Vegetation plays an important role in mediating future water resources

2016 Environ. Res. Lett. 11 094022

(http://iopscience.iop.org/1748-9326/11/9/094022)

Environmental Research Letters

OPEN ACCESS

RECEIVED
8 May 2016

ACCEPTED FOR PUBLICATION
10 August 2016

PUBLISHED
14 September 2016

LETTER

Vegetation plays an important role in mediating future water resources

A M Ukkola[1,2], T F Keenan[1,3], D I Kelley[1,4,5] and I C Prentice[1,6]

[1] Department of Biological Sciences, Macquarie University, North Ryde, New South Wales 2109, Australia
[2] ARC Centre of Excellence for Climate System Science, University of New South Wales, Kensington, New South Wales 2052, Australia
[3] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[4] Centre for Past Climate Change and School of Archaeology, Geography and Environmental Sciences (SAGES), University of Reading, Whiteknights, RG6 6 AH, Reading, UK
[5] Centre for Ecology and Hydrology, Maclean building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK
[6] AXA Chair of Biosphere and Climate Impacts, Department of Life Sciences and Grantham Institute—Climate Change and the Environment, Imperial College, Silwood Park Campus, Ascot SL5 7PY, UK

E-mail: amukkola@gmail.com

Keywords: CO_2 effect, water resources, climate change, vegetation dynamics, climate projections

Supplementary material for this article is available online

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 CO_2) 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 CO_2-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 CO_2 can both increase and decrease vegetation water use, with consequences for runoff generation. Higher CO_2 concentrations lower stomatal conductance (Field *et al* 1995), reducing water loss through leaves and leaf-scale transpiration. Simultaneously, elevated CO_2 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 CO_2-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 CO_2-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 CO_2 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 CO_2 assimilation. LPX is based on a coupled photosynthesis-water balance scheme that explicitly couples CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 sensitivities. The corrected AET (E) and NDVI were then regressed against log-transformed annual CO_2 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 CO_2 response is dominated by stomatal closure reducing ET and a positive coefficient indicates CO_2-induced greening dominates over stomatal closure increasing ET. Despite spatial variability in the CO_2 response in both the model and observations, LPX captures mean AET sensitivity to CO_2 and precipitation successfully across aridity gradients, with

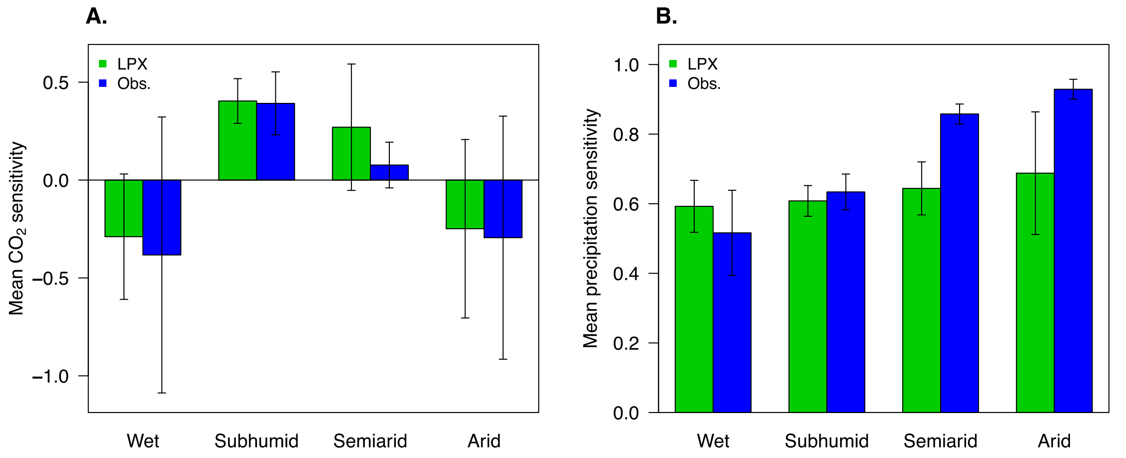

Figure 1. Evaluation of the LPX DGVM for observed ET sensitivity to CO_2 and precipitation. Comparison of LPX-predicted and observed (A) CO_2 and (B) precipitation sensitivity for river basins grouped by aridity. The error bars show 95% confidence intervals.

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):

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

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 CO_2 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 CO_2 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 CO_2 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).

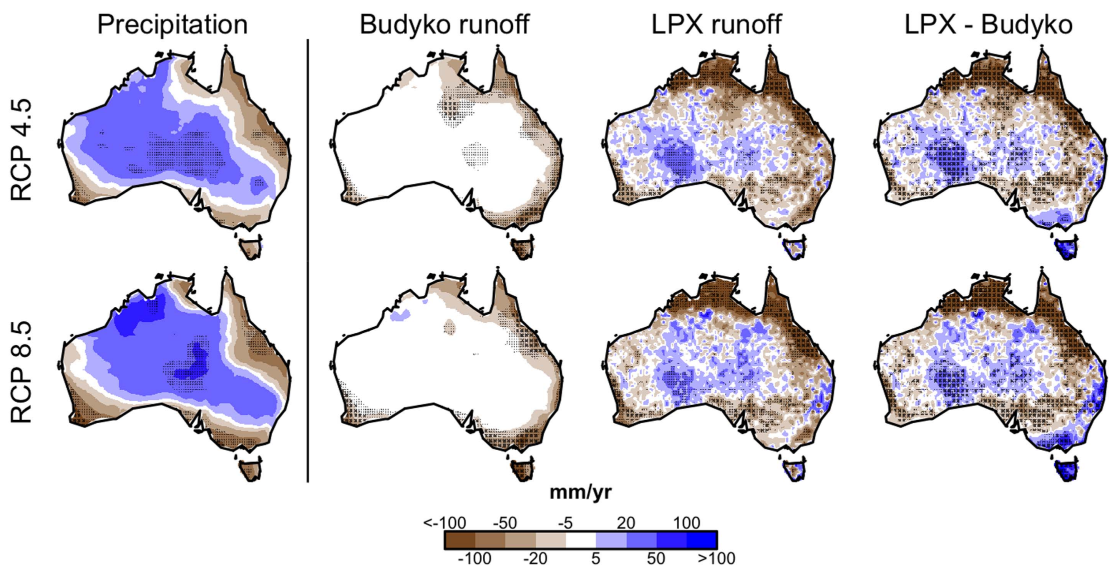

Figure 2. Projected future anomalies in precipitation and Budyko- and LPX-simulated runoff under two projected climate scenarios. LPX–Budyko shows the difference between Budyko- and LPX-simulated future ensemble runoff anomaly. Here stippling indicates where Budyko and LPX simulations differ significantly, as determined from a two-tailed Student's t-test (large stippling shows where t-test p-value $\leqslant$ 0.5 and small stippling where 0.5 $<$ p-value $\leqslant$ 1.0); elsewhere stippling indicates the robustness of signal as measured by the standard deviation (sd) of the model results divided by the ensemble mean (large stippling shows where sd $\leqslant$ 0.5 and small stippling where 0.5 $<$ sd $\leqslant$ 1.0). The anomalies were calculated as the difference between the 2070 and 2099 future ensemble mean and the 1960 and 1990 historical mean of the variable.

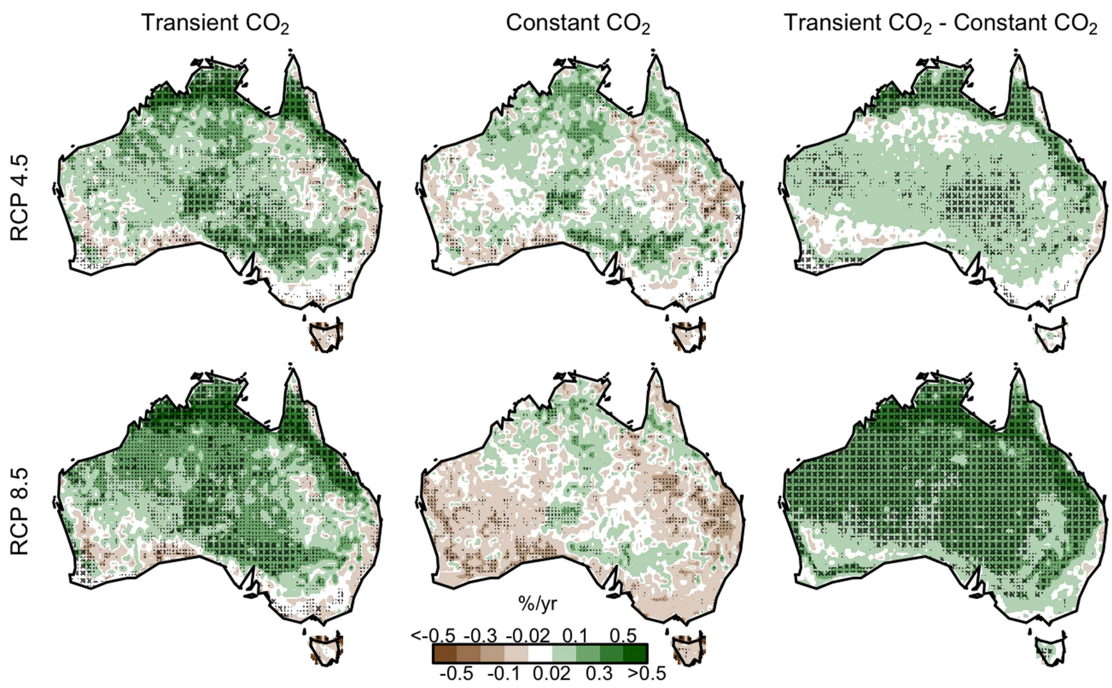

Figure 3. Projected future anomalies in LPX-simulated foliage cover under transient and constant (380.8 ppm; the 2006 level) CO_2 concentration for RCP4.5 and RCP8.5. Transient CO_2—constant CO_2 shows the difference between the transient and constant CO_2 simulations. Here stippling indicates where the two simulations differ significantly, as determined from a two-tailed Student's t-test (large stippling shows where t-test p-value $\leqslant$ 0.5 and small stippling where 0.5 $<$ p-value $\leqslant$ 1.0); elsewhere stippling indicates the robustness of signal as measured by the standard deviation (sd) of the model results divided by the ensemble mean (large stippling shows where sd $\leqslant$ 0.5 and small stippling where 0.5 $<$ sd $\leqslant$ 1.0). The anomalies were calculated as the difference between the 2070 and 2099 future ensemble mean and the 1960 and 1990 historical mean of the variable.

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.

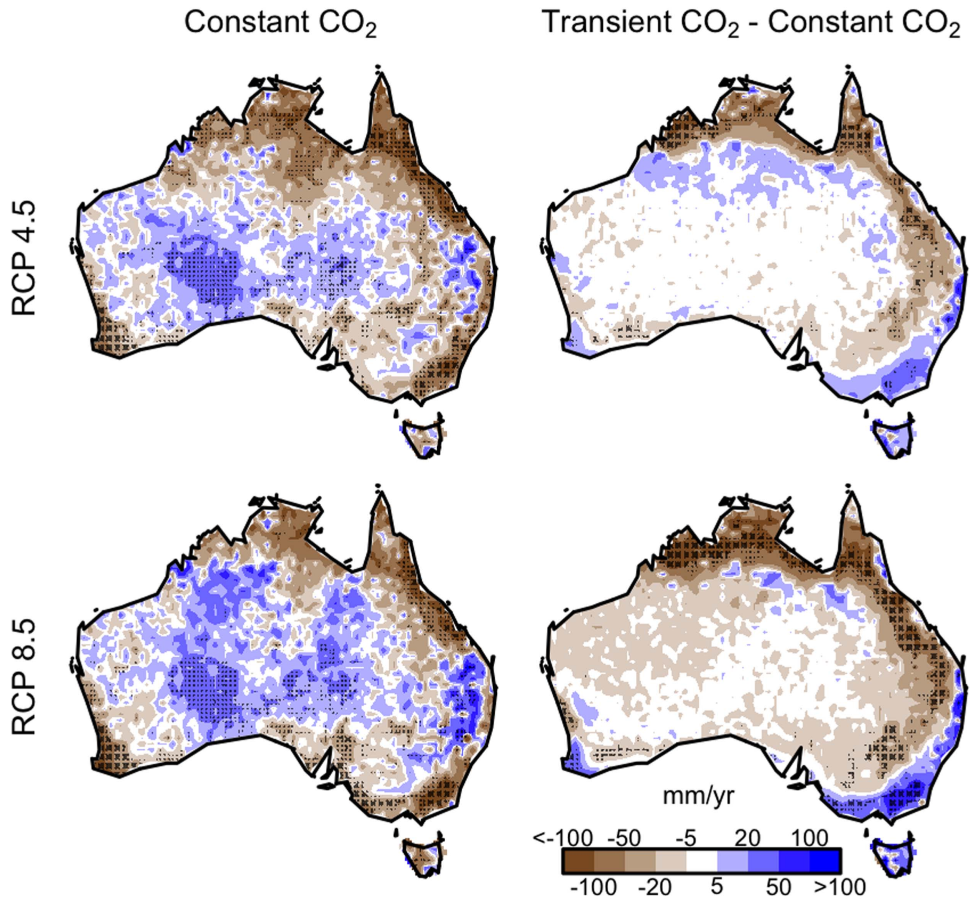

Figure 4. Projected future anomalies in annual runoff under constant CO_2 and comparison to transient CO_2 projections. Left column shows LPX-simulated future runoff anomaly with constant CO_2 at 380.8 ppm (2006 level) under RCP4.5 and RCP8.5. The anomalies were calculated as the difference between the 2070 and 2099 future ensemble mean and the 1960 and1990 historical mean of the variable. Stippling indicates the robustness of signal as measured by the standard deviation (sd) of the model results divided by the ensemble mean (large stippling shows where sd $\leqslant$ 0.5 and small stippling where 0.5 $<$ sd $\leqslant$ 1.0). Right column shows the difference between simulated future runoff anomaly under transient (presented figure 1) and constant CO_2. Here stippling indicates where the two simulations differ significantly, as determined from a two-tailed Student's t-test (large stippling shows where t-test p-value $\leqslant$ 0.5 and small stippling where 0.5 $<$ p-value $\leqslant$ 1.0).

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).

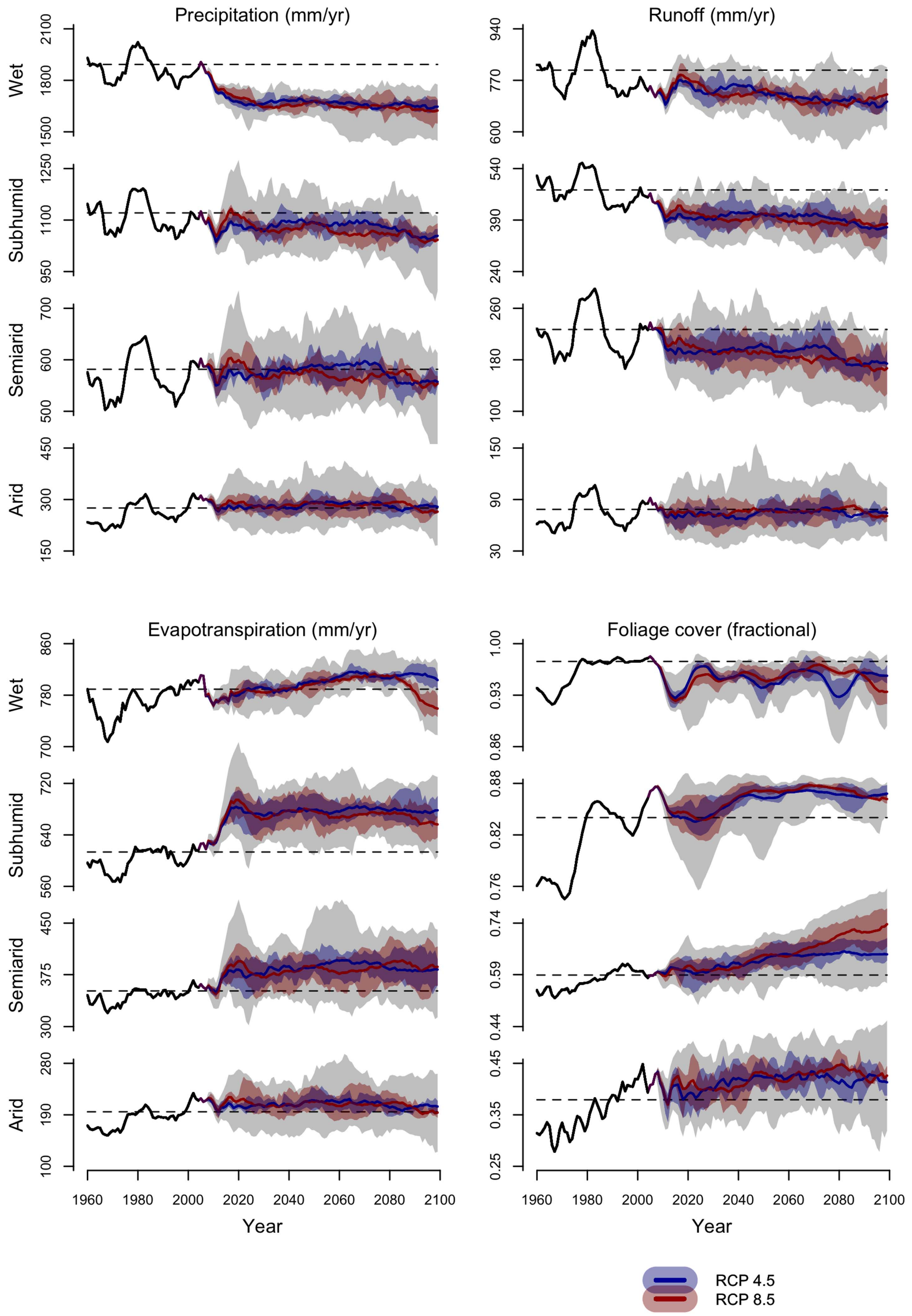

Figure 5. Historical and future time series of precipitation and LPX-simulated runoff, ET and foliage cover in different aridity regimes. The solid black line shows the historical period (1960–2005) and the dotted line the historical mean of the variable during 1960–1990. The coloured lines show the 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 interannual 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), CO_2-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 CO_2, 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.

Acknowledgments

We thank the CMIP5 project for making future climate simulations publicly available. Patrick Bartlein and Kenji Izumi (University of Oregon) assisted with the production of the future model inputs. AU was supported by an iMQRES scholarship from Macquarie University and currently receives funding from the Australian Research Council Centre of Excellence for Climate System Science (CE110001028). TFK acknowledges support from a Macquarie University Research Fellowship. This work is a contribution to AXA Chair Programme in Biosphere and Climate Impacts and the Grand Challenges in Ecosystems and the Environment initiative at Imperial College London.

References

Cai W *et al* 2014a Increasing frequency of extreme El Niño events due to greenhouse warming *Nat. Clim. Change* **4** 111–6

Cai W, Santoso A, Wang G, Weller E, Wu L, Ashok K, Masumoto Y and Yamagata T 2014b Increased frequency of extreme Indian ocean dipole events due to greenhouse warming *Nature* **510** 254–8

Chiew F H S and McMahon T A 1993 Detection of trend or change in annual flow of Australian rivers *Int. J. Climatol.* **13** 643–53

Collins M *et al* 2010 The impact of global warming on the tropical Pacific Ocean and El Niño *Nat. Geosci.* **3** 391–7

Collins M *et al* 2013 Long-term climate change: projections, commitments and Irreversibility *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press) pp 1029–136

Davie J C S *et al* 2013 Comparing projections of future changes in runoff from hydrological and biome models in ISI-MIP *Earth Syst. Dyn.* **4** 359–74

Donohue R J, Roderick M L, McVicar T R and Farquhar G D 2013 Impact of CO_2 fertilization on maximum foliage cover across the globe's warm, arid environments *Geophys. Res. Lett.* **40** 1–5

Field C B, Jackson R B and Mooney H A 1995 Stomatal response to increased CO_2: implication from the leaf to the global scale *Plant. Cell Environ.* **18** 1214–25

Gedney N, Cox P M, Betts R A, Boucher O, Huntingford C and Stott P A 2006 Detection of a direct carbon dioxide effect in continental river runoff records *Nature* **439** 835–8

Gerten D, Schaphoff S, Haberlandt U, Lucht W and Sitch S 2004 Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model *J. Hydrol.* **286** 249–70

Keenan T F, Hollinger D Y, Bohrer G, Dragoni D, Munger J W, Schmid H P and Richardson A D 2013 Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise *Nature* **499** 324–7

Kelley D I and Harrison S P 2014 Enhanced Australian carbon sink despite increased wildfire during the 21st century *Environ. Res. Lett.* **9** 104015

Kelley D I, Harrison S P and Prentice I C 2014 Improved simulation of fire–vegetation interactions in the land surface processes and eXchanges dynamic global vegetation model (LPX-Mv1) *Geosci. Model Dev.* **7** 2411–33

Kelley D I, Prentice I C, Harrison S P, Wang H, Simard M, Fisher J B and Willis K O 2013 A comprehensive benchmarking system for evaluating global vegetation models *Biogeosciences* **10** 3313–40

King A D, Donat M G, Alexander L V and Karoly D J 2014 The ENSO-Australian rainfall teleconnection in reanalysis and CMIP5 *Clim. Dyn.* **44** 2623–35

Knutti R and Sedláček J 2012 Robustness and uncertainties in the new CMIP5 climate model projections *Nat. Clim. Change* **3** 369–73

Murphy B P, Lehmann C E R, Russell-Smith J and Lawes M J 2014 Fire regimes and woody biomass dynamics in Australian savannas *J. Biogeogr.* **41** 133–44

Murray S J, Foster P N and Prentice I C 2011 Evaluation of global continental hydrology as simulated by the land-surface processes and eXchanges Dynamic Global Vegetation Model *Hydrol. Earth Syst. Sci.* **15** 91–105

Petrone K C, Hughes J D, Van Niel T G and Silberstein R P 2010 Streamflow decline in southwestern Australia, 1950–2008 *Geophys. Res. Lett.* **37** L11401

Pinzon J E and Tucker C J 2014 A non-stationary 1981–2012 AVHRR NDVI3g time series *Remote Sens.* **6** 6929–60

Potter N J, Chiew F H S and Frost A J 2010 An assessment of the severity of recent reductions in rainfall and runoff in the Murray–Darling basin *J. Hydrol.* **381** 52–64

Prentice I C, Dong N, Gleason S M, Maire V and Wright I J 2014 Balancing the costs of carbon gain and water transport: testing a new theoretical framework for plant functional ecology *Ecol. Lett.* **17** 82–91

Prentice I C, Kelley D I, Foster P N, Friedlingstein P, Harrison S P and Bartlein P J 2011 Modeling fire and the terrestrial carbon balance *Glob. Biogeochem. Cycles* **25** GB3005

Prudhomme C *et al* 2014 Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment *Proc. Natl Acad. Sci. USA* **111** 3262–7

Roderick M L and Farquhar G D 2011 A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties *Water Resour. Res.* **47** W00G07

Sitch S *et al* 2003 Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model *Glob. Change Biol.* **9** 161–85

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98

Ukkola A M and Murray S J 2014 Hydrological evaluation of the LPX dynamic global vegetation model for small river catchments in the UK *Hydrol. Process.* **28** 1939–50

Ukkola A M, Prentice I C, Keenan T F, van Dijk A I J M, Viney N R, Myneni R B and Bi J 2016 Reduced streamflow in water-stressed climates consistent with CO_2 effects on vegetation *Nat. Clim. Change* **6** 75–8

van Vuuren D P *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31

Xu T and Hutchinson M F 2013 New developments and applications in the ANUCLIM spatial climatic and bioclimatic modelling package *Environ. Model. Softw.* **40** 267–79

Yang D, Sun F, Liu Z, Cong Z, Ni G and Lei Z 2007 Analyzing spatial and temporal variability of annual water-energy balance in nonhumid regions of China using the Budyko hypothesis *Water Resour. Res.* **43** W04426

Zhang L, Hickel K, Dawes W R, Chiew F H S, Western A W and Briggs P R 2004 A rational function approach for estimating mean annual evapotranspiration *Water Resour. Res.* **40** W02502

Zhang Y, Viney N, Frost A, Oke A, Brooks M, Chen Y and Campbell N 2013 Collation of Australian modeller's streamflow dataset for 780 unregulated Australian catchments *Water for a Healthy Country Flagship Report* CSIRO 115 pp