Response to the editor's assessment and comments on "Reconciling the dynamic relationship between climate variables and vegetation productivity into a hydrological model to improve streamflow prediction under climate change" and "Effect of year-to-year variability of leaf area index on Variable Infiltration Capacity model performance and simulation of streamflow during drought" by Z. K. Tesemma, Y. Wei, M. C. Peel, and A. W. Western,"

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Dear Dr. Harman,

We are very appreciative of your valuable comments and thoughtful assessment of our manuscripts titled "Effect of year-to-year variability of leaf area index on Variable Infiltration Capacity model performance and simulation of streamflow during drought" and "Reconciling the dynamic relationship between climate variables and vegetation productivity into a hydrological model to improve streamflow prediction under climate change", which were published in HESSD. We have responded extensively and made the requested changes in these two manuscripts posted separately as replies to the reviewers as well as the relevant public comments. Here we give a short summary of our responses to your points.

We fully understand your suggestion of combining the two papers into a single manuscript. However, we believe the revised manuscripts address the requested changes and now highlight the separate contributions of these two manuscripts. Therefore, we think it is better to keep them as separate papers for following reasons:

1) These two manuscripts have very different research objectives. Manuscript 1 addresses the question of whether including vegetation variations into a hydrological model improve model performance in terms of runoff simulation. Manuscript 2 examines the relative effects on mean annual runoff of direct climate forcing (mainly precipitation and temperature) and when LAI responds to climate forcing under changed climate scenarios. This demonstrates that modelling LAI in a way that responds to changing climatic conditions is important for modelling runoff during projected climate change. It also provides a wide range of possible

net impacts of climate change on catchment streamflow in the study area. In addition we also demonstrated the importance of including LAI which respond to recent observed prolonged drought which is comparable to projected climate change under RCP8.5 emission scenarios. In both analyses the climate change induced LAI effect offsets the effect on streamflow of changed climate.

2) Both papers are very lengthy (word count = 9800 and 10760), have 7 and 12 figures and 5 and 2 tables. Combining the manuscripts would lose a significant amount of important information which in our opinion should be available to readers.

3) The revised manucripts now clearly highlight the seperate contributions to exsting knowledge gaps.

4) We found that Reviewer 1 of hess-2014-363 was positive and thought our approach advances climate change impact assessment of ecohydrological process provided that we could address according to their comments.

We are looking forward to your assessment of the revised manuscripts.

Regards,

Dr Yongping Wei

Responses to reviewers' comments

We thank the reviewer for considering our manuscript and our response (in blue) to their comments (in black) are provided below. We propose to implement most of the major changes suggested by the reviewers. In the few cases where we do not agree we explain our reasoning.

Responses to major comments of Reviewer #1

General Comments: The authors have attempted to tease out the influence of vegetation adaptation to drought and future climate change in order determines the impact evapotranspiration will have on the catchment water balance. The paper lacks some of the specifics needed to determine the impact of some significant assumption made in the downscaling of GCM output.

Agreed. We will revise the manuscript to provide more details about the downscaling of GCM output to the catchment scale.

Additionally, how these downscaled datasets were then applied to VIC needs elaborating.

The delta change values were applied to all VIC grid pixels separately assuming the same spatial distribution in the climatic variables (precipitation and temperature). We will revise the manuscript accordingly.

The paper focuses on deviations from 'mean' conditions for the majority of the result reporting; however runoff processes are often triggered by precipitation events on the edge of the distributions. Without further statistical analysis it is impossible to determine how significant the modelled results are. There is no discussion on the precipitation characteristics of the region, and how these characteristics are predicted to change, which arguably might have the greatest impact on the partitioning of precipitation.

We agree with the reviewer that runoff processes are influenced by precipitation events on the edge of the distribution and that this issue would be important for studies that focus on the impact of climate change on runoff generation mechanisms and runoff at sub-daily to daily time scales. However in this study we are interested in the impact of including climate induced LAI change on the annual runoff results. Therefore, consideration of extreme precipitation events is less important in this study. In the study area, the monthly LAI is strongly related to three month and or nine month moving average moisture state (precipitation – potential evapotranspiration) (Tesemma et al., 2014). Therefore, so long as the precipitation is consistent between the two runs we can assess the importance of the change in LAI modelling on annual runoff.

Responses to specific comments (S.C) of Reviewer #1

S.C1: Pg 10598 "statistically downscaled using the delta change method" citations would be appropriate, Chen Fowler.

Agreed. We will cite Fowler et al., 2007 in the revised manuscript.

S.C2: GCM output has known difficulties with regions of high relief. How different are the 4 grid cells chosen for this study from each other? The authors aim to capture a precipitation gradient across several catchments, is this possible given the granularity of the GCM output?

Partially Agree. We will revise the manuscript to provide more detail about the observed data used to drive VIC and the spatial resolution of VIC. The mean elevation of the four GCM grid cells is 172.3m, 347.7m, 83.3m and 128.5m above mean sea level respectively, which is not representative of the catchment relief. However, since we use the delta change method to statistically downscale the GCM output, the observed spatial variation of the climatic variables is maintained in the future projected climate. The GCM data only provide the degree of scaling up or down of the observed spatial pattern in the future projections.

S.C3: Pg 10599 downscaling precipitation has several pitfalls. In particular the 'wet bias' due to the size of the gcm grid cells. When averaging 4 cells, this problem will be exaggerated. Based on equation (3) and (4) I see no methodology to solve the 'a little rain all the time' problem.

Agree, but not relevant. The delta change downscaling technique takes the spatial variability and the temporal sequence of the observed baseline period re-scales it for the future projection, so the drizzle, or little rain all the time, problem is not relevant here. The delta change is calculated from 30 year monthly mean values so any GCM daily drizzle issues are aggregated. We will revise the manuscript to reflect this discussion.

S.C4: There are no descriptive statistics examining the performance of the downscaling methodology. A validation/calibration test of the ability of the downscaling methodology to accurately capture the seasonality and the magnitude of precipitation is at the foundation of this study.

Agreed. We will revise the manuscript to include the figure showing the seasonality between the GCM and observation in the historical period.

S.C5: Pg 10600 What method was used for the calculation of PET? The calculation of future PET was undertaken by only varying temp and precipitation patterns. Vapor pressure deficit is a critical component to evapotranspiration and in this case is kept constant. Some sensitivity analysis of this assumption would put the readers at ease that the results obtained are not just a function of the assumptions made in the paper.

Agree. The PET calculation method used is the FAO56 Penman-Monteith. We will do a sensitivity analysis of this assumption and revise the manuscript to inform the readers of the importance of this assumption on the overall results.

S.C6: Pg 10601 What was the initial condition for each of these simulations? Was there a spin up time? Where the periods examined assumed to be stationary?

Agree. We will revise the manuscript to provide more detail about VIC and direct the readers to the detailed discussion of VIC and our modelling procedure in Tesemma et al., (2014, HESS discussion), which is currently under review.

Most land surface models require a spin up period for stabilizing the internal equilibrium of the equations which are solved iteratively. The spin up period depends on the type of model and the purpose of the studies. In this study the VIC model was run at a daily interval for 30 years from January 1981 to December 2010 to spin up the model and produce a restart file to be used as the initial condition for experiment runs. All experimental runs were initiated with the state produced from model spin up. The spatial resolution used to run VIC model was 5km by 5km.

S.C7: Pg 10601 The VIC model is a critical part of this work, but little detail of the model setup is given. What timestep, grid resolution etc were used? What PET method, infiltration scheme?

Agree. We will revise the manuscript to provide more detail about VIC and direct the readers to the detailed discussion of VIC and our modelling procedure in Tesemma et al., (2014, HESS discussion), which is currently under review.

We used a daily time step, a 5km by 5km spatial grid resolution and Penman-Monteith for potential evapotranspiration. VIC estimate infiltration and runoff using the variable infiltration capacity model which is a non-linear function of the soil moisture storage within the grid cell (Liang et al., 1994; Zhao et al., 1995).

S.C8: Pg 10603 "Most of the projected seasonal precipitation simulations showed a shift towards drier climates in all seasons except summer in both emission scenarios and periods. The variability in the projected mean monthly precipitation among climate models indicates great uncertainty but all climate models clearly deviated from the baseline period 20 (1981–2010), underlining the change signal (Fig. 3)." Based on figure 3 I don't see a 'drying' trend, the models seem to be split to me. I think just reporting the mean is not enough in this case. Perhaps a box plot or the standard deviations would help examine the change (same comment for tables 3 and 4).

Agreed. We will convert the point graph into box plot to show the trend more clearly.

S.C9: Figure 5: Caption doesn't explain the 'proportion of LAI effect'

Agreed. We will change and explain the proportion of LAI effect in the figure caption.

S.C10: Pg 10608 "Projections of climate-induced vegetation dynamics and their hydrological impacts are influenced by various sources of uncertainties that arise from inputs from downscaled GCM outputs." The authors discuss in depth the differences in means; however runoff processes in semi-arid catchments are rarely triggered by 'mean' conditions. There is no discussion on the precipitation characteristics of the regions (intensity, duration, interstorm) and how these are predicted to change. If interstorm periods are expected to increase, this will significantly alter the hydrologic fluxes even if the mean precipitation is maintained. Vegetation response to long dry periods would be more significant that response to changes in mean conditions. There is no discussion of existing models that use a more sophisticated vegetation module to model these effects. A review of these models would be useful to readers.

The main objective of this study is to investigate the indirect effect of drought and future anticipated climate change on mean monthly /annual runoff through allowing vegetation LAI to change with climate. Therefore, consideration of extreme precipitation events is less important in this study; so long as the precipitation is consistent between the two runs we can assess the importance of the change in LAI modelling. Changes in precipitation characteristics would be important for studies with the objective of predicting climate change impact on flood behaviour, reservoir management and so on.

Agreed. We will add a discussion of existing models that use a more sophisticated vegetation module to model these effects for readers' interest.

References

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Zhao, F., Chiew, F. H. S., Zhang, L., Vaze, J., Perraud, J.-M., and Li, M.: Application of a macroscale hydrologic model to estimate streamflow across southeast Australia, J. Hydrometeorol., 13, 1233-1250, doi:10.1175/jhm-d-11-0114.1, 2012.

Responses to major comments of Reviewer #2

This manuscript presents the VIC model results under climate change scenarios for 13 different watersheds in southeastern Australia. Based on their simulations, the reduction in water yield was (or will be) mitigated by the vegetation responses to hydroclimate changes (warmer). Although the manuscript presents an interesting point and is worthy of publication (somewhere), I am not sure it rises to the level of a HESS paper. Some of the results are quite obvious to me (the mitigation role of vegetation in climate changes). It could have been greatly improved by incorporating much more details in several sections, particularly the model description, results, and their interpretation. Especially, I cannot find any further or in-depth discussion in the manuscript, which makes me feel more like reading a modeling exercise rather than a paper. My recommendation comes w/ three caveats:

Noted – we respond to these concerns below.

First, I'm a bit concerned about overlaps with two papers listed in references (Tessema et al. 2014a and b). It seems that the LAI models and predictions were already covered by the first paper, and the modeling part (calibration and validation) were presented in the paired paper (Tessema et al. 2004b). In these kinds of scenario-based hydrological simulations, downscaling and bias correction processes would be most interesting to many readers (Hay, L. E., et al. "Use of regional climate model output for hydrologic simulations." Journal of Hydrometeorology 3.5 (2002): 571-590.) . However, I cannot find any merit about those processes. The presented downscaling process seems like a simple data generator based on the baseline climate data rather than actual statistical downscaling. It seems that the study site is located along the strong orographic gradient, however this factor was completely ignored in those processes. Check this paper (Praskievicz, Sarah, and Patrick Bartlein. "Hydrologic modeling using elevationally adjusted NARR and NARCCAP regional climate-model simulations: Tucannon River, Washington." Journal of Hydrology 517 (2014): 803-814.). They used a topographic correction of regional climate-model data for modeling the hydrology of mountainous basins for simulating hydrology under past or future climates. With the current downscaling method (I am not sure I can say 'downscaling'), the predicted scenarios would be too much constrained by the baseline climate data, and will only produce averaged responses from GCM models. 2.2.2 section definitely overlaps with Tessema et al.

2014a. 2.2.3 session is about how to deconvolve the simulation results into CC and vegetation effect. What are the unique methods and equations in this manuscript? I briefly read the first paper in review. I am not sure whether this manuscript can be a stand-alone paper in a current form.

Partially agree. The unique contribution of this manuscript is that we examine the relative effects of direct climate forcing (rainfall, atmospheric ET drivers) and direct climate forcing combined with climate induced LAI change on runoff under changed climate scenarios. Comparing these enables the LAI effect to be separated out. Most studies to date have looked at either only the direct climate forcing effects or only the combination of climate forcing change coupled with vegetation change. Specifically, our study was done by coupling the LAI-Climate model developed in Tesemma et al. (2014a) into the VIC hydrologic model and assess the impact on catchment runoff of how LAI is modelled (constant seasonal LAI or LAI varying in response to climate) under changing climatic conditions. We investigate two sets of changing climatic conditions: (1) the observed Millennium Drought, which is a persistent (>10 year) large change; and (2) projected climate change for both wet and dry sub-catchments. Our results suggest that modelling LAI in a way that responds to changing climatic conditions is important for modelling runoff during drought and projected climate change. We believe this paper makes a significance contribution to the existing body of knowledge and is a stand-alone paper.

Nevertheless, we do agree that we need to make this clearer in the introduction. We also agree that we need to provide more details about the model description, downscaling methodology, results, and their interpretation so that the significance of this work is more apparent. See our response to Review #1 who also made a similar request for more detail.

Second, the manuscript starts with the critiques of stationarity assumption in future hydrological simulations (P10595 L24). I totally agree to this point in that the traditional hydrologic modeling has often ignored the importance of vegetation response during hydrologic regime changes. Many papers related to climate changes have mentioned the importance of vegetation in mitigating the effect of anthropogenic CO_2 emission and resulting temperature increases. I think that the authors should have written in depth discussion regarding this point. However, it would be also the same problem to use the equation 5 for the prediction of LAI values in the future. It is naive to predict LAI values in 100 years only with 6-9 months P - PET deficits. Leaving nutrient and CO_2 issues aside, the authors assumes the constant PFT (plant functional types) for their simulations. However, tree lines will definitely move upward with warmer climate. I am sure this constant PFT assumption led to the conclusion that ET would decrease and soil remain wetter even with warmer climate (P10608 L5), which I cannot agree to. The constant PFT assumption would decrease LAI values for tree dramatically, which might result in wetter soils with warmer climate. However, you would never get wetter soils under warmer climate. Rather, all trees would die off due to drought stress, and be substituted by other drought tolerant species.

Partially agree. We agree with the reviewers concern about changes in plant functional types (PFTs) and we discussed our assumption that PFTs did not change in the manuscript. We make this limitation clearer in the paper and will add a comment about timescale of adjustment. Notwithstanding this, we note that our LAI-climate relationships were developed in a region that experienced a ten year drought (2000–2009, called the "Millennium drought"), which is comparable to projected climate conditions under the highest CO_2 emission scenario. The observed Millennium drought makes this study very interesting because we have a chance to see how vegetation responded to such severe water stresses under a prolonged (ten years) climate change. We believe our LAI-climate relationships developed under extreme drought conditions could reasonably represent how LAI may change under comparable anticipated changes in future climate. Furthermore, most over-story trees in our study area are Eucalypts and while some movement of boundaries between dominant species may be expected, water use characteristics are likely to be relatively similar and there is not sufficient information to represent species specific details of either migration or water use.

In addition, it is know that in Australia vegetation growth is highly controlled by precipitation (water supply), and is less controlled by temperature and radiation (Nemani et al. 2003). Hence, most vegetation dynamics can be explained by variation in climate, which formed the basis of the LAI-climate model developed in Tesemma et al. (2014a). We acknowledge changing CO_2 levels could influence vegetation growth, but to a smaller extent than climate does. Finally, while the reviewer has mentioned possible changes in PFTs under climate change, in our study area PFTs are strongly influenced by land use (human activities) such as forest clearing for agriculture, which are difficult to project into the future. It is likely that issues such as fire regime changes (Heath et al., 2014) and changes to forest age (Cornish and Vertessy, 2001) which change water use would dominate over differences between species. We will acknowledge these limitations in the revised manuscript.

We will revise the manuscript to emphasis the unique opportunity that the Millennium drought has provided to investigate this issue. We will include a discussion of these issues in the introduction section to help readers to be aware of the assumptions made in this analysis at the beginning of the paper, and deepen our discussion section as well.

Third, I am not comfortable with the equivalence between LAI and productivity. Throughout the manuscript, those two terms were assumed as the same, but it is definitely not. Hydrologists often made the same mistake (e.g. Rodriguezâ˘AR˘ Iturbe, I., et al. "On the spatial and temporal links between vegetation, climate, and soil moisture." Water Resources Research 35.12 (1999): 3709-3722). Although LAI can be a result of accumulated productivity through allocation of photosynthates, the allocation ratios between above and belowground would be quickly responding to water and nutrient availability (Litton, Creighton M., James W. Raich, and Michael G. Ryan. "Carbon allocation in forest ecosystems." Global Change Biology 13.10 (2007): 2089-2109). This allocation process should be understood under the optimality principle for the compromise between different resources (light and water/nutrient). For example, this would lead to the conclusion that the vegetation with the same LAI values would have the same productivity regardless of their locations and climates, such as semiarid and tropical environment. This is why most remote sensing based models incorporate different environmental constraints, such as VPD, temperature, ET/PET etc., to convert LAI values to NPP/GPP terms (e.g. MODIS GPP/NPP), rather than using a constant radiation use efficiency value. Please remove the productivity term throughout the manuscript.

Agreed. We will replace vegetation productivity with LAI throughout in the revised manuscript.

Responses to specific comments (S.C) of Reviewer #2

P10596 L9-12: This sentence is not clear to me.

Agreed. We will revise the whole sentence for clarity.

P10596 L11: Please do more literature reviews. There are tons of papers that examine the relationship between vegetation water use and streamflow generation under climate changes especially in Mediterranean climate regions (e.g. Walko, Robert L., et al. "Coupled atmosphere-biophysics-hydrology models for environmental modeling." Journal of applied meteorology 39.6 (2000): 931-944). Check the recent papers from Dr. Christina Tague at UCSB.

Agreed. We will expand the literature reviews and include those papers mentioned-above in the revised manuscript.

Equations 6 and 7; Qclim, Qnet, and Qlai are confusing because they look like the water yields, but actually percent terms. Change those.

In case where some catchments are wet and some catchments are dry, the percentage is preferable to use which allows comparison across catchments.

P10608 L3-5: This is the most controversial result from the paper. I cannot agree. Do you need Table 2 to Table 5. Nobody would read those.

Agreed. We will move the detailed results provided in those tables to Supplementary Material and convert the results in the tables into figures that are easier to follow.

References:

Cornish, P. M., and Vertessy, R. A.: Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest, J. Hydrol., 242, 43-63, 10.1016/S0022-1694(00)00384-X, 2001.

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Nemani, R. R., Keeling C. D., Hashimoto H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B., Running, S. W.: Climate-driven increases in global terrestrial net primary production from 1982 to 1999, Science, 300, 1560-1563, 2003.

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Including the dynamic relationship between climate variables and leaf area index in a hydrological model to improve streamflow prediction under a changing climate

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Abstract

Anthropogenic climate change is projected to enrich the atmosphere with carbon dioxide, change vegetation dynamics and influence the availability of water at the catchment. This study combines a non-linear model for estimating changes in leaf area index (LAI) due to climate fluctuations with the Variable Infiltration Capacity (VIC) hydrological model to improve catchment streamflow prediction under a changing climate. The combined model was applied to thirteen gauged catchments with different land cover types (crop, pasture and tree) in the Goulburn-Broken Catchment, Australia for the "Millennium Drought" (1997–2009) relative to the period (1983–1995), and for two future periods (2021–2050 and 2071–2100) for two emission scenarios (RCP4.5 and RCP8.5) were compared with the baseline historical period of 1981–2010. This region was projected to be warmer and mostly drier in the future as predicted by 38 Coupled Model Inter-comparison Project Phase 5 (CMIP5) runs from 15 Global Climate Models (GCMs) and for two emission scenarios. The results showed that during the Millennium Drought there was about a 29.7%–66.3% reduction in mean annual runoff due to reduced rainfall and increased temperature. When drought induced changes in LAI are included, smaller reductions in mean annual runoff of between 29.3% and 61.4% were predicted. The proportional increase in runoff due to modelling LAI was 1.3%–10.2% relative to not including LAI. For projected climate change under the RCP4.5 emission scenario ignoring the LAI response to changing climate could lead to a further reduction in mean annual runoff of between 2.3% and 27.7% in the near-term (2021–2050) and 2.3% to 23.1% later in the century (2071–2100) relative to modelling the dynamic response of LAI to precipitation and temperature changes. Similar results (near-term 2.5% to

25.9% and end of century 2.6% to 24.2%) were found for climate change under the RCP8.5 emission scenario. Incorporating climate-induced changes in LAI in VIC model reduced the projected declines in streamflow and confirms the importance of including the effects of changes in LAI in future projections of streamflow.

Key words: Climate change, leaf area index, drought, catchment streamflow, vegetation dynamics, VIC hydrological model.

1 Introduction

Recently, climate changes have been observed in different parts of Australia (Chiew et al., 2011; Cai and Cowan, 2008; Hughes et al., 2012; Lockart et al., 2009; Potter and Chiew, 2011). Specifically, south-eastern Australian catchments have experienced changes in streamflow due to fluctuations in climate as observed during the recent "Millennium Drought'' (1997-2009) which lasted more than a decade (Chiew et al., 2011; Verdon-Kidd and Kiem, 2009). This drought may be representative of future climatic conditions in this region.

The projected water availability for future climates derived from downscaled outputs from global and regional climate models indicate increases of mean annual runoff by 10% to 40% in some parts of the world (high northern latitudes) and 10% to 30% reduction elsewhere (southern Europe, Middle East and south-eastern Australia) (Milly et al., 2005). More recently, Roderick and Farquhar (2011) examined climate and catchment characteristics for sensitivity to changes in runoff in Murray-Darling Basin (MDB) in southeast Australia from a theoretical point of view and estimated that a 10% change in rainfall would lead to a 26% change in runoff and a 10% change in potential evaporation would lead to a 16% change in runoff with all other variables being constant. In south-eastern Australia it has been projected that there will be a reduction in mean annual runoff of 10% on average when different climate models are used as input to hydrological models (Cai and Cowan, 2008; Chiew et al., 2009; Roderick and Farquhar, 2011; Teng et al., 2012a; Vaze and Teng, 2011). These studies assessed the possible impacts of climate change on total runoff based on rainfall-runoff relationships which only considered first order effects of changes in precipitation and temperature with subsequent impacts on evaporative demand.

There is evidence that such relationships are not stationary over time (Chiew et al., 2014; Peel and Blöschl, 2011; Vaze et al., 2010), which implies that the studies discussed in the previous paragraph may be missing an important factor. One approach to improving modelling under changing conditions is to use variable monthly leaf area index (LAI) in the hydrologic model. Using observed climate variability and streamflow responses, observed monthly LAI has been shown to improve model performance relative to using mean monthly LAI (Tesemma et al., 2014b). The improvements are largest under either relatively wet or dry climatic conditions, i.e. in wet and dry years, rather than average years. In most south-eastern Australia, LAI primarily responds to the availability of water and changes in vegetation type, such as conversion of forest to cropland or pasture, but also responds, to a lesser extent, to changes in temperature and rising atmospheric CO_2 concentrations. Most of these LAI responses are expected to be affected by projected climate change. These climate-induced changes in vegetation LAI may impact on evapotranspiration and runoff and hence should be considered when making runoff projections for climate change scenarios.

Dynamic Global Vegetation Models (DGVMs) have been used to assess the vegetation effect of climate change on large-scale hydrological processes and patterns (Murray et al., 2012a, 2011). A list of available DGVMs and their processes representations (photosynthesis, respiration, allocation, and phenology) can be found in Wullschleger et al. (2014), while Scheiter et al. (2013) provides a review of the possible sources of uncertainty related to representation of plant functional type (PFT) in DGVMs. Most DGVMs overestimate runoff; mainly due to model structure problems along with operating at low spatial and temporal resolution (Murray et al., 2012b). While the relationships between LAI and climate fluctuation have been modelled (Ellis and Hatton, 2008; O'Grady et al., 2011; Jahan and Gan, 2011; Palmer et al., 2010; Tesemma et al., 2014a; White et al., 2010), none of them have been incorporated in hydrological models for the purpose assessing future climate change impacts on streamflow. The poor hydrological sub models in DGVMs and the static vegetation in most hydrological models mean that importance of the indirect vegetation-related (LAI) effects relative to the direct effects of changes in precipitation and temperature on hydrological response at catchment scale have rarely been studied. This limits understanding of the linkages between climate fluctuations and vegetation dynamics, and their combined impacts on hydrological processes.

The main objective of this study is to examine the relative effects on mean annual runoff of changes in direct climate forcing (mainly precipitation and temperature) and direct climate forcing combined with climate-induced LAI changes under changed climate scenarios. Comparative analysis of these two cases enables the effect on mean annual runoff of allowing LAI to respond to a changing climate to be identified. Specifically, our study combined the LAI–Climate model developed in Tesemma et al. (2014a) with the VIC hydrologic model to assess the impact on catchment runoff of how LAI is modelled (constant seasonal LAI or LAI varying in response to climate) under changing climatic conditions. As noted above, this combined model showed significant improvements in runoff simulations under historic conditions. Here we investigate two sets of changing climatic conditions: (1) the observed Millennium Drought (1997–2009), which is a persistent (>10 year) large change in climate; and (2) projected climate change for both wet and dry catchments using 38 Coupled Model

Inter-comparison Project Phase 5 (CMIP5) runs from 15 different Global Climate Models (GCMs) for two future periods, 2021–2050 and 2071–2100, for two emission scenarios, RCP4.5 and RCP8.5). The results obtained from this study are expected to demonstrate whether modelling LAI in a way that responds to changing climatic conditions is important for modelling runoff during projected climate change in the study area.

2 Research approach

This section provides details about the characteristics of the selected catchments and the modelling exercises. The climate and land cover of the study catchments are briefly described in section 2.1. The application of multiple GCMs and emission scenarios output method are explained in section 2.2. The relationship between LAI and climatic variables are presented in section 2.3, and the hydrologic modelling experiment approach used to assess the impact of changes in climate on runoff are described in section 2.4.

2.1 Characteristics of selected catchments

All the study catchments are located in the Goulburn-Broken Catchment which is a tributary of the Murray-Darling Basin (MDB), Australia. The Goulburn-Broken Catchment extends between 35.8^0 to 37.7^0 S and between 144.6^0 to 146.7^0 E (Figure 1a) with a range of altitude from approximately 1790 m on the southern side to 86 m above mean sea level on the northern side of the catchment. The mean annual rainfall of the study catchments ranges from 659 (in the north) to 1407 mm/year (in the south) calculated for the period (1982–2012). The majority of the rainfall (about 60%) occurs during winter and spring. The reference evapotranspiration (PET) calculated using the Food and Agricultural Organization (FAO56) method, ranges from 903 (in the north) to 1046 mm/year (in the south). Hence, the dryness index (mean annual reference evapotranspiration divided by mean annual precipitation) varies from 0.64 to 1.6 (Figure 1b). The dominant land cover type in most of the catchments is forest (mainly tall open Eucalyptus forest and Eucalyptus woodlands) with some pasture in all catchments. A small amount of cropland is located in some of the catchments (Figure 1c).

2.2 Applying multiple GCMs and multiple emission scenarios

Outputs from many climate models from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) (Taylor et al., 2012) are used as input to the hydrological model. CMIP5 contains model runs for four representative concentration pathways (RCPs), which provide radiative forcing scenarios over the 21st century (Moss et al., 2010; Vuuren et al., 2011). In this study two emission scenarios were chosen: a midrange mitigation scenario, referred to as RCP4.5 and a high emissions scenario RCP8.5 (Meinshausen et al., 2011). RCP4.5 results in a radiative forcing value of 4.5 Wm^{-2} at the end of the 21st century relative to the preindustrial value, while RCP8.5 provides a radiative forcing increase throughout the 21st century to a maximum of 8.5 Wm^{-2} at the end of the century.

CMIP5 Global Climate Model (GCM) data were obtained from (http://climexp.knmi.nl accessed 28 February 2014). These data were re-sampled to a common grid resolution of 2.5° since each GCM has a different spatial resolution (some are the same, but most are different). A total of 38 RCP4.5 and RCP8.5 runs from 15 different GCM models have been used in this study to include the possible uncertainty among climate models. For each of the 38 runs, daily precipitation, minimum and maximum temperature data were collected for three periods, 1981–2010 (historical run), 2021–2050 and 2071–2100 (future runs). An assessment of the ability of the CMIP5 runs to reproduce the observed base line seasonality of precipitation, minimum and maximum temperature is shown in Figure 2. The seasonality in precipitation and temperature were well captured by most CMIP5 runs with biases which require correction.

Low spatial resolution GCM outputs require downscaling for application in catchment hydrology studies. Here the 'delta-change' statistical downscaling technique was used to downscale and bias-correct the GCM outputs (Fowler et al., 2007). Delta-change was selected due to its low computational intensiveness and easy applicability to a range of GCMs. We acknowledge the limitations of this method include an assumption of stationarity in change factors, climate feedbacks are not incorporated and an inability to capture changes in extreme events and year to year variability. Dynamic downscaling, which solves some of these problems, was not used as it has high computational demand and is not readily available for a range of GCM runs and scenarios (Fowler et al., 2007). A simple statistical downscaling method was appropriate for this study as we were interested in the impact of including climate induced LAI change on the runoff results. In the study area, the monthly LAI is strongly related to three month and/or nine month moving average moisture state (precipitation – potential evapotranspiration) (Tesemma et al., 2014a). Therefore, so long as the precipitation is consistent between the two runs we can assess the importance of the change in LAI representation between model runs. It has been suggested that extreme rainfalls might change differently to mean rainfalls under climate change (Harrold et al., 2005) and the delta-change method does not capture this. Nevertheless delta-change was used as this study concentrates on average runoff which is strongly linked to overall catchment wetness, rather than floods which are linked to a combination of catchment wetness and extreme rainfall. Hence consideration of extreme precipitation events is less important in this study.

Statistical downscaling was applied to each of the GCM outputs and emission scenarios. Since the study area is covered by four GCM grid cells, the area weighted average precipitation, minimum and maximum temperatures of the GCM grid cells covering the study area were computed. The area weighted average values were then statistically downscaled using the delta change approach. Delta changes were calculated separately for each of the 12 months. For temperatures the delta changes were calculated using

$$\Delta_T(j) = \overline{T}_{projn}(j) - \overline{T}_{baseline}(j) \quad (1)$$

where $\Delta_T(j)$ is the delta change in the 30-year mean monthly minimum or maximum temperature as simulated by the climate model for the future period and RCP of interest (2021–2050 or 2071–2100, RCP4.5 or RCP8.5), $\overline{T}_{projn}(j)$, relative to the mean for the baseline period (1981–2010) climate model simulation, $\overline{T}_{baseline}(j)$. j represents the month. $\Delta_T(j)$ is then applied to the daily baseline (1980–2010) observations, $T_{obs}(j,i)$, for each pixel of the climate gridded data (which is the same as the VIC model grid pixels) to obtain the statistically downscaled minimum or maximum daily temperature, $T_{\Delta}(j, i)$ for month j and day i.

$$T_{\Delta}(j, i) = T_{obs}(j, i) + \Delta_T(j) \quad (2)$$

For precipitation, the delta changes value is computed as a proportional change rather than a shift:

$$\Delta_p(j) = \frac{\overline{P}_{projn}(j)}{\overline{P}_{baseline}(j)} \quad (3)$$

and then applied to the observations using:

$$P_{\Delta}(j, i) = P_{obs}(j, i) \times \Delta_p(j) \quad (4)$$

Here $\Delta_P(j)$ is the delta change in 30-year mean monthly precipitation as simulated by the climate model $\overline{P}_{projn}(j)$ for two future periods (2021–2050 and 2071–2100) relative to the baseline simulation $\overline{P}_{baseline}(j)$; $P_{\Delta}(j, i)$ is the statistically downscaled daily precipitation for the projected future climate change scenario for month j and day i, $P_{obs}(j, i)$ is observed daily precipitation for the historical period (1981–2010) for month j and day i for each of the precipitation pixel of the gridded climate data. The delta change approach maintains a similar (but shifted or scaled) spatial variation of temperature and precipitation as that in the historical observed gridded data. The daily pattern of weather variation and the relationships between the various weather variables are also maintained. Because historic weather data provides the basis for the temporal patterns, the well-recognized issue of “GCM drizzle” is eliminated. The delta change method also corrects for differences between the mean elevation of the four GCM grid cells by scaling up or down the historical spatial variation of temperature and precipitation across the catchment.

2.3 Relationship between LAI and climate variables

Tesemma et al. (2014a) showed that monthly LAI of each vegetation type was closely related to changes in moisture state (precipitation minus reference evapotranspiration) of six-monthly moving averages for crop and pasture, and nine-monthly moving averages for trees. Differences in LAI response for the same change in moisture state among the three vegetation types were also observed as differences in model parameters of the LAI–Climate relationship. Tesemma et al. (2014a) provides details on the derivation of the LAI–Climate relationship for the Goulburn-Broken Catchment. The three LAI models developed for crop, pasture and tree are given below.

$$\mathrm{LAI} = \begin{cases} \dfrac{136.4836}{1+\exp\left(-\left(\frac{(P-PET)-159.4555}{42.5607}\right)\right)}, & \text{if Crop} \\ \vdots & \\ \dfrac{6.2495}{1+\exp\left(-\left(\frac{(P-PET)-43.6157}{62.8487}\right)\right)}, & \text{if Pasture} \\ \vdots & \\ \dfrac{4.2091}{1+\exp\left(-\left(\frac{(P-PET)+57.1849}{36.9481}\right)\right)}, & \text{if Tree} \end{cases} \quad (5)$$

Where LAI is the leaf area index of the cover type (tree/pasture/crop), P is the six month moving average of precipitation for crop and pasture, and the nine month moving average for trees, and PET is the respective reference evapotranspiration.

The monthly LAI was then simulated for both historical and future climate scenarios using the LAI–Climate model (Eq. 5) driven with the appropriate climate inputs. In this study monthly average reference evapotranspiration (PET, mm day^{-1}) was estimated using the standard FAO Penman-Monteith daily computations (Allen et al., 1998) and then aggregating to monthly values. The reference evapotranspiration (PET) for future climate scenarios was computed using the projected minimum and maximum temperatures,while incoming shortwave radiation and vapour pressure were derived from daily temperature range using the algorithms of Kimball et al. (1997) and Thornton and Running (1999). The wind speed was kept the same as the historical observations. A significant literature exists (see discussion in

Supplementary Material of McMahon et al., 2015) around the issue of using temperature to drive future changes in PET. We acknowledge this assumption and note that it is likely to have limited impact on our runoff results in the mainly water limited catchments modelled here. The historical or future precipitation was used in Eq. 5 according to the scenario being modelled. Potential LAI variations in the baseline years (1981–2010) and the two future periods (2021–2050 and 2071–2100), for each of the two future emission scenarios, were simulated using the downscaled outputs from the 38 CMIP5 runs of the 15 GCMs, as input into the LAI–Climate model (Eq.5). The uncertainty ranges in modelled LAI that come from the difference in climate input were determined by using the downscaled 38 CMIP5 runs individually in Eq. 5.

2.4 Hydrological model and experimental design

In this study we used the three layer Variable Infiltration Capacity model (VIC) model which has been used in different parts of the world and found to successfully simulate water balance components. The study used a rigorously calibrated and validated VIC model for each of the 13 study catchments. The VIC models were calibrated separately using the Multi-Objective Complex Evolution (MOCOM-UA) algorithm (Yapo et al., 1998). For details on the model calibration and validation procedures and model evaluation results see Tesemma et al. (2014b). More detail about the modelling approach used in this study is described below. We used a daily time step, a 5km by 5km spatial grid resolution and FAO56 Penman-Monteith for potential evapotranspiration computation. VIC estimate infiltration and runoff using the variable infiltration capacity model which is a non-linear function of the soil moisture storage within the grid cell (Liang et al., 1994; Zhao et al., 1995). The ability of the model to incorporate spatial representation of climate and inputs of soil, vegetation and other landscape properties make it applicable for climate and land use / land cover change impact studies.

Most land surface models require a spin up period to reach a dynamic equilibrium between the climate forcing and various model state-variables. The spin up period depends on the type of model and the purpose of the studies. In this study the VIC model was run at a daily time step for 30 years from January 1981 to December 2010 to spin up the model and to produce a restart file to be used as the initial condition for experiment runs. All experimental runs were initiated with the state produced from model spin up. The calibrated and validated VIC model used in this study is described by Tesemma et al. (2014b). Two model experiments were run: the first experiment considered the recent historical climate (Millennium Drought, 1997–

2009) and LAI estimates using the simple LAI-Climate model against the relatively normal historical climate period (1983–1995). The second experiment considered the future climate from 38 CMIP5 runs and corresponding LAI derivatives for two periods (2021–2050 and 2071–2100), and two emission scenarios RCP4.5 and RCP8.5 with respect to the historical period (1981–2010). Both sets of simulations were performed over the thirteen calibrated study catchments within the Goulburn-Broken Catchment (Figure 1b). A flow chart of the modelling method is given in (Figure 3).

To identify the effect on mean annual runoff of allowing LAI to respond to a changing climate, compared with LAI not responding, we used the following steps: (1) the calibrated model was forced with inputs of historical climate data and LAI data modelled from using the historical climate data (1981–2010) to establish baseline streamflow estimates; (2) the model was forced with projected future climate inputs and corresponding modelled LAI to produce projected streamflow for future scenarios; (3) the future climates were input along with the LAI data used in step 1 to produce projected streamflows that ignore project LAI changes . The difference in mean annual runoff between steps 3 and 1 represents the climate effect (CC effect); on mean annual runoff of only Precipitation and Temperature. Whereas the difference in mean annual runoff between steps 2 and 1 represents the net effect (CC + LAI effect); on mean annual runoff of allowing LAI to respond to a changing climate in addition to the direct climate forcing (Precipitation and Temperature). The difference in mean annual runoff between steps 2 and 3 represents the component of the runoff response related to climate-induced changes in LAI. For the millennium drought (1997–2009) the above two changes in mean annual runoff were estimated in a similar fashion taking (1983–1995) time period as relatively normal period. The percentage change of mean annual runoff against the historical mean annual runoff for climate change effect (Q_{clim}) (Eq. 6), climate change and LAI effect (Q_{net}) (Eq. 7); and the percentage of CC effect offset by LAI effect (Q_{lai}) (Eq. 8) were estimated as follows:

$$Q_{clim} = \left[\frac{100 * (Q_{historical\ LAI}^{future\ climate} - Q_{historical\ LAI}^{historical\ climate})}{Q_{historical\ LAI}^{historical\ climate}}\right] \quad (6)$$

$$Q_{net} = \left[\frac{100 * (Q_{future\ LAI}^{future\ climate} - Q_{historical\ LAI}^{historical\ climate})}{Q_{historical\ LAI}^{historical\ climate}}\right] \quad (7)$$

$$Q_{lai} = \left[\frac{100 * (Q_{clim} - Q_{net})}{Q_{net}}\right] \quad (8)$$

3 Results

This section provides results from the modelling exercises. The change in climate variables during: (1) the recent observed prolonged drought; and (2) future climate change projections for the study catchments are presented in section 3.1. The impact on both LAI (section 3.2) and catchment streamflow (section 3.3) of changes in climate input during the Millennium Drought and future climate change projections are also provided. These results provide readers with a comparison of the anticipated future change in climate with the recently observed drought.

3.1 Change in the climate variables from change in climate

3.1.1 Millennium drought

The Millennium Drought brought a decline in the mean annual precipitation over the selected catchments which ranged from 17.9% to 24.1%, with a mean of 20.9% when compared with the period (1983–1995). It also brought an increase in mean annual temperature which ranged from 0.2 ^{0}C to 0.4 ^{0}C, with an average of 0.3 ^{0}C as compared to the temperature in the period (1983–1995). All thirteen study catchments experienced a similar change in both precipitation and temperature (Table 1).

3.1.2 Future climate

Averaged over all 38 CMIP5 runs, the mean annual precipitation in 2021–2050 over the selected catchments is projected to decline by 2.9% and 3.7%, relative to the historical period 1981–2010, under the RCP4.5 and RCP8.5 scenarios respectively. By the end of the century (2071–2100) mean annual precipitation is projected to decline by 5% and 5.2% under the RCP4.5 and RCP8.5 scenarios respectively (Table 2). The mean annual temperature is also projected to increase in both future periods and emission scenarios (Table 2).

Most precipitation projections showed a shift towards drier climates in all seasons except summer in both emission scenarios and periods. The variability in projected mean monthly precipitation among climate models indicates great uncertainty between GCMs (Figure 4a-d). The mean monthly temperature of all climate models clearly deviated from the baseline period (1981-2010), underlining the consistent change signal between GCMs (Figure 4e-h). The median of the 38 CMIP5 mean monthly precipitation data over the Goulburn-Broken Catchment in the RCP4.5 emission scenario showed declines in most of the months. The decreases were up to 6% in 2021–2050 (Figure 4a) and up to 11% in 2071–2100 (Figure 4c). Similarly, under the RCP8.5 emission scenario the median monthly precipitation, other than in January and February for both periods, showed decreases up to 7% in 2021–2050 (Figure 4b) and up to 18% in 2071–2100 (Figure 4d). The simulations for January and February showed median increases of up to 4% and 5% respectively in 2071–2100 from the historical baseline. Some climate models projected very wet future climates while others projected relatively dry climates. There are relatively high uncertainties in the projected mean monthly precipitation results in summer when compared with the mean monthly precipitation in winter among the climates models.

In contrast to precipitation the projected mean monthly temperatures from all CMIP5 runs showed increases, the median of the mean monthly temperatures of all CMIP5 38 runs increased by about 0.8 ^{0}C in winter and 1 ^{0}C in summer in 2021–2050 (Figure 4e), and by about 1.3 ^{0}C in winter and 1.8 ^{0}C in summer in 2071–2100 (Figure 4g) under the RCP4.5 scenario. Under the RCP8.5 emission scenario the temperatures increased by 1 ^{0}C in winter and by 1.4 ^{0}C in summer during 2021–2050 (Figure 4f) and by 2 ^{0}C and 3 ^{0}C in winter and summer respectively by the end of the 21st century (Figure 4h). After precipitation the second variable that drives water availability is potential evapotranspiration. Here PET is expected to increase among all CMIP5 runs as it is being driven solely by changes in temperature given that actual vapour pressure and solar radiation was also simulated as a function of temperature. In the near future period (2021–2050) the median of all CMIP5 mean monthly reference evapotranspiration projections increase by 5% to 13% in both emission scenarios, with the largest change in winter and the smallest in summer. In the future period of 2071–2100, the mean monthly reference evapotranspiration increased by 7% in summer and 25% in winter under RCP4.5 emission scenarios, and by 10% in summer and 28% in winter under the RCP8.5 emission scenarios.

3.2 Impact on LAI from change in climate

3.2.1 Millennium drought

The effects of the Millennium Drought (1997–2009) on modelled crop LAI were very severe with reductions in mean annual LAI between catchments of 38.1% to 48.0%, with a mean of 42.7% (Table 1). The reduction in LAI of pasture was between 16.7% and 21.6% across the thirteen selected catchments with a spatial average of 19.4% (Table 1). The LAI of trees responded less than crop and pasture, and reductions were in the range 5.7% to 14.0%, with a spatial mean of 9.2% (Table 1). A significant reduction in each cover type also brought an overall decline in areal weighted sum of all land cover types LAI in the selected catchments which ranged from 5.8% to 17.9% (Table 1), which is similar to the reduction for trees, where tree is the dominant land cover type.

3.2.2 Future climate

The changes in mean monthly LAI of crop, pasture and trees averaged over the whole Goulburn-Broken Catchment under future climates are vary between the CMIP5 runs and global warming scenarios. Averaged over all 38 CMIP5 runs, the near future (2021–2050) results for the study catchment showed that the mean annual LAI of cropland, pasture and trees declined up to 13%, 6.7% and 5.4% under the RCP4.5 scenarios, and by up to 16%, 8% and 6.6% under the RCP8.5 scenario (Table 2). A further reduction in the mean annual LAI of each land cover was simulated by the end of the 21st century for both emission scenarios (Table 2).

The effect of projected climate change on monthly total LAI (area weighted sum of all land cover types LAI) for the study catchments is given in (Figure 5). The median of the 38 CMIP5 runs simulated mean monthly LAI showed declines in all three land cover types. Despite similar percentage changes in mean monthly precipitation and temperature forcing, the mean monthly total LAI across the catchment shows the largest decline in autumn and the smallest decline in spring during both future periods and scenarios. This difference reflects the seasonality of moisture availability influencing plant growth. Based on the median of the 38 CMIP5 runs, the predicted decline in the mean monthly LAI for crop, pasture and trees was 18.1%, 10.3% and 7.9% respectively in the period 2021–2050 (Figure 5a, e, i) and 27.7%, 16.6% and 12.8% respectively in the period 2071–2100 under RCP4.5 (Figure 5c, g, k). Larger reductions were simulated under the RCP8.5 emission scenario with 21.4%, 12.7% and 9.5% in the period 2021–2050 (Figure 5b, f, j) and 36.5%, 22.5% and 17.9% respectively for crop, pasture and tree in the period 2071–2100 (Figure 5d, h, l).

3.3 Impacts on runoff from change in climate

3.3.1 Millennium drought

The impact of the Millennium Drought on streamflow due to changes in precipitation and temperature alone and changes in precipitation and temperature and modelled LAI were simulated using the VIC model. The simulated reductions in mean annual streamflow during the Millennium Drought (1997–2009) as compared with the relatively normal period (1983–1995) across the selected catchments due to the change in climate alone ranged from 29.7% to 66.3% with a mean of 50% (Table 1). The reductions in LAI resulting from the decline in precipitation and increase in temperature increased mean annual streamflow by between 1.3% and 10.2% relative to the direct climate effect above (Table 1 and Figure 6).

3.3.2 Future climate

The average of the 38 CMIP5 runs under the RCP4.5 scenario produced declines in mean annual runoff due to the change in precipitation and temperature alone (Q_{clim}) that ranged from 6.8% to 20.3% in the period 2021–2050, and 11.5% to 30.1% for the period 2071–2100 (Table 2 and Figure 7). For the higher emission scenario (RCP8.5), the reductions were a little larger-ranging from 8.3% to 23.3% in 2021–2050 and from 14.5% to 35.1% by the end the 21st century (Table 2 and Figure 6). The reductions in runoff due to climate are offset through the LAI effect (Q_{lai}) that ranged from 2.3% to 27.7% and from 2.3% to 23.1% in the near and far future periods respectively under the RCP4.5 emission scenario. Similar offsets of 2.5% to 25.9% and 2.6% to 24.2% in the near and far future periods respectively were also found under the RCP8.5 emission scenario (Table 2 and Figure 7).

The differences between GCMs in terms of the net climate change impacts (CC + LAI) on mean annual runoff and the LAI contribution to that effect are shown in Figure 8 and Figure 9 respectively. While large uncertainty exists among the 38 CMIP5 runs, the median between the models showed declines in the net climate change (CC + LAI) projections of mean annual runoff in all catchments (Figure 8). The median decline in the mean annual runoff due to the net climate change impact was 15.3% and 26.7% in 2021–2050 and 2071–2100 respectively, under RCP4.5. A larger decline of 21.6% and 31.8% in 2021–2050 and 2071–2100 respectively occurred under RCP8.5 (Figure 8). The simulated LAI effects of the climate change showed smaller variation between GCMs than the net climate change (CC + LAI) effect on mean annual runoff. The LAI effect works to offset the reduction in mean annual runoff resulting from lower precipitation and higher temperature. Figure 9 shows the magnitude of the LAI effect as a percentage of the magnitude of direct climate change effect (noting they work in opposite directions). The median of this across the 38 CMIP5 runs was up to 20%, depending on the month. The simulated LAI effect on mean annual runoff showed smaller variation between GCMs than the net climate change (CC + LAI) effect on mean annual runoff.

The direct climate change (CC) effect, the LAI effect of climate change and the net climate change (CC+LAI) effect on the mean monthly runoff for the selected catchments are given: Catchments 6 (Figure 10a, d, g , j), Catchment 10 (Figure 10b, e, h , k), and Catchment 11

(Figure 10c, f, i , l). Catchments 6 and 10 are located in a high annual precipitation zone with trees as the dominant vegetation cover; whereas Catchment 11 is covered mostly with pasture and has relatively lower annual precipitation than Catchments 6 and 10. Depending on the month, for the 38 CMIP5 runs in 2021–2050 the median reduction in mean monthly runoff (Q_{net}) were up to 10%, 24%, and 34% for catchment 6, 10, and 11, respectively for both the RCP4.5 and RCP8.5 scenarios (Figure 10). Further reductions projected by the end of the 21st century were up to 17%, 37% and 52% for catchments 6, 10, and 11, respectively, under both scenarios (Figure 10). Catchment 6 showed the lowest seasonality in the climate change effects for both emission scenarios and the LAI-related effects of climate change also showed the smallest seasonal variation. Catchment 11 runoff was the most impacted by projected climate changes and had the greatest benefit from LAI effects of climate change under both emission scenarios and future periods. The seasonal pattern of the LAI effect of climate change is similar under both RCP scenarios. The magnitude of this effect is relatively higher for drier projected future climates.

4 Discussion and Conclusion

This study investigated the importance of incorporating the relationship between changing climate, in terms of precipitation and temperature, and vegetation LAI into a hydrological model to estimate changes in mean monthly and mean annual runoff under changing climatic conditions in the Goulburn-Broken Catchment, south-eastern Australia. A combination of Variable Infiltration Capacity (VIC) hydrological simulations with a simple model that relates climatic fluctuations with LAI for three different vegetation types revealed that 21st century climate change impacts on LAI significantly influence the projected runoff in the study catchments. LAIs of forest, pasture and crop were predicted to decline in the 21st century due to reductions in precipitation and increases in temperature.

Reduced LAI in response to a drier and warmer climate would reduce transpiration from vegetation and evaporative losses from canopy interception, which leaves the soil relatively wetter than if LAI response to climate was not included. This is important for runoff generation process as it promotes saturation excess runoff and subsurface flow, which are the dominant cause of runoff generation in the study region (Western et al., 1999). Previous studies in the region (Chiew et al., 2009; Chiew et al., 2011; Teng et al., 2012a; Teng et al., 2012b) concluded that runoff would decrease due to increases in evaporative demand and decreases in precipitation as a result of ongoing warming in the 21st century. However, the relationship between LAI and climate fluctuations was not taken into account in their modelling experiments. Therefore, in these studies the LAI effect is ignored and there is consequent overestimation of the runoff decline in the range of 2.3% to 27.7% (Figure 6 and Figure 7).

Projections of climate-induced vegetation dynamics and their hydrological impacts are influenced by various uncertainties that arise from using downscaled GCM outputs as inputs to the hydrologic model. These include large uncertainties in projections for precipitation from the various CMIP5 simulations (Teng et al., 2012b). In addition, the method used to downscale the GCM outputs really only captures changes the mean; however, any change in variability, which could have an effect on the projected future runoff, is ignored. The ensemble of 38 CMIP5 simulations from 15 GCMs was used to determine the range of uncertainty between GCMs. The results showed that the range of future climate projections from the various GCMs is wide, one climate model could project a very wet future climate while another a relatively dry climate. This suggests future analyses in other catchments should apply downscaled climate change scenarios from several CMIP5 runs from a range of

GCM models to the study area to get a sense of the possible range of climate change impact on both LAI and streamflow.

The results of this study illustrate that reduction of future precipitation and increase in mean temperature lead to reduction of runoff in a general sense. However, if the hydrologic model incorporated dynamic LAI information, as a function of changing climate, it would reduce the impact on runoff that comes from the climate alone. Reduction of LAI due to reduction of precipitation and increase in temperature decreases the evapotranspiration from vegetation and leaves the soil relatively wetter than if climate-induced changes in LAI was not represented in the modeling. The higher catchment moisture contents slightly increased runoff and partially offset the reduction in runoff due to changes in climate.

In interpreting the results presented here it is important to examine the assumptions that were made and the extent to which the results are dependent on those assumptions. Runoff processes can also triggered by other precipitation characteristics (intensity, duration, inter-storm duration) which have not been considered in this study. If inter-storm durations are expected to increase, this will alter the hydrologic fluxes even if the mean precipitation is maintained. However, the climate-LAI model used in the study area (Tesemma et al., 2014a) is related mainly to precipitation and potential evapotranspiration during the previous 6 to 9 months. This limits the impact of changes in extreme precipitation characteristics in terms of modelling the climate-LAI relationship. In order to satisfy the aim of this paper, which is to assess the impact of allowing LAI to respond to a changing climate, so long as the precipitation series is consistent between the runs with and without LAI responding to climate, we can assess the importance of the change in LAI on runoff simulation. Hence, in this study consideration of changing extreme precipitation events is less important; although it would be important for studies with the objective of predicting future floods or reservoir management.

Another assumption was that the effects of rising atmospheric CO_2 concentrations on LAI and stomatal conductance are small compared with the moisture availability effects (i.e. we assume LAI responds to precipitation and PET changes, not CO_2). In addition to the effects of changes in precipitation and temperature, changes in atmospheric CO_2 concentrations could affect vegetation through increasing LAI and narrowing stomata (Ainsworth and Rogers, 2007; Ewert, 2004; Warren et al., 2011). However, increased LAI may be limited by the availability of nutrients, particularly nitrogen (Fernández-Martínez et al., 2014; Körner, 2006). Most of the results on this effect are derived from point experiments which could not be extrapolated to the catchment scale where there is a complex interaction between soil, vegetation and climate. Rising atmospheric CO_2 could also have two other effects on vegetation dynamics. First, biomass allocation may shift towards more above-ground plant structure (Obrist and Arnone, 2003), which implies more canopy leaf than active rooting area. This change could influence the water balance in either direction by increasing evapotranspiration due to interception losses or by decreasing evapotranspiration through limiting plant water uptake. Second, rising atmospheric CO_2 may favor C_3 species over C_4 species, which could lead to more woody plants compared to some grass species (Yu et al., 2014). This could influence the water balance by increasing evapotranspiration and decreasing runoff. In addition at the canopy scale, the evapotranspiration effect of increased LAI can be masked by shading among leaves, soil cover and raised canopy humidity (Hikosaka et al., 2005; Bunce, 2004). A study that considered both effects suggested that the fertilization effect of rising CO_2 is larger than the stomatal pore reduction effect, and the net effect is decreases in runoff (Piao et al., 2007). These two effects of increasing atmospheric CO2 concentrations on vegetation work in opposite directions from a water balance perspective and may offset each other if they are close in magnitude (Gerten et al., 2008). In south-east Australia, it is known that vegetation growth is highly controlled by precipitation (water supply), and is less controlled by temperature and radiation (Nemani et al., 2003). Hence, most vegetation dynamics can be explained by variation in climate, which formed the basis of the LAI - Climate model developed in Tesemma et al. (2014a). We acknowledge changing CO_2 levels could influence vegetation growth, but to a smaller extent than climate does. Hence, exclusion of the fertilization and stomata suppression effects of rising atmospheric CO_2 on vegetation may not change the results significantly.

The other assumption was that any effect of climate change on plant functional type (PFT) was kept ignored. That is the same spatial distribution of vegetation was used but with changed LAI. In the agricultural parts of our study area PFTs are strongly influenced by historical land use change (human activities) such as forest clearing for agriculture. Changes in agricultural crops and pastures are difficult to project into the future. In the forested areas, it is likely that issues that change water use such as changes in fire regime (Heath et al., 2014) and forest age (Cornish and Vertessy, 2001) would dominate over differences between species. Eucalyptus species already occupy high-altitude areas of the study catchment, which leaves little room for PFT changes due to up-slope migration in a warming climate. Most over-story trees in our study area are Eucalypts and while some movement of boundaries between dominant species may be expected, water use characteristics are likely to be relatively similar and there is insufficient information to represent species specific details of either migration or water use. Including these effects in the model may improve the results, but there is insufficient understanding at the granularity required to do so at present.

In summary, in this paper we use the VIC hydrological model to assess the impact on mean annual streamflow of ignoring climate induced changes in LAI for two changing climatic situations: (1) the recently observed "Millennium Drought"; and (2) for downscaled projected future climate change scenarios from 38 CMIP5 runs in the Goulburn-Broken catchment, Australia. In the Millennium Drought (1997–2009) not modelling the response of LAI to changing climatic variables led to further reduction in mean annual runoff, relative to the pre-drought period (1983–1995), of between 1.3% and 10.2% relative to modelling the dynamic response of LAI to decreased precipitation and increased temperature (Table 1 and Figure 6). For projected climate change under the RCP4.5 emission scenario ignoring the LAI response to changing climate could lead to a further reduction in mean annual runoff of between 2.3% and 27.7%, relative to the baseline period (1981–2010), in the near-term (2021–2050) and 2.3% to 23.1% later in the century (2071–2100) relative to modelling the dynamic response of LAI to precipitation and temperature changes. Similar results (near-term 2.5% to 25.9% and end of century 2.6% to 24.2%) were found for climate change under the RCP8.5 emission scenario (Table 2 and Figure 7). Due to the strong relationship between climatic variation and LAI, the climate–LAI interaction should be included in hydrological models for improved climate change impact assessments and modelling under changing climatic conditions, particularly in arid and semi-arid regions where vegetation is strongly influenced by climate.

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Table 1. Vegetation type distributions for each catchment and changes in mean annual precipitation, temperature, LAI and streamflow during the Millennium Drought (1997–2009) relative to (1983–1995).

Catchments ID **Variables***	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Crop cover (%)	0.6	1.0									1.5	1.2	1.2
Pasture cover (%)	14.4	32.7	3.3	6.4	0.92	5.5	9.94	2.57	25.9	7.62	63.5	56.3	48.8
Tree cover (%)	85.0	66.3	96.7	93.6	99.1	94.5	90.1	97.4	74.1	92.4	35	42.6	50.1
P (%)	-23.2	-23.6	-21.1	-18.0	-17.9	-21.0	-20.1	-20.1	-19.4	-21.7	-19.5	-22.6	-24.1
T (^{0}C)	0.2	0.3	0.3	0.4	0.4	0.3	0.3	0.2	0.3	0.2	0.3	0.3	0.3
LAI crop (%)	-44.2	-48.0									-38.1	-41.8	-41.4
LAI pasture (%)	-20.5	-21.6	-19.5	-16.9	-16.7	-18.7	-19.0	-19.1	-19.5	-19.7	-19.6	-20.2	-20.8
LAI tree (%)	-11.4	-10.3	-8.2	-6.6	-5.7	-5.9	-7.0	-6.3	-9.1	-9.2	-14.0	-12.5	-13.9
LAI total (%)	-12.9	-14.4	-8.6	-7.3	-5.8	-6.6	-8.2	-6.6	-11.8	-10.0	-17.9	-17.2	-17.6
Q_{clim} (%)	-49.3	-61.5	-43.7	-39.1	-42.9	-29.7	-44.0	-41.2	-55.2	-57.1	-66.3	-61.8	-57.9
Q_{net} (%)	-48.0	-59.7	-42.8	-38.3	-42.3	-29.3	-43.2	-40.6	-53.3	-55.2	-61.4	-56.1	-53.2
Q_{lai} (%)	2.6	3.0	2.1	2.1	1.5	1.3	1.9	1.4	3.6	3.4	8.0	10.2	8.9

[illegible] T (^{0}C) is the change in mean annual temperature in Degree Celsius, Q_{clim} indicates the climate effect on runoff, Q_{net} is the net effect of climate and LAI on runoff and Q_{lai} is proportion of the climate effect (Q_{clim}) that is offset by the LAI effect.

Table 2. Impacts on mean annual precipitation, temperature, LAI and streamflow of projected climate change averaged over 38 CMIP5 runs relative to (1981–2010).

Catchments ID														
Periods	**Variables***	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
	P (%)	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9	-2.9
	T (^{0}C)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	LAI crop (%)	-12.9	-13.0									-12.9	-13.0	-12.8
	LAI pasture (%)	-5.9	-5.6	-5.4	-5.6	-5.3	-4.8	-5.4	-5.4	-6.1	-6.1	-6.7	-6.3	-6.3
2021-2050	LAI tree (%)	-3.9	-2.9	-2.5	-2.4	-2.0	-1.7	-2.1	-1.9	-3.0	-3.0	-5.4	-4.6	-4.8
RCP4.5	LAI total (%)	-4.2	-3.9	-2.6	-2.6	-2.0	-1.8	-2.5	-1.9	-3.8	-3.2	-6.3	-5.6	-5.7
	Q_{clim} (%)	-12.3	-17.6	-11.4	-11.5	-13.5	-6.8	-12.4	-12.6	-17.4	-18.4	-20.3	-18.9	-14.2
	Q_{net} (%)	-11.4	-16.3	-10.9	-11.1	-13.2	-6.6	-11.9	-12.2	-15.8	-17.0	-16.3	-14.8	-11.7
	Q_{lai} (%)	7.9	8.0	4.6	3.6	2.3	3.0	4.2	3.3	10.1	8.2	24.5	27.7	21.4
	P (%)	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7	-3.7
	T (^{0}C)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	LAI crop (%)	-15.7	-15.7									-15.7	-15.7	-15.5
	LAI pasture (%)	-7.2	-6.9	-6.7	-6.8	-6.5	-5.9	-6.6	-6.6	-7.4	-7.5	-8.1	-7.7	-7.7
2021-2050	LAI tree (%)	-4.8	-3.7	-3.1	-3.0	-2.5	-2.1	-2.7	-2.3	-3.7	-3.7	-6.6	-5.6	-5.9
RCP8.5	LAI total (%)	-5.2	-4.8	-3.3	-3.2	-2.5	-2.3	-3.1	-2.4	-4.7	-4.0	-7.7	-6.9	-6.9
	Q_{clim} (%)	-14.6	-20.7	-13.7	-13.8	-16.3	-8.3	-14.8	-15.0	-20.1	-21.3	-23.3	-21.4	-16.1
	Q_{net} (%)	-13.6	-19.2	-13.2	-13.3	-15.8	-8.1	-14.3	-14.5	-18.3	-19.7	-19.0	-17.0	-13.4
	Q_{lai} (%)	7.4	7.8	3.8	3.8	3.2	2.5	3.5	3.4	9.8	8.1	22.6	25.9	20.1
	P (%)	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0	-5.0
	T (^{0}C)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
	LAI crop (%)	-21.1	-21.3									-20.8	-21.0	-20.7
	LAI pasture (%)	-9.8	-9.5	-9.2	-9.4	-9.0	-8.2	-9.2	-9.2	-10.2	-10.3	-11.0	-10.4	-10.5
	LAI tree (%)	-6.6	-5.1	-4.4	-4.2	-3.5	-3.0	-3.9	-3.4	-5.3	-5.3	-9.2	-7.8	-8.2
2071-2100	LAI total (%)	-7.2	-6.7	-4.6	-4.5	-3.6	-3.3	-4.4	-3.5	-6.6	-5.7	-10.5	-9.4	-9.5
RCP4.5	Q_{clim} (%)	-19.7	-27.5	-18.6	-18.8	-22.1	-11.5	-20.3	-20.7	-26.9	-28.1	-30.1	-27.7	-21.7
	Q_{net} (%)	-18.3	-25.7	-17.9	-18.1	-21.6	-11.2	-19.6	-20.1	-24.7	-26.2	-25.2	-22.5	-18.6
	Q_{lai} (%)	7.7	7.0	3.9	3.9	2.3	2.7	3.6	3.0	8.9	7.3	19.4	23.1	16.7
	P (%)	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2
	T (^{0}C)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	LAI crop (%)	-28.3	-28.3									-28.5	-28.5	-28.1
	LAI pasture (%)	-13.6	-13	-12.5	-12.9	-12.2	-11.1	-12.5	-12.5	-14	-14.1	-15.4	-14.6	-14.7
2071-2100	LAI tree (%)	-9.5	-7.4	-6.3	-6.0	-5.1	-4.3	-5.5	-4.8	-7.6	-7.6	-13.2	-11.2	-11.8
RCP8.5	LAI total (%)	-10.2	-9.4	-6.5	-6.5	-5.2	-4.7	-6.2	-5.0	-9.2	-8.1	-14.9	-13.3	-13.4
	Q_{clim} (%)	-24.0	-33.5	-23.9	-24.2	-27.4	-14.5	-25.0	-25.6	-32.0	-33.0	-35.1	-32.8	-25.3
	Q_{net} (%)	-22.3	-31.3	-23.0	-23.3	-26.7	-14.1	-24.0	-24.8	-29.4	-30.8	-29.2	-26.4	-21.7
	Q_{lai} (%)	7.6	7.0	3.9	3.9	2.6	2.8	4.2	3.2	8.8	7.1	20.2	24.2	16.6

[illegible] T (^{0}C) is the change in mean annual temperature in Degree Celsius, Q_{clim} indicates the climate effect on runoff, Q_{net} is the net effect of climate and LAI on runoff and Q_{lai} is proportion of the climate effect (Q_{clim}) that is offset by the LAI effect.

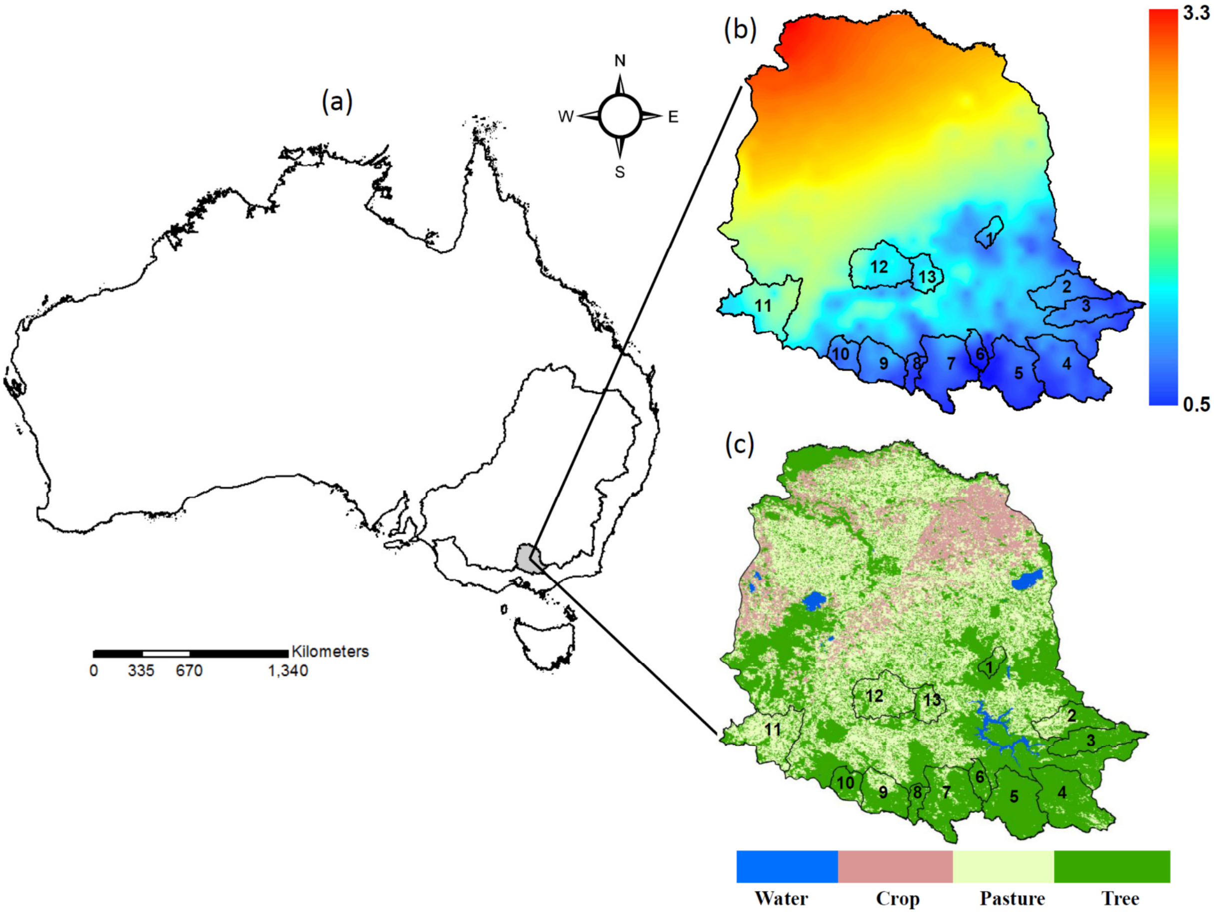

Figure 1. Location map of the study area (a), dryness index (mean annual reference evapotranspiration divided by mean annual precipitation) (b) and land cover type (c).

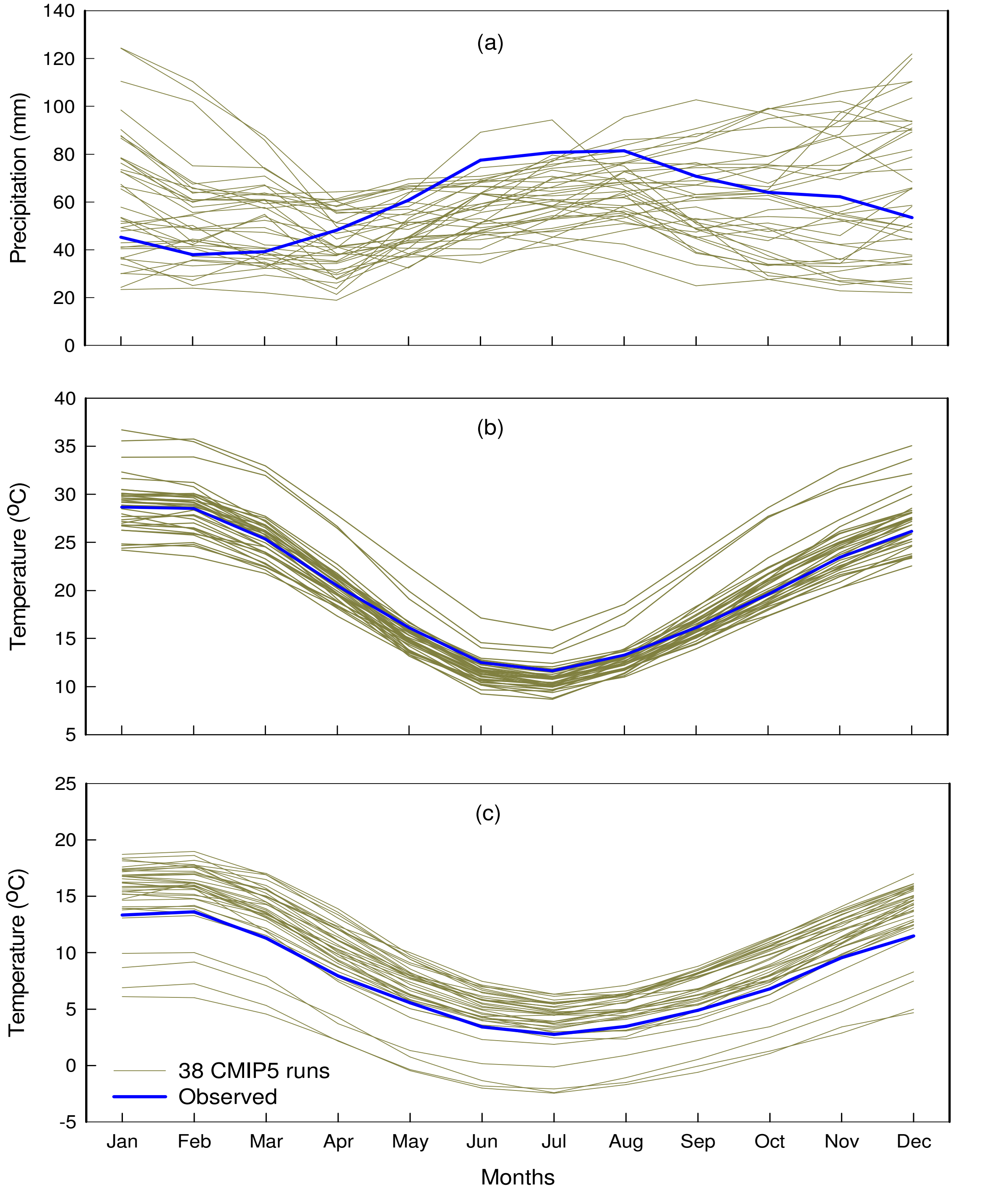

Figure 2. Long-term mean monthly climate observations plotted with the 38 CMIP5 runs during the baseline period (1980–2010) for Goulburn-Broken Catchment (a) long-term mean monthly precipitation (b) long-term mean monthly maximum temperature and (c) long-term mean monthly minimum temperature.

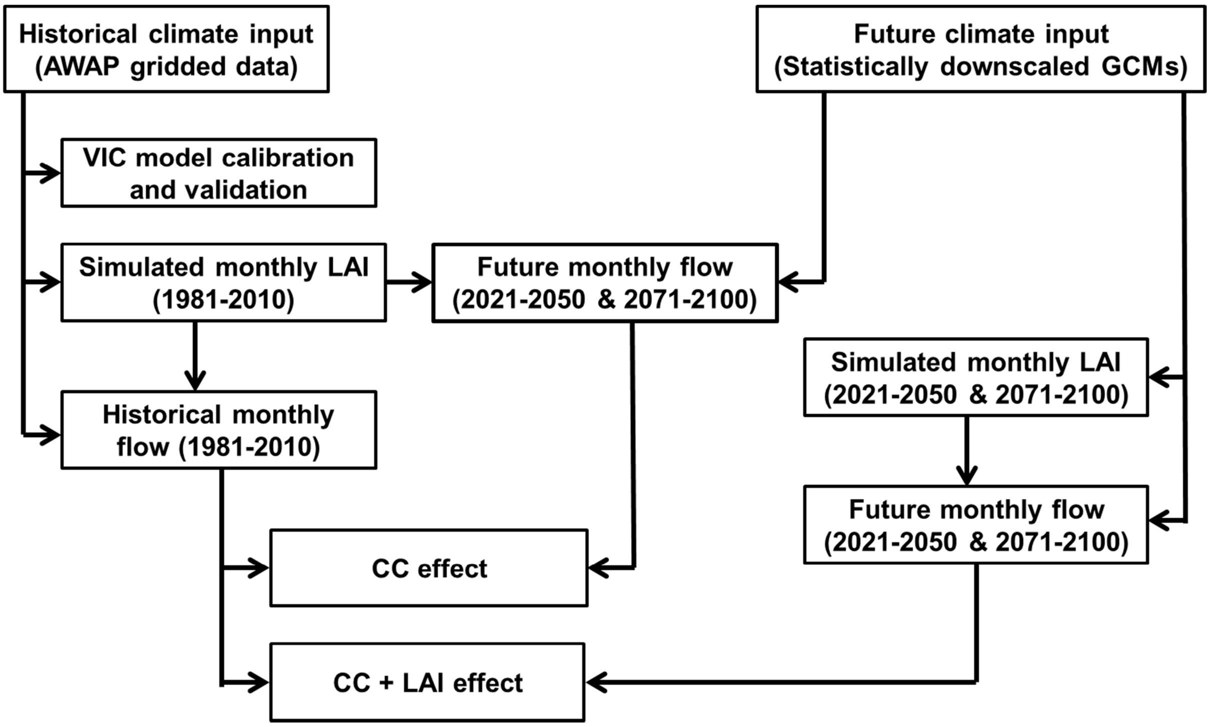

Figure 3. Flowchart showing the modelling experiments and calculation of effects: CC effect indicates the climate change effect of precipitation and temperature with unchanged LAI, CC + LAI effect indicates the climate change effect of precipitation, temperature and leaf area index.

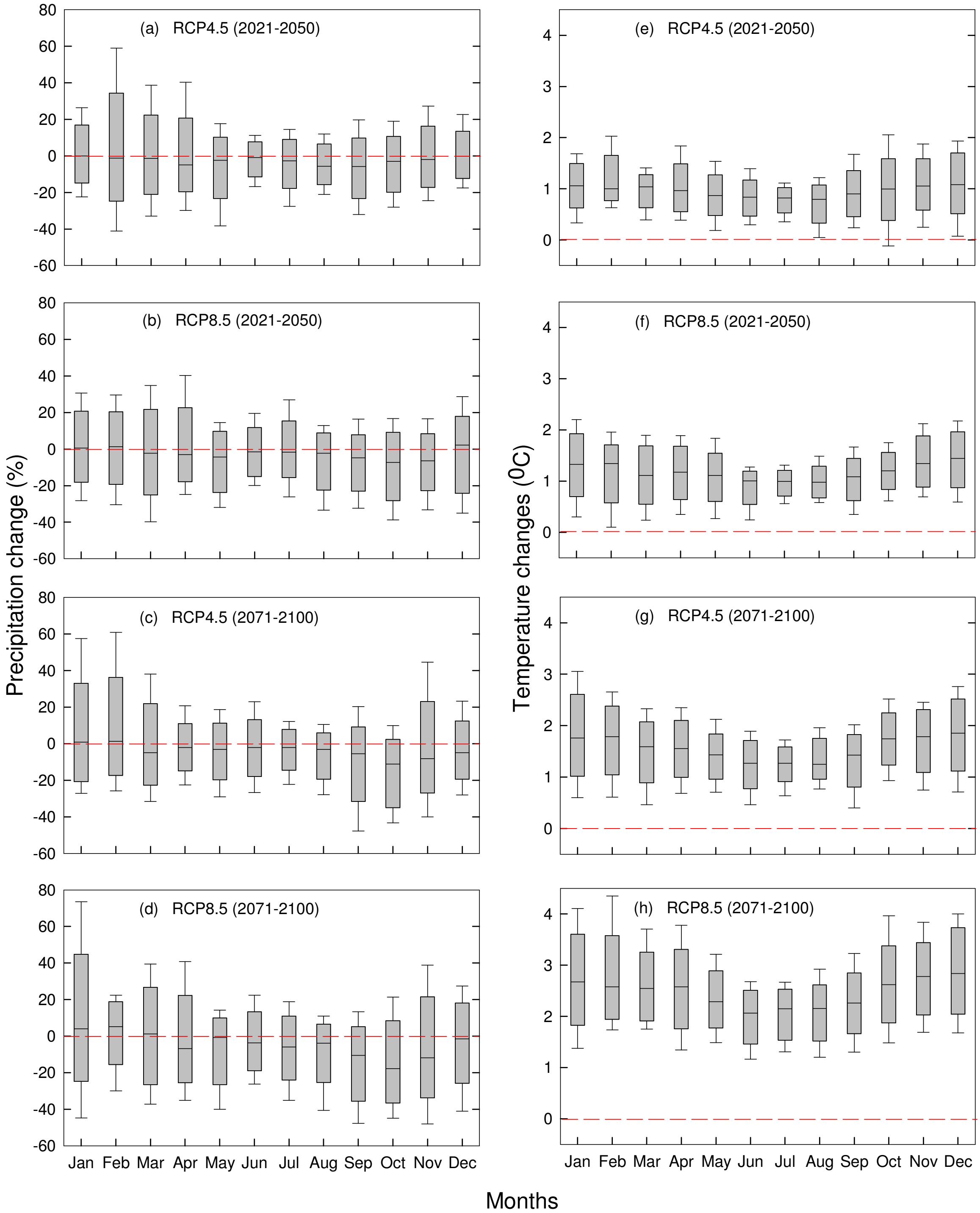

Figure 4. Box plots of percentage changes in the mean monthly precipitation (a, b, c, d) and changes in mean monthly temperatures (e, f, g, h) in the Goulburn-Broken Catchment for the future periods 2021–2050 and 2071–2100 for the 38 CMIP5 runs of climate projections. Changes are relative to the historical (1981–2010) mean monthly precipitation and temperatures. The lower boundary of the box indicates the 25th percentile, a line within the box marks the median, and the upper boundary of the box indicates the 75th percentile and the whiskers are delimited by the maximum and minimum.

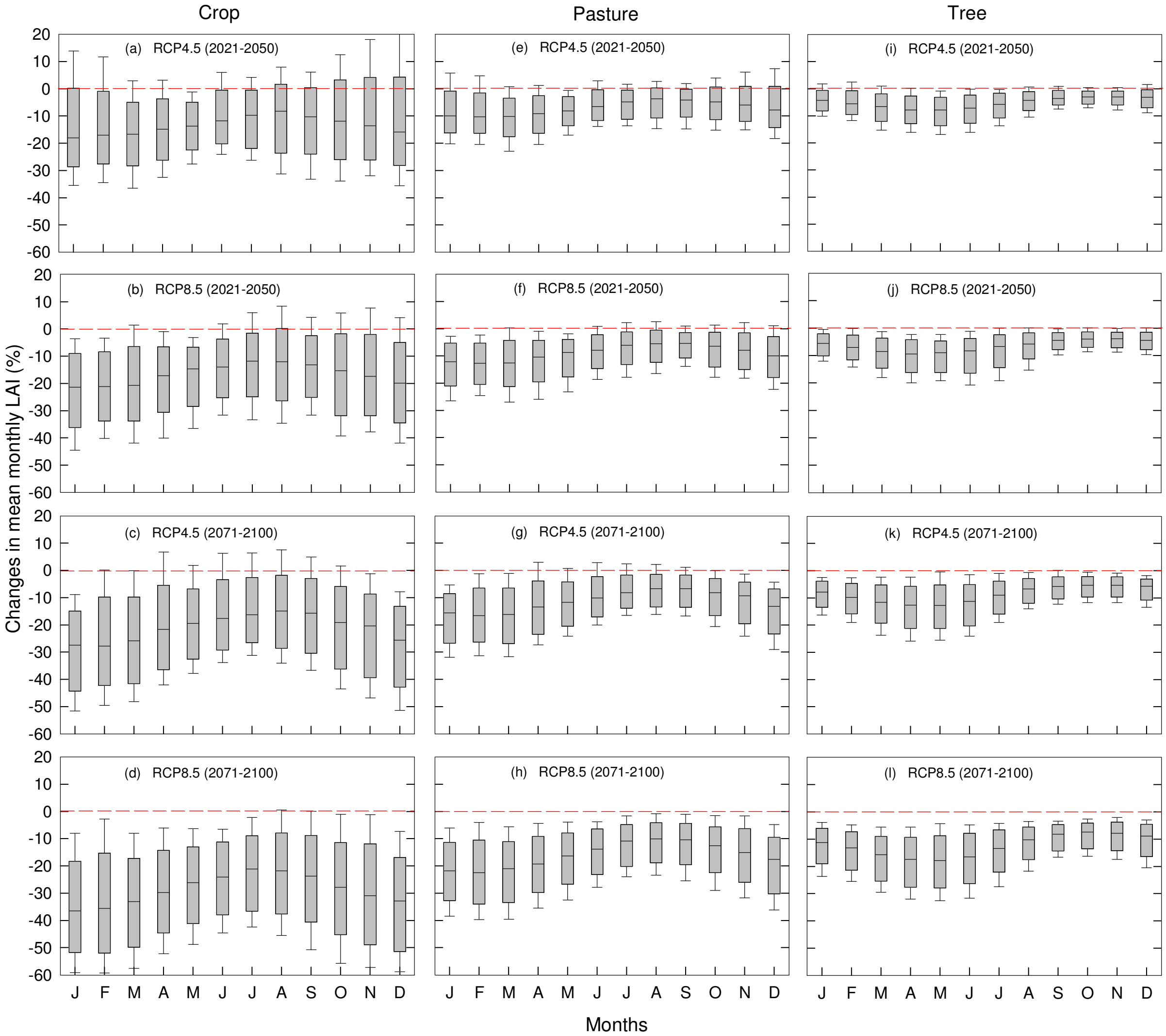

Figure 5. Box plots of changes in mean monthly LAI derived from the 38 CMIP5 runs for climate projections during 2021–2050 and 2071–2100 under RCP4.5 and RCP8.5 scenarios for crop (a, b, c, d); pasture (e, f, g, h) and tree (i, j, k, l) in the Goulburn-Broken Catchment. Changes are relative to LAI calculated using climate time series for the 1981–2010 baseline. The lower boundary of the box indicates the 25^{th} percentile, a line within the box marks the median, and the upper boundary of the box indicates the 75^{th} percentile and the whiskers are delimited by the maximum and minimum.

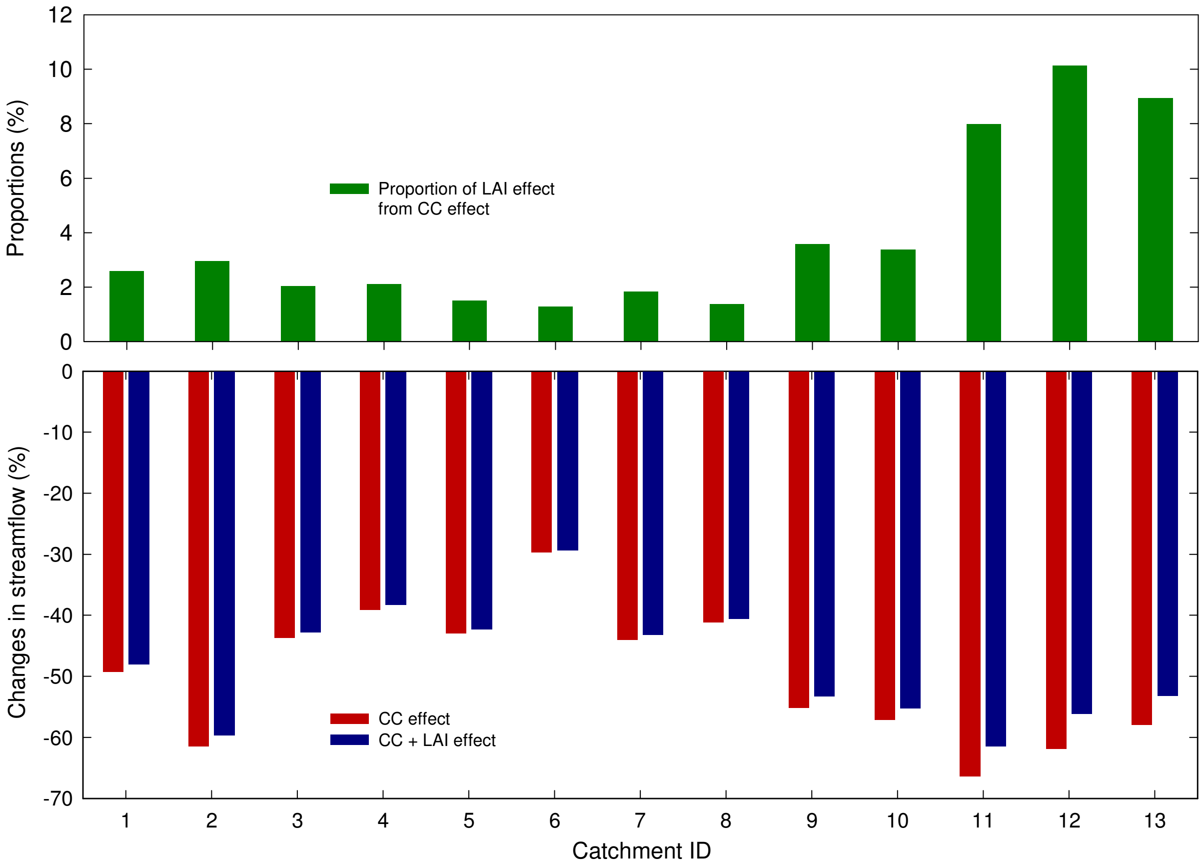

Figure 6. Impacts on catchment mean annual streamflow of the Millennium drought (1997–2009) relative to the period 1983–1995. CC effect indicates precipitation and temperature effect with unchanged LAI; CC + LAI effect indicates precipitation, temperature and LAI effect. The proportional LAI effect indicates the LAI effect as a percentage of the CC effect.

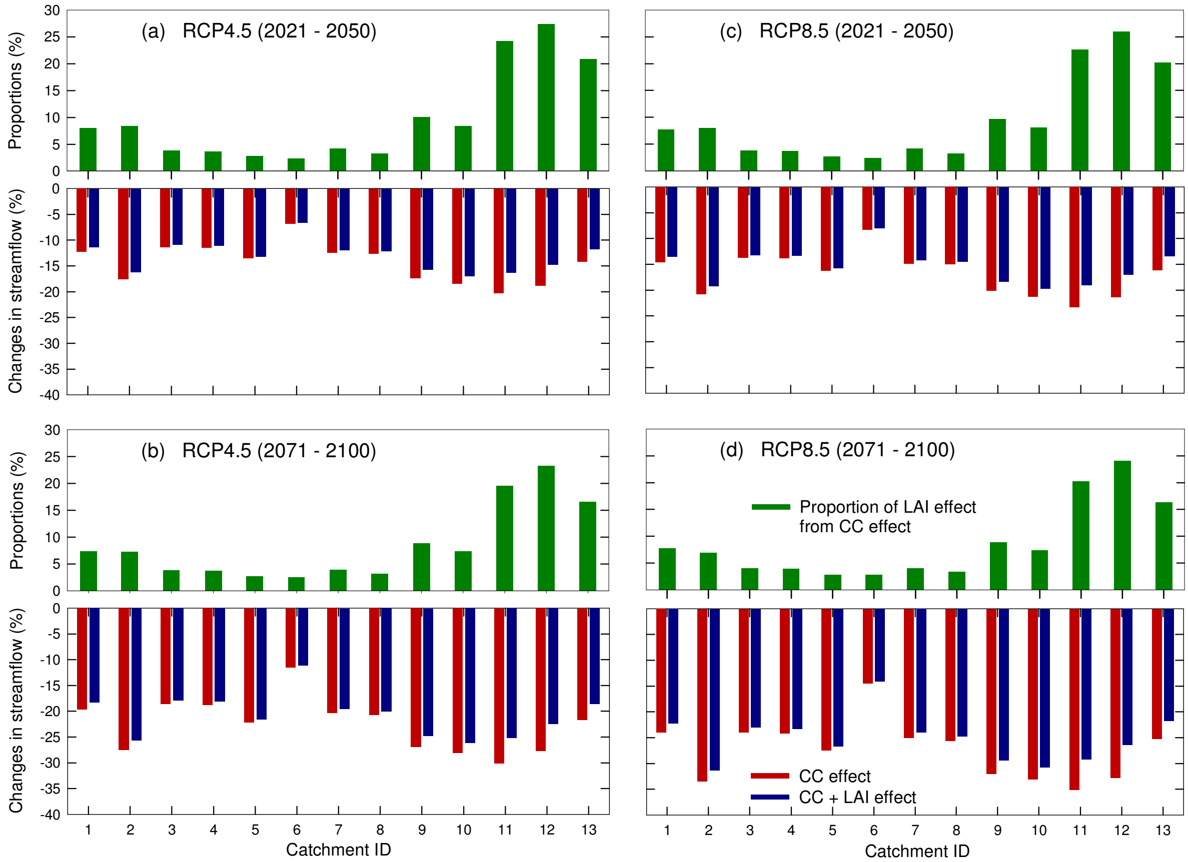

Figure 7. Impact on catchment mean annual streamflow average over the 38CMIP5 runs of projected climate change for the future periods 2021–2050 and 2071–2100 under RCP4.5 (a, b) and RCP8.5 (c, d), relative to the 1981–2010 base period. CC effect indicates precipitation and temperature effect with unchanged LAI; CC + LAI effect indicates precipitation, temperature and LAI effect. The proportional LAI effect indicates the LAI effect as a percentage of the CC effect.

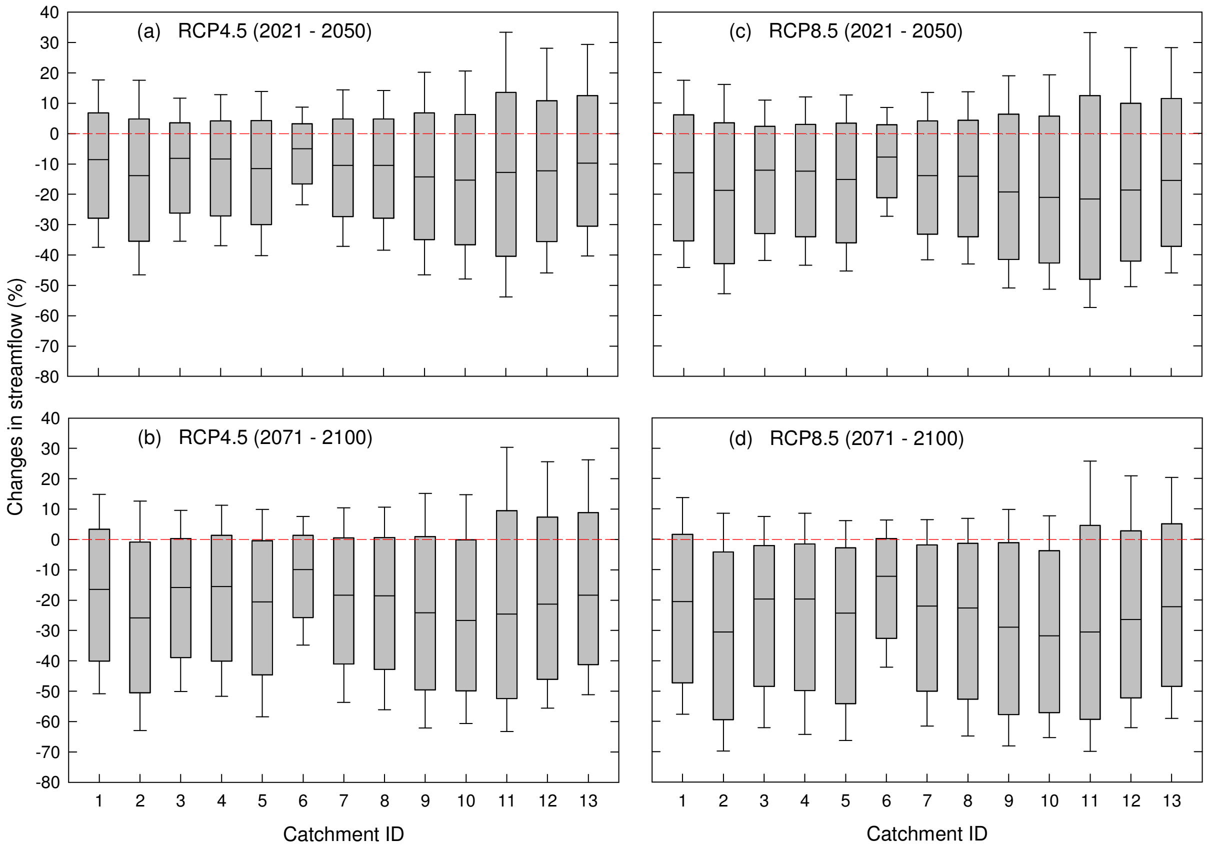

Figure 8. Box plots of the net climate change (CC + LAI) effect on mean annual runoff during (2021–2050, 2071–2100) under RCP4.5 (a, b) and RCP8.5 (c, d) emission scenarios from each of the 38 CMIP5 runs. Changes are relative to the historical (1981–2010) period. The lower boundary of the box indicates the 25th percentile, a line within the box marks the median, and the upper boundary of the box indicates the 75th percentile and the whiskers are delimited by the maximum and minimum.

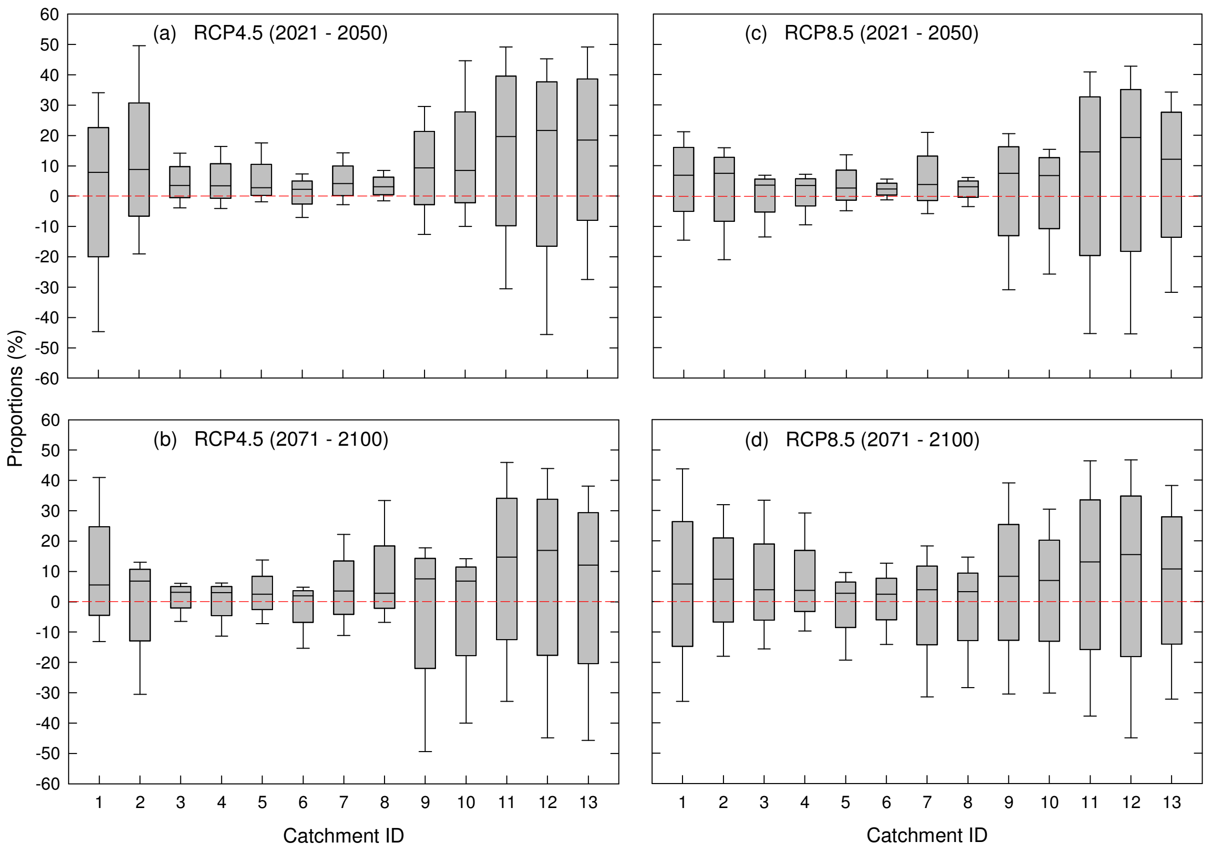

Figure 9. Box plots of contribution of LAI to the climate change effect on mean annual runoff for future (2021–2050, 2071–2100) climate forcing under RCP4.5 (a, b) and RCP8.5 (c, d) emission scenarios from each of the 38 CMIP5 runs as compared to the historical (1981–2010) period. The LAI effect is normalized by the effect of precipitation and temperature with unchanged LAI (i.e. CC effect) and expressed as a percentage. The lower boundary of the box indicates the 25th percentile, a line within the box marks the median, and the upper boundary of the box indicates the 75th percentile and the whiskers are delimited by the maximum and minimum.

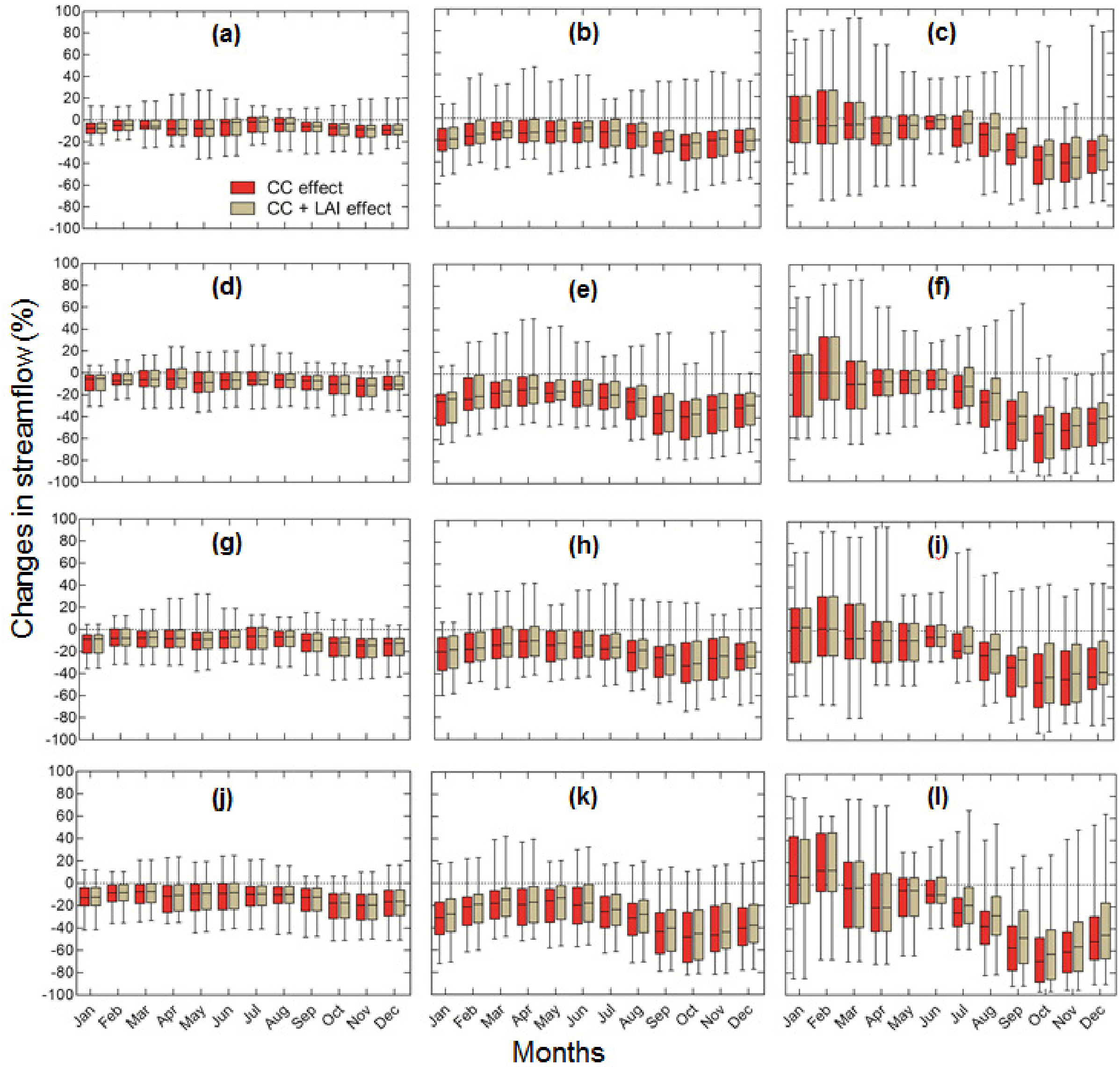

Figure 10. Box plots of impacts on mean monthly streamflow from 38 CMIP5 runs of catchment 6 (a, d, g and j), catchment 10 (b, e, h and k), and catchment 11 (c, f, i and l) of projected climate change for future periods (2021–2050) and (2071–2100) under RCP4.5 and RCP8.5 respectively relative to the 1981–2010 base period. CC effect indicates precipitation and temperature effect with unchanged LAI; CC + LAI effect indicates precipitation, temperature and LAI effect. The lower boundary of the box indicates the 25th percentile, a line within the box marks the median, and the upper boundary of the box indicates the 75th percentile and the whiskers are delimited by the maximum and minimum.