain. Using two representative concentration pathways and nine climate models, we estimate 21st century water resources across Australia, employing both a process-based dynamic vegetation model and a simple hydrological framework commonly used in water resource studies to separate the effects of climate and vegetation on water resources. We show surprisingly robust, pathway-independent regional patterns of change in water resources despite large uncertainties in precipitation projections. Increasing plant water use efficiency (due to the changing atmospheric CO₂) and reduced green vegetation cover (due to the changing climate) relieve pressure on water resources for the highly populated, humid coastal regions of eastern Australia. By contrast, in semi-arid regions across Australia, runoff declines are amplified by CO₂-induced greening, which leads to increased vegetation water use. These findings highlight the importance of including vegetation dynamics in future water resource projections.

1. Introduction

General circulation models (GCMs) from the newest generation of the Coupled Model Intercomparison Project (CMIP5; Taylor *et al* 2012) suggest consistent 21st century temperature increases and, on average, increasing precipitation globally (Collins *et al* 2013). But changes in regional precipitation patterns remain stubbornly uncertain, despite advances in modelling capability (Knutti and Sedláček 2012, Collins *et al* 2013). High uncertainty has hindered robust projections of water resources, especially in regions with naturally hypervariable climates. Australia is a continent with exceptionally high interannual and inter-decadal climate variability, with runoff

variability about twice that typical in the Northern Hemisphere (Chiew and McMahon 1993). Due to the general aridity of the continent its water resources are vulnerable to future precipitation changes, and it has been identified as a likely hotspot for future water scarcity (Prudhomme *et al* 2014).

Water resources are also dependent on vegetation processes, which are affected by environmental change. Elevated CO₂ can both increase and decrease vegetation water use, with consequences for runoff generation. Higher CO₂ concentrations lower stomatal conductance (Field *et al* 1995), reducing water loss through leaves and leaf-scale transpiration. Simultaneously, elevated CO₂ stimulates plant photosynthesis, in principle increasing green vegetation cover and

canopy-scale transpiration. Studies of historical and future runoff (Gedney *et al* 2006, Davie *et al* 2013) often point to increased runoff due to CO₂-induced increases in water use efficiency (in particular, stomatal closure allowing water to be conserved), which can be observed both at the leaf (Field *et al* 1995) and ecosystem (Keenan *et al* 2013) scales. However, a recent analysis of historical observations (Ukkola *et al* 2016) showed these water savings do not necessarily lead to increased runoff in drier climates due to CO₂-induced vegetation greening (Donohue *et al* 2013), which acts to increase vegetation water use at the ecosystem scale. Changes in vegetation water use due to CO₂ as well as climatic factors may play a large, yet to date poorly constrained, role in mediating future water resources.

Here we examine potential future changes in water resources in Australia and how they are influenced by climatic and vegetation processes. To do so, we use two contrasting approaches, in combination with climate projections from nine GCMs. The first approach is the Fu-Zhang formulation of the simple Budyko hydrological framework (Zhang *et al* 2004), a well-established empirical model widely employed in studies of water resources (Zhang *et al* 2004, Yang *et al* 2007). It accounts for the effects of climate (precipitation and potential evapotranspiration) on actual evapotranspiration (AET) and runoff. The second is the process-oriented Land surface Processes and eXchanges Dynamic Global Vegetation Model (LPX DGVM), a complex biosphere model which simulates coupled effects of climate, vegetation, carbon and fire on hydrology. We limit our analysis to Australia to make use of high-quality hydrological observations to assess the performance of LPX for observed historical changes in evapotranspiration (see methods for detailed model descriptions and historical evaluation).

By contrasting results from the LPX and Budyko models, we separate the effects of vegetation processes from direct effects of climate on future runoff projections. We show that, despite widespread disagreement regarding precipitation projections between GCMs and scenarios, vegetation acts to both buffer and aggravate future climate impacts, and reduce uncertainty in future water resource projections.

2. Methods

2.1. LPX DGVM

The LPX DGVM is a process-based model that simulates interactions between terrestrial vegetation dynamics, and land-atmosphere carbon and water cycles. The model explicitly simulates dynamic ecosystem structure and function, including foliage cover, primary production and carbon allocation, evapotranspiration, competition and disturbances, but in common with most other vegetation models does not include nutrient constraints on CO₂ assimilation. LPX is based on a coupled photosynthesis-water balance

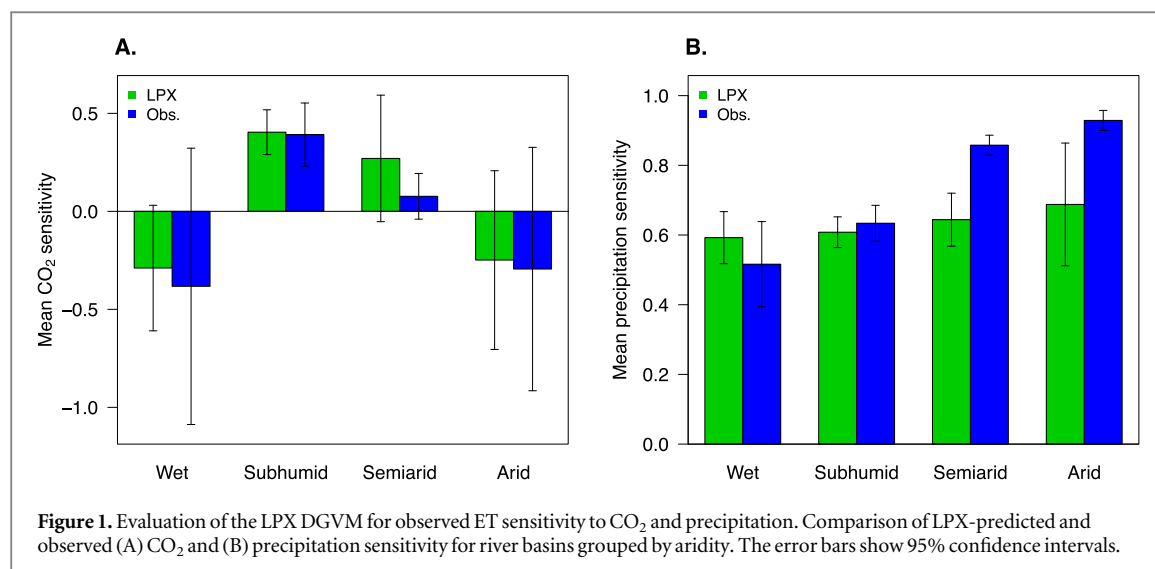
scheme that explicitly couples CO₂ assimilation with transpiration (see supplementary section 1 for further details on key model processes). The model has been extensively evaluated for hydrology (Gerten *et al* 2004, Murray *et al* 2011, Kelley *et al* 2013, Ukkola and Murray 2014) and ecosystem dynamics (Sitch *et al* 2003, Prentice *et al* 2011, Kelley *et al* 2013) and is here shown to successfully capture historical CO₂ and precipitation effects on AET and vegetation (section 2.1.1). We use the latest model version (LPX-Mv1) with improved fire-vegetation dynamics, benchmarked specifically for Australia (Kelley *et al* 2014). LPX simulates AET directly but for consistency with historical observations, we have defined AET as the difference between precipitation and runoff in this study.

2.1.1. Evaluation of historical LPX simulations

We evaluated the model's ability to capture observed precipitation and CO₂ effects on water-balance AET and vegetation across 190 Australian river basins grouped by aridity using sensitivity coefficients (Ukkola *et al* 2016) (see supplementary section 1.4 for full details). Observed vegetation sensitivities were determined from GIMMS3g normalised difference vegetation index data (NDVI) (Pinzon and Tucker 2014) at 0.083° spatial resolution and ET from water-balance evapotranspiration calculated from observed runoff (Zhang *et al* 2013) and gridded precipitation at 0.05° spatial resolution from the ANUCLIM archive (Xu and Hutchinson 2013). These were compared to LXP-simulated AET and foliage projective cover (FPC).

The effects of precipitation (and PET for AET) were removed from observed and LPX-simulated AET and vegetation cover prior to determining CO₂ sensitivities. This was achieved using linear regression: separately for each basin, annual AET and FPC were regressed against precipitation (and PET in the case of AET) and the annual corrected values were calculated as the sum of the regression residual and the 1982–2006 mean of the variable. All variables were then log-transformed for the calculation of precipitation and CO₂ sensitivities. The corrected AET (E) and NDVI were then regressed against log-transformed annual CO₂ concentrations (C_a) to derive sensitivity coefficients (σ) $\sigma_{ET} = \partial \ln E / \partial \ln C_a$ and $\sigma_{veg} = \partial \ln NDVI / \partial \ln C_a$; and similarly for precipitation.

The sensitivity coefficient of AET to C_a has a clear theoretical expectation in terms of underlying processes (Prentice *et al* 2014) whereby a negative coefficient implies the CO₂ response is dominated by stomatal closure reducing ET and a positive coefficient indicates CO₂-induced greening dominates over stomatal closure increasing ET. Despite spatial variability in the CO₂ response in both the model and observations, LPX captures mean AET sensitivity to CO₂ and precipitation successfully across aridity gradients, with



the exception of slightly underestimating precipitation sensitivity in dry climates (figure 1). Model evaluation for foliage cover is presented in figure S1.

2.2. Budyko framework

The Budyko framework is a widely employed empirical hydrological model based on the premise of water and energy availability as the controls on evapotranspiration and runoff. The model simulates AET (E_a) from precipitation (P) and PET (E_p), assuming no net change in soil water storage (Zhang *et al* 2004):

$$E_a = E_p [1 + MI - (1 + MI^\omega)^{1/\omega}], \quad (1)$$

where MI is the moisture index, P/E_p . The model parameter ω represents catchment properties, including vegetation, soil and topography (Yang *et al* 2007). Although several studies have suggested that the model's single parameter ω is in part a function of vegetation properties, there is no generally accepted way to account for vegetation effects on ω (Roderick and Farquhar 2011). The model was thus employed to represent the effects of climate alone and the parameter was set to a constant value of 3.09. This value was derived by nonlinear optimisation against historical observed E_a from 190 Australian river basins (Ukkola *et al* 2016) and is close to values used in previous studies (Zhang *et al* 2004, Yang *et al* 2007). Budyko-simulated runoff was calculated as the difference between precipitation and simulated E_a .

2.3. Historical simulations

LPX was forced using monthly fields of climate (maximum, minimum and mean air temperature, precipitation, cloud cover, number of wet days and wind speed), monthly lightning climatology and annual CO₂ concentrations. The Budyko model was driven with annual precipitation and Priestley–Taylor PET calculated from cloud cover and mean air temperature (see equation (3) of supplementary

information). Full model and spin-up protocols and input data sources are detailed in supplementary section 2.

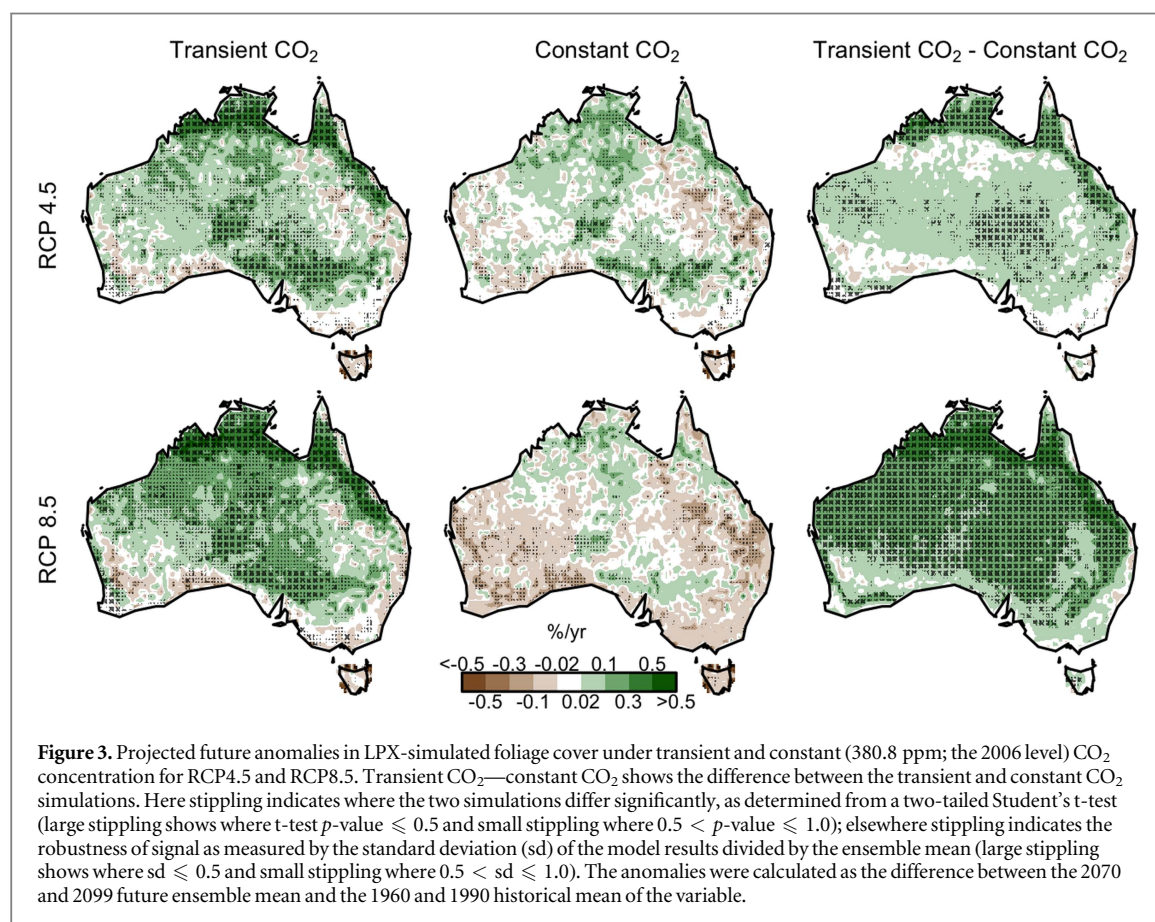
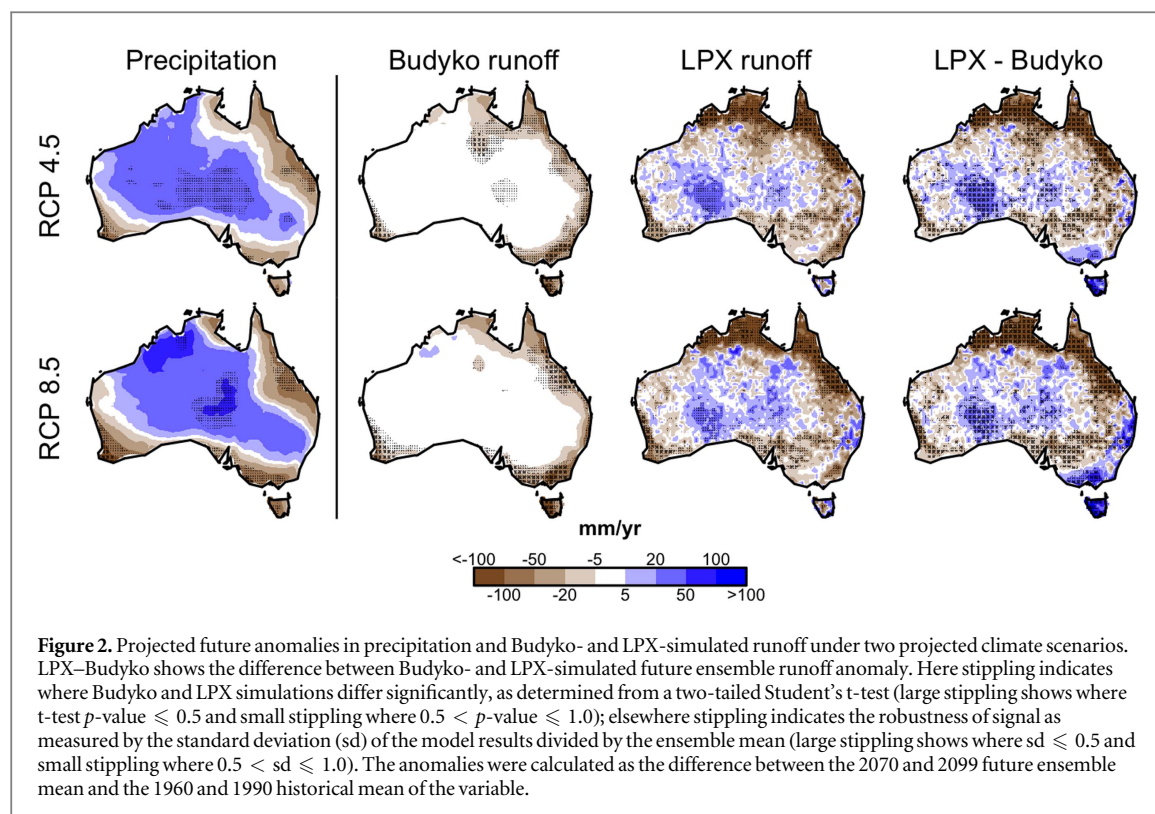
2.4. Future projections

Both models were forced from 2006 to 2099 with bias-corrected climate projections at 0.5° spatial resolution from nine global climate models from the CMIP5 archive (Taylor *et al* 2012) (see supplementary section 3) under two representative concentration pathways (RCP; van Vuuren *et al* 2011) (RCP4.5 and RCP8.5), leading to 18 projections for each model. RCP4.5 is an intermediate scenario where radiative forcing (RF) stabilises at 4.5 W m⁻² by 2100 and atmospheric CO₂ concentration reaches 576 ppm (ensemble average) by 2080 after which it stabilises. RCP8.5 is an extreme trajectory where RF reaches 8.5 W m⁻² and atmospheric CO₂ concentration 1231 ppm by 2100. The GCMs, bias correction and modelling protocols are further detailed in supplementary section 3.

3. Results and discussion

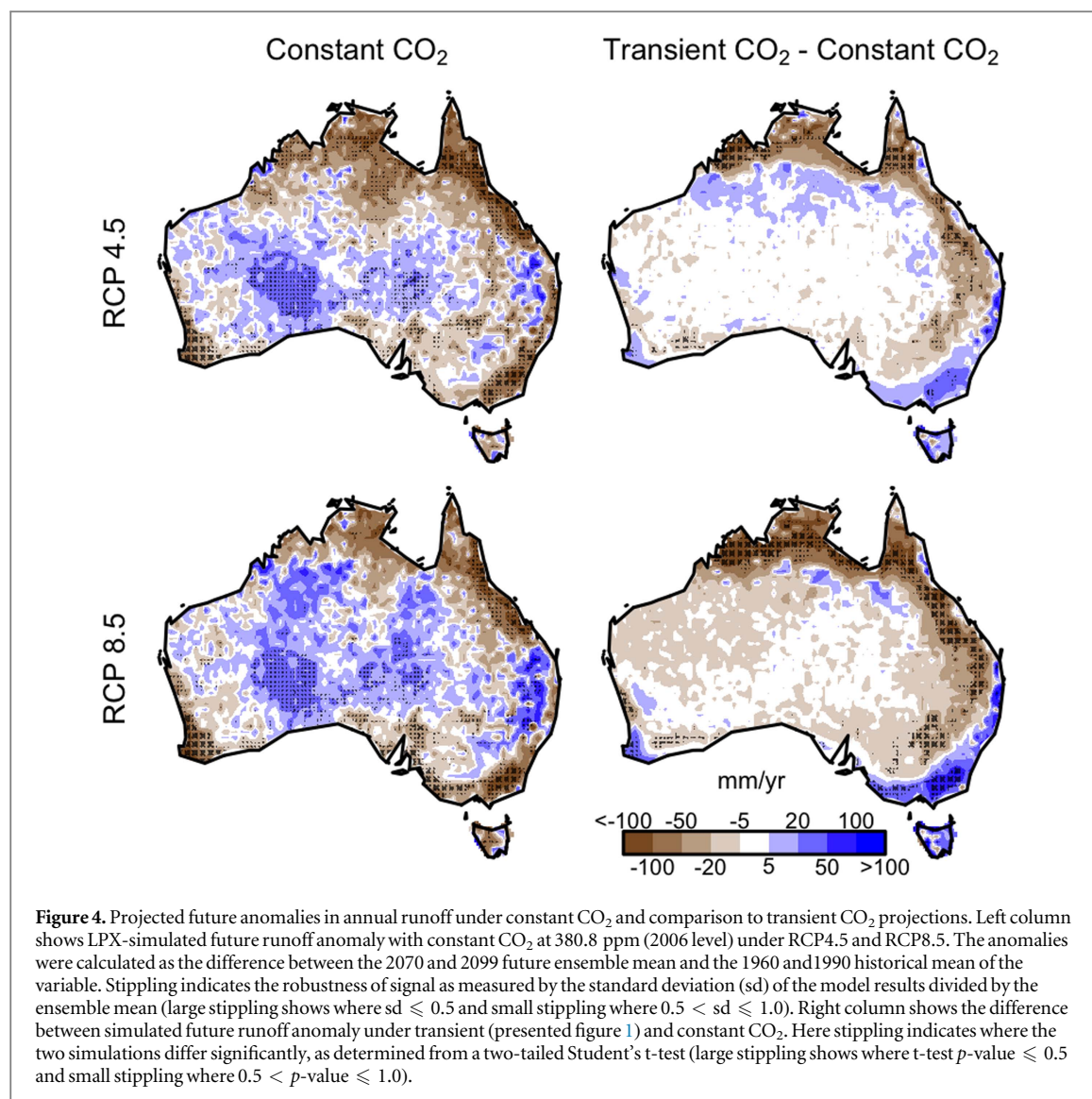
In agreement with previous studies (reviewed in Collins *et al* 2013), the nine GCMs included in this study show large uncertainties in projected future precipitation patterns in large parts of Australia, including key economic and agricultural areas in eastern Australia, where the majority of the Australian population resides. The climate models project a robust decrease in precipitation in south-western Australia, irrespective of the RCP (figure 2) and are in modest agreement on decreased precipitation along south-east and north-east coastal regions and increased precipitation in parts of arid central Australia.

Despite uncertainties in future precipitation, we project robust regional reductions in runoff along much of coastal and inland eastern Australia (figure 2).



Some of these reductions are precipitation-driven, particularly in south-western Australia, and exacerbated by increasing PET (figure S2). South-western

Australia has experienced declining streamflow since the mid-1970s (Petrone *et al* 2010) and our results thus suggest this trend is likely to continue into the future.



A comparison of Budyko and LPX projections shows that the reductions in runoff in south-western Australia are further aggravated when vegetation processes are considered (figure 2). Similarly, in northern Australia where the future precipitation changes are highly uncertain, strong CO_2 -induced greening (figure 3) leads to increased AET (figure S3) and reduced runoff (figure 4). These strong reductions are not, or hardly, present under constant CO_2 (particularly under RCP8.5; figure 4) with the LPX model or in the Budyko model projections. The CO_2 effect is accompanied by decreased fire, primarily due to increased dry-season fuel moisture (figure S4), further enabling the expansion of tree cover (woody thickening) in savanna ecosystems (Kelley and Harrison 2014) and increasing vegetation water use in the north. This is in agreement with historical observations, which have suggested woody thickening in northern Australian savannas is primarily controlled by climate and CO_2 , with fire imposing a secondary effect (Murphy *et al* 2014). By contrast, in southeastern Australia CO_2 -induced increase in vegetation water use efficiency,

and modest decreases in green vegetation cover, alleviate the runoff declines predicted (by the Budyko approach) from direct climate effects. The tendency for runoff decreases due to CO_2 in drier sub-humid and semi-arid regions, and increases in wetter regions is in agreement with historical observations across Australian river basins (Ukkola *et al* 2016).

The largest deviations in hydrology and vegetation cover from historical levels are projected to take place relatively soon, during the first half of the 21st century (figure 5). Declines in precipitation and runoff are projected from the LPX ensemble mean in wet and sub-humid regions. These declines are accompanied by increasing AET and foliage cover (consistent with CO_2 -induced greening and consequent increases in vegetation water use) in sub-humid climates, even though these regions are also projected to become progressively more arid (as measured by the aridity index; figure S5). Although large inter-model variations persist, the projected changes are largely independent of the RCP, despite strong divergence in projected temperatures and PET under the two RCPs (figure S5).

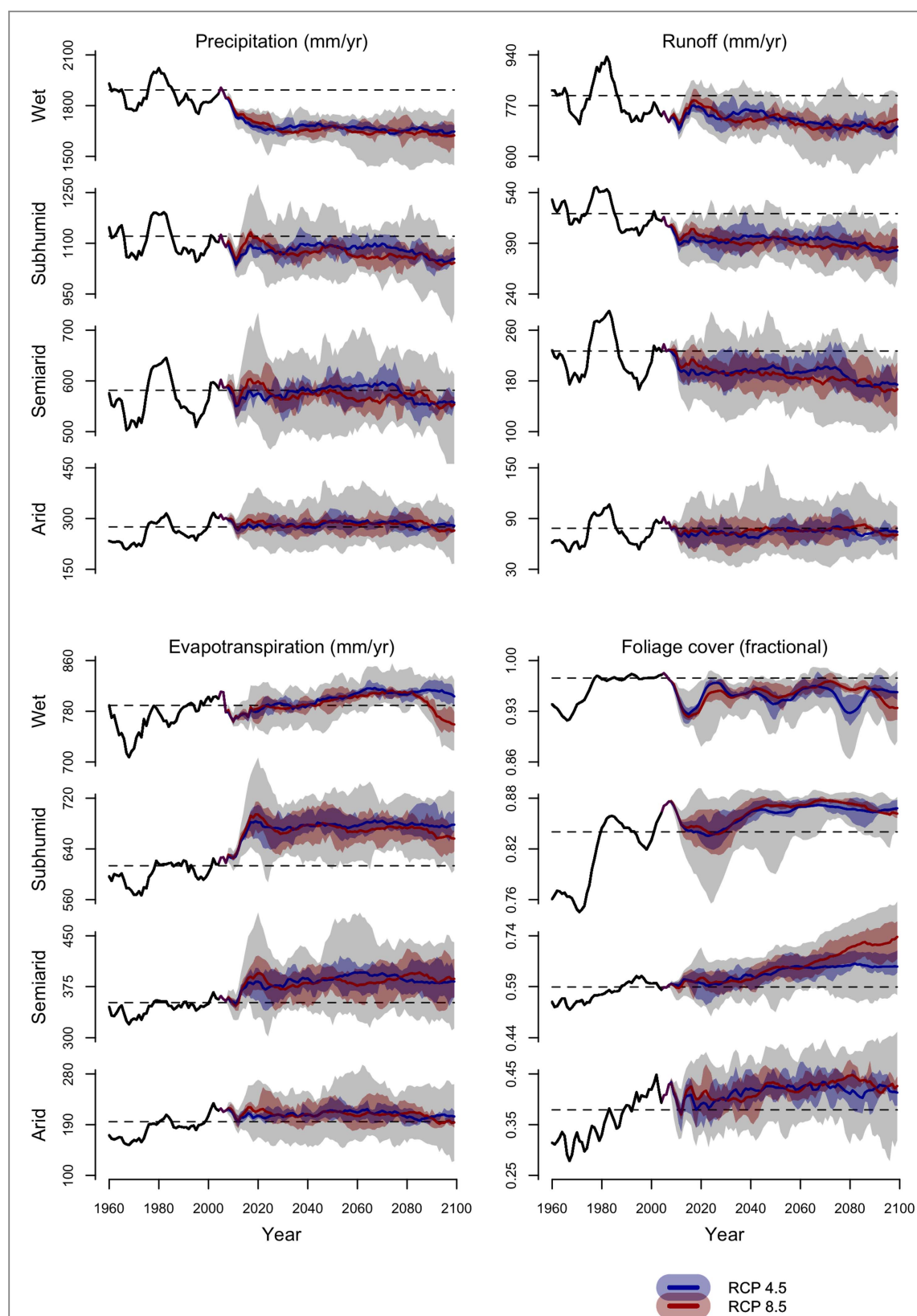


Figure 5. Historical and future time series of precipitation and LPX-simulated runoff, ET and foliage cover in different aridity regimes. The solid black line shows the historical period (1960–2005) and the dotted line the historical mean of the variable during 1960–1990. The coloured lines show the future ensemble means and the coloured shading indicates model interquartile ranges for each RCP. The grey shading shows the combined full model range of both RCPs. Aridity categories were constructed as described in figure S5. The time series were subsequently smoothed using 10 year running means.

The global greenhouse emissions trajectory therefore does not appear to be the most important uncertainty for the prediction of future water resources.

Larger uncertainties are associated with the use of different climate models, and natural variability as represented by the models. Interannual variability in

runoff and precipitation is expected, and projected, to remain large (figure 5). The El Niño Southern Oscillation (ENSO) is a major driver of climate in Australia, and brings extreme conditions including droughts and floods particularly to the eastern parts of the continent (King *et al* 2014). Although future changes to the mean ENSO state remain uncertain (Collins *et al* 2010), extreme El Niño events are projected to become more frequent (Cai *et al* 2014a). The Indian Ocean Dipole is also prominent in its effects on precipitation in central, southern and northern Australia, and its extreme phases are also projected to increase in frequency in the future (Cai *et al* 2014b). The continuing high inter-annual variability in Australia, together with more frequent extreme states of the two principal variability modes, will inevitably pose challenges for water management.

4. Conclusions

Our results demonstrate the importance of including vegetation dynamics in projections of water resources and the need to consider coupled water, carbon and vegetation effects on evapotranspiration and runoff. Despite large uncertainties in future precipitation projections, our analysis suggests significant and coherent changes in runoff across large parts of the continent. In northern and southwestern Australia as well as parts of the Murray–Darling basin, the largest river system on the continent and a key agricultural area accounting for 40% of the value of Australia's agricultural production (Potter *et al* 2010), CO₂-induced vegetation responses are projected to reduce water resources but are accompanied by enhanced natural vegetation productivity. Despite vegetation water savings due to reduced stomatal conductance under elevated CO₂, parts of highly populated coastal regions, along with agricultural areas in southwestern Australia, are projected to suffer reductions in water resources. Independent of the assumed greenhouse emissions scenario, large reductions in Australian water resources are projected to occur within a few decades and may be further aggravated by vegetation responses in many water-stressed regions.

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