Seasonal and regional signature of the projected southern Australian rainfall reduction

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A projected drying of the extra-tropics under enhanced levels of atmospheric greenhouse gases has large implications for natural systems and water security across southern Australia. The drying is driven by well studied changes to the atmospheric circulation and is consistent across climate models, providing a strong basis from which adaptation planners can make decisions. However, the magnitude and seasonal expression of the drying is expected to vary across the region. Here we describe the spatial signature of the projected change from the new CMIP5 climate models and downscaling of those models, and review various lines of evidence about the seasonal expression.

Winter rainfall is projected to decline across much of southern Australia with the exception of Tasmania, which is projected to experience little change or a rainfall increase in association with projected increases in the strength of the westerlies. Projected winter decrease is greatest in southwest Western Australia. A 'seasonal paradox' between observations and CMIP5 model projections in the shoulder seasons is evident, with strong and consistent drying projected for spring and less drying projected for autumn, the reverse of the observed trends over the last 50 years. The models have some biases in the simulation of certain synoptic types (e.g. cutoff lows), the rainfall brought by those synoptic types, and the mechanism of rainfall production. Rainfall projections based on statistical downscaling are examined in relation to some of these biases, projecting stronger future declines in some regions of southeast Australia in autumn than indicated by the host models, as well as little change to the magnitude of the projected declines in spring. Apart from Tasmania in winter, the decline of rainfall in southern Australia during the cool season remains a confident projection but the seasonal expression of change remains an ongoing research topic.

Introduction

Under the influence of increased greenhouse gas concentrations and a warming of the climate system, there is projected to be increased rainfall in the tropics and high latitudes, as well as decreases in rainfall in some midlatitude regions such as the Mediterranean, parts of southern Africa and southwest Australia (Collins et al., 2013). The direction of change in rainfall is presented with less certainty in many other regions of the world. The drying of southern Australia is highly consistent across all global climate models (GCMs) included in both the Coupled Climate Model Inter-comparison Project phase 3 (CMIP3) (Meehl et al., 2007) and phase 5 (CMIP5) (Taylor et al., 2012). (See, for example Figure SPM.7 of IPCC (2007) and Figure 3 of Thematic Focus Element 1 (TFE.1) of the Technical Summary of IPCC (Stocker et al., 2013)). The projected decrease in rainfall in southern Australia is also given with relatively higher confidence than other regions in IPCC Assessment Reports because it has a link to plausible changes in climate phenomena, including an intensification of the local sub-tropical ridge (Timbal and

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Drosdowsky, 2013) and a positive trend in the Southern Annular Mode (SAM; IPCC, 2013). For these reasons, this projection of reduced rainfall may be viewed with higher confidence for climate change impacts and adaptation research and planning activities. However, before using this projection it is useful to assess the magnitude, spatial extent and seasonal expression of the projected rainfall reduction, as well as critically evaluate the degree of confidence in the projection based on multiple lines of evidence.

Several factors affect the confidence in climate projections at regional and seasonal scales. Confidence can be lowered by the presence of biases in the models' simulation of processes relevant to producing rainfall, from global to regional scale. Confidence is also lowered if models don't reproduce past trends in observations that are due to known anthropogenic effects (rather than natural variability). Greater spatial detail and more plausible projections may be possible from dynamical downscaling (running a numerical model at higher resolution over the area of interest) and statistical downscaling (running a statistical model of local scale variables from larger-scale predictors).

There are a variety of mechanisms that play a role in southern Australian rainfall variability and change, and the range of influences varies in different sub-regions of southern Australia (Risbey et al., 2009b). The simulation of these processes with fidelity is essential for reliable projections. The most relevant feature of the atmospheric circulation to southern Australian rainfall is the westerly storm tracks, and features that influence these such as the phase and strength of the SAM (Hendon et al., 2007) and the incidence of atmospheric blocking (Pook et al., 2013). However, along with the influence of the westerly circulation there are also teleconnections between southern Australian rainfall and remote drivers such as the Indian Ocean Dipole (IOD: Ashok et al., 2003; Cai et al., 2011) and the El Niño Southern Oscillation (ENSO: McBride and Nicholls, 1983) in certain regions and seasons. Rainfall in southern Australia has high inter-annual variability, and has experienced a decline in autumn and early winter in recent decades. In the southeast, the features associated with the recent Millennium Drought are described by van Dijk et al. (2013), while Hope and Ganter (2010) describe some of the atmospheric changes associated with the recent further declines in the southwest.

Rainfall across southern Australia derives from a number of different weather systems that, in turn, respond to the various large-scale circulation features described above (Pook et al., 2014). Frontal systems are very important for rainfall in southern Australia (Berry et al., 2011; Simmonds et al., 2012) particularly in the southeast in autumn (Catto et al., 2012) and the southwest in winter, where they have been found to be declining in number (Hope et al., 2014). Fronts in an example GCM, ACCESS1.3, tend to be well represented in their frequency and the proportion of precipitation associated with them (Catto et al., 2013), although the intensity of that precipitation is underestimated. Frontal systems tend to intensify via a confluence of subtropical and polar jets, and thus the observed and projected large-scale meridional shifts in pressure and the polar jet align with a reduction in the number of fronts impacting upon southern Australia (Catto et al., 2014; Hope, 2006).

Other large-scale circulation features in the Australia region include blocking, the splitting of the subtropical jet and the long wave pattern. Atmospheric blocking to the east of Australia is associated with reduced westerly wind speeds and reduced rainfall over western Tasmania, but is also closely related to cutoff lows, which occur right across southern Australia (Reboita et al., 2010). Cutoff systems intensify in Australia's southeast in association with local increases in baroclinicity and the subtropical jet. They are an important source of rainfall for many regions (Pook et al., 2013; Risbey et al., 2009a). For many parts of southeast Australia, rainfall variability and trends are determined more by the variation in rain from cutoff low systems than from frontal systems (Risbey et al., 2013). The Millennium Drought in southeast Australia was at least partly associated with a reduction in blocking and cutoff rainfall (Risbey et al., 2013). In southwest Australia the recent reductions in rainfall are more strongly driven by rainfall from fronts than rainfall from cutoff lows, but cutoff lows still play a role there (Pook et al., 2012). The representation of all these features in models has an influence on confidence.

Regarding past long-term trends, if the models simulate trends that are similar to observed, this adds confidence in the projections. If not, then natural variability may dominate over forced responses or there may be some limitations in the models' ability to simulate southern Australian rainfall accurately. There has been a significant decrease in autumn rainfall, of the order 10-20%, observed in much of southeast Australia in recent decades, but relatively small changes or an increase in spring rainfall (CSIRO, 2012). Similarly, there has been an observed drying in May to July in southwest Australia, but not in spring (Hope et al., 2006). Previous model projections have shown a greater rainfall decline in the shoulder season of spring rather than autumn, which is in direct contrast to recent trends and has been named the 'seasonal paradox' (Timbal, 2010). Timbal (2010) determined that the observed autumn decline in recent decades in the southeast is partly due to the high inter-annual variability of rainfall, with summer-like weather systems contributing to high rainfall totals in the autumn of some years but not others. However, even taking this into account, there is still a significant decrease in autumn rainfall.

GCMs can provide a good representation of the large-scale general circulation of the atmosphere, but have a spatial resolution that is coarse compared to some regional climatic features. For example, they currently do not have sufficient resolution to adequately represent the scales or intensity of the rainfall events associated with cut-off lows (Dowdy et al., 2013; Grose et al., 2012). Downscaling can potentially provide more spatial detail leading to more plausible projections by (a) incorporating known associations between large-scale drivers and local rainfall and (b) better representing the effects of topography (e.g. mountains, valleys and coast lines) (Feser et al., 2011; Maraun et al., 2010). However, down-

Table 1. CMIP5 models used in this study, and those used for downscaling using BOM-SDM and CCAM.

	Model name	*BOM-SDM*	*CCAM*
1	ACCESS1.0	X	X
2	ACCESS1.3	X	
3	BCC-CSM1.1		
4	BCC-CSM1.1(m)	X	
5	BNU-ESM	X	
6	CanESM2	X	
7	CCSM4	X	X
8	CESM1(BGC)		
9	CESM1(CAM5)		
10	CESM1-FASTCHEM		
11	CESM1-WACCM		
12	CMCC-CESM		
13	CMCC-CM		
14	CMCC-CMS	X	
15	CNRM-CM5	X	X
16	CSIRO-Mk3.6.0	X	
17	EC-EARTH		
18	FGOALS-g2		
19	FIO-ESM		
20	GFDL-CM3		X
21	GFDL-ESM2G	X	
22	GFDL-ESM2M	X	
23	GISS-E2-H		
24	GISS-E2-H-CC		
25	GISS-E2-R		
26	GISS−E2−R−CC		
27	HacCM3		
28	HadGEM2-AO		
29	HadGEM2-CC	X	
30	HadGEM2-ES		
31	INM-CM4		
32	IPSL-CM5A-LR	X	
33	IPSL-CM5A-MR	X	
34	IPSL-CM5B-LR	X	
35	MIROC5	X	
36	MIROC−ESM	X	
37	MIROC−ESM−CHEM	X	
38	MPI-ESM-LR	X	X
39	MPI−ESM−MR	X	
40	MRI-CGCM3	X	
41	NorESM1-M	X	X
42	NorESM1-ME		

scaling has some limitations: the downscaling output described here was run only for a subset of models, each downscaling method introduces new uncertainties and downscaling has a limited capacity to modify the large-scale circulation.

As part of the 'Projections for Natural Resource Management' project (CSIRO and Bureau of Meteorology, 2015) the southern Australian region was divided into seven sub-clusters, providing the opportunity for a more detailed analysis of the temporal and regional variation of the climate change signal in rainfall. This study aims to describe the regional and seasonal detail of projected rainfall changes across southern Australia from the set of CMIP5 models and downscaling, and assess the confidence in the projections based on multiple lines of evidence.

Data and methods

Changes to rainfall, mean sea level pressure (MSLP), winds and relative humidity are examined in reanalyses, observations and climate models from CMIP5. Rainfall data from the Australian Water Availability Project (AWAP) gridded climate dataset (Jones et al., 2009) and MSLP and humidity from National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 data (Kalnay et al., 1996) are used to evaluate model simulations of the current climate. Trends in MSLP from the National Ocean and Atmospheric Administration and Cooperative Institute for Research in Environmental Science (NOAA-CIRES) 20th Century Reanalysis (Compo et al., 2011) were also considered to give an indication of the observed uncertainty in these trends. For the same reason, relative humidity data from HadCRUH were also considered (Willett et al., 2008).

Modelled outputs are drawn from Run 1 of up to 42 CMIP5 models (Table 1) using the historical simulations and those forced using the Representative Concentration Pathways (RCPs: van Vuuren et al., 2011) for the 21st Century, with a particular focus on RCP8.5. This RCP represents the highest forcing scenario, with ongoing increases in greenhouse gases through to 2100. Not all models were available for each analysis, and the number of models used for each is noted in the results.

Much analysis of these model outputs was done as part of the Projections for NRM project. Projected changes are examined as a difference over the entire 21st century, between 1986-2005 and 2080-2099. An analysis of linear trends from 1956 to 2005 in models and observations, and the downscaled results from 1970 to 2005, are also discussed. Results for the entire CMIP5 ensemble are compared to those from subsets or weightings of the ensemble based on model performance or resolution.

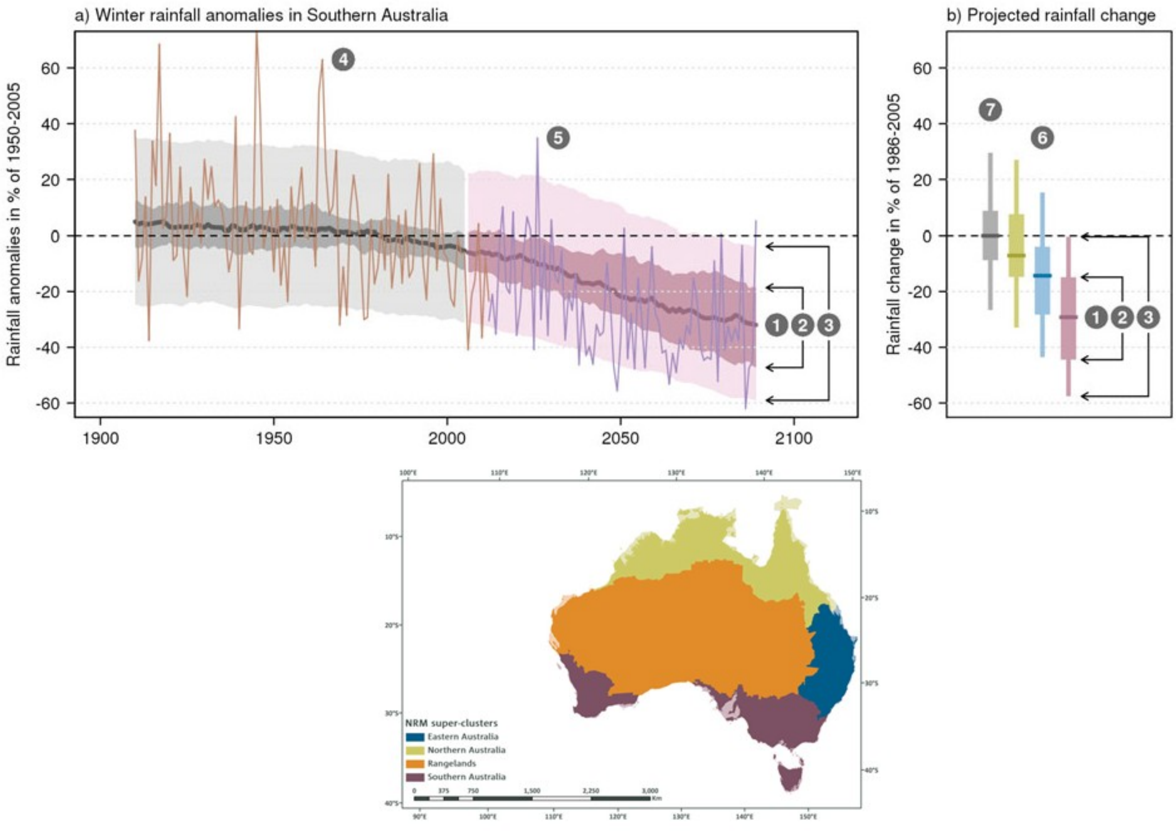
Downscaling results were generated by the Australian Bureau of Meteorology statistical downscaling model (BOM-SDM) of Timbal and McAvaney (2001). This yields data on a 0.05 °Lat/Lon grid based on the output from 22 CMIP5 models (Table 1), although only the median response of five models that are common with the dynamical downscaling are shown. The dynamical downscaling model is the Cubic Conformal Atmospheric Model (CCAM) of McGregor (2005) produced on a global uniform 0.5 °Lat/Lon grid using 6 CMIP5 models as input (Table 1). Detailed descriptions of these downscaling methods can be found in CSIRO and Bureau of Meteorology (2015).

Results

Rainfall projections from CMIP5

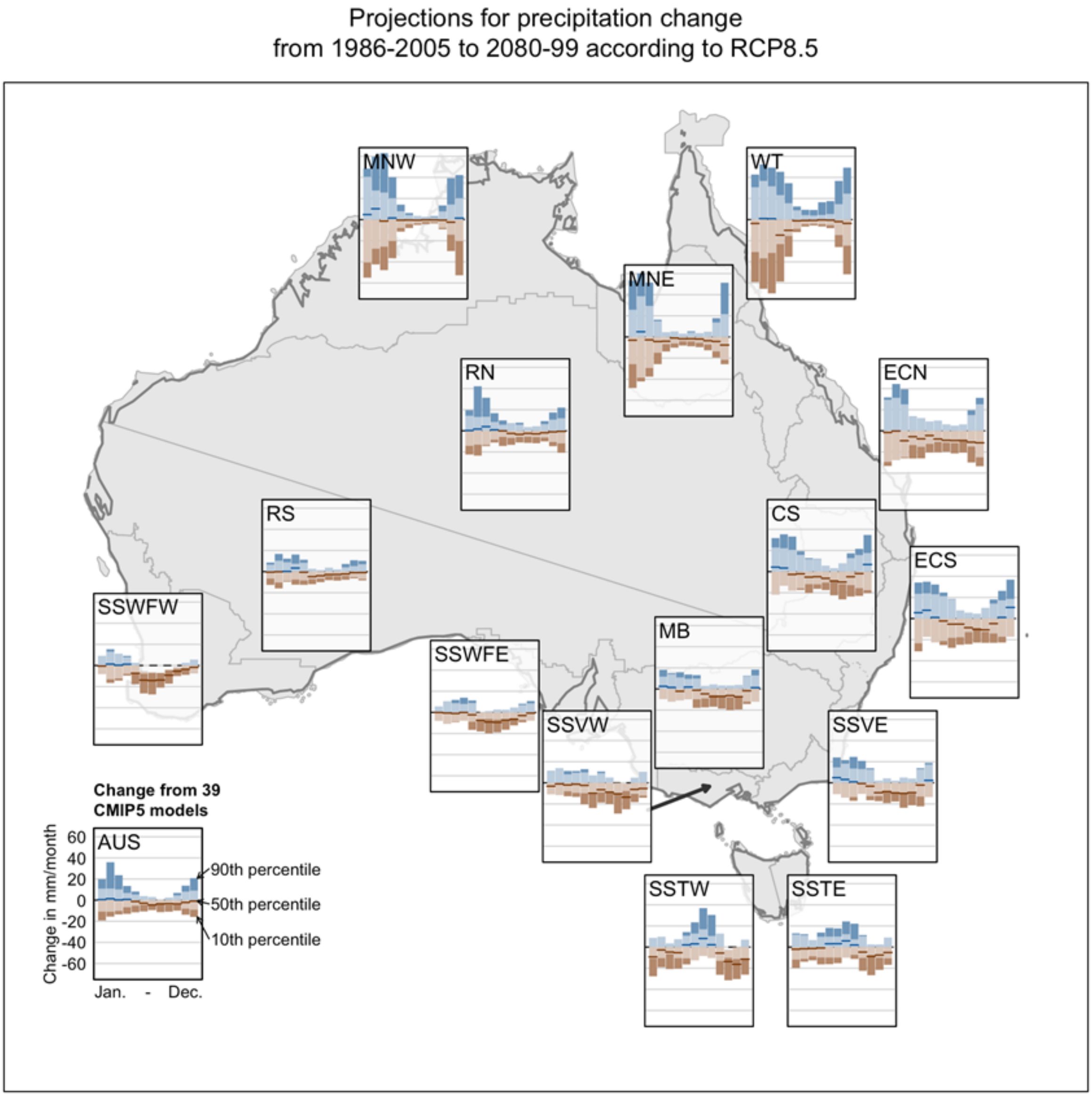
The CMIP5 models are very consistent in projecting an ongoing, strong rainfall decline in winter across southern Australia as a whole (Figure 1a). There is large inter-annual variability in observed rainfall of recent decades and also in an example model for projections of the 21st Century, but a similar negative trend in both the model ensemble mean and observations is evident in the recent past (Figure 1a). The magnitude of the projected change by the end of the 21st century is approximately proportional to the greenhouse forcing in each RCP and the decrease under the higher RCPs is clearly greater than that expected from natural variability (Figure 1b), However, using this large region and these seasonal boundaries obscures some important regional and seasonal differences that may have significant impacts on adaptation planning. Rainfall projections for the 15 NRM sub-clusters for each month of the year (Figures 2 and 3) reveal some interesting patterns.

Figure 1 Time series of observed and simulated rainfall change (a) and projected change according to different scenarios (b) for winter (JJA) rainfall in Southern Australia (see region shaded purple in inset map). The range of model results is summarised using the median (1) and 10th to 90th percentile range of the projected change (2) in all available CMIP5 simulations. The change in mean climate is shown as 20-year moving averages. Dark shading (2) indicates the 10th to 90th percentile range for 20-year averages, whilst light shading (3) indicates change in the 10th to 90th percentile for individual years. The AWAP time series of each year (4) is overlaid to enable comparison between observed variability and simulated model spread, while the variability from one climate model (ACCESS1.0) is shown for the future period (5).The reference period in (a) is 1950-2005, to avoid 'pinching' of the model range around a narrow recent time window. The bar graphs (b) are the difference between two periods: 2080-2099 minus 1986-2005 for in green: RCP2.6, blue: RCP4.5, purple: RCP8.5 (6) and grey: natural variability only (7). (Source: NRM Technical Report: CSIRO and Bureau of Meteorology, 2015)



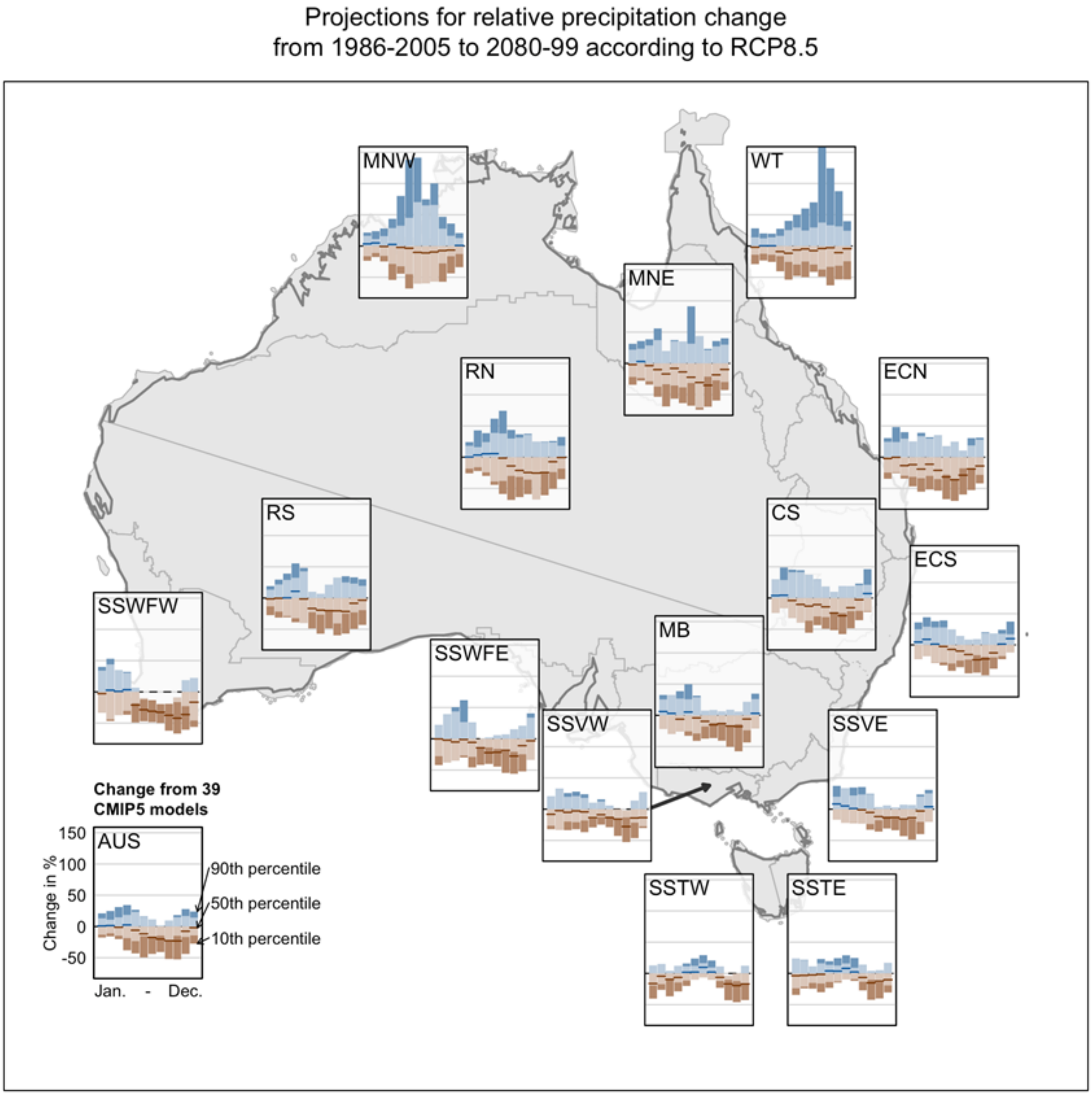
Winter rainfall is projected to decrease by many models in many sub-clusters of southern Australia and some in eastern Australia, in contrast to regions further north (Figure 2 and 3). Model agreement varies by sub-cluster, and the strongest agreement for decrease is found in southwest Western Australia (SSWFW), both in absolute terms (Figure 2) and as a relative change (Figure 3). The models tend to project little change or an increase in rainfall in both Southern Slopes Tasmania West (SSTW) and Southern Slopes Tasmania East (SSTE) from May to August, with a similar pattern in eastern and western Tasmania. There is little distinction between the sub-clusters of southern Victoria and Tasmania as this spatial scale is similar to that of typical GCM grid cells (200 to 300 km). A decline in winter rainfall is a clear feature of CMIP5 projections (as was the case with previous generations of models (IPCC, 2007), but there are differences in the magnitude and model agreement in different regions.

Figure 2 Monthly mean rainfall change for each sub-cluster for 2080-2099 relative to the 1986-2005 in absolute units (mm/month) from 39 CMIP5 models. Bars show the 10th to 90th percentile of the model range, with dark colours showing changes greater than expected through natural variability and the model median shown as a dark line. The Australia-wide average (AUS) is shown in the lower left panel. Sub-cluster acronyms: SSWFW: Southern and South Western Flatlands West, SSWFE: Southern and South Western Flat-lands East, SSVW: Southern Slopes Victoria West, SSVE: Southern Slopes Victoria East, SSTW: Southern Slopes Tasmania West, SSTE: Southern Slopes Tasmania East, MB: Murray-Darling Basin. Sub-clusters to the north are Rangelands South and North(RS, RN), East Coast North and South (ECN, ECS), Monsoonal North East and West (MNE, MNW) and Wet Tropics (WT).



There are also differences in the projections for autumn and spring (often termed the ‘shoulder’ seasons). From west to east along southern mainland Australia (SSWFW across to SSVE), there is a progressive shift in the seasonal expression of the rainfall decline (Figure 2) with the decrease more evident in spring towards the east. Tasmania is also seen to have a greater projected spring decrease than in autumn. In terms of percentage changes (Figure 3), there is an emphasis on spring across all of southern Australia. This is because of the different rainfall amounts in each season in different regions of southern Australia, for example in SSWFW, spring rainfall totals are smaller than those in winter, leading to a relatively greater percentage change. There is no clear and consistent rainfall decline in autumn in any sub-cluster.

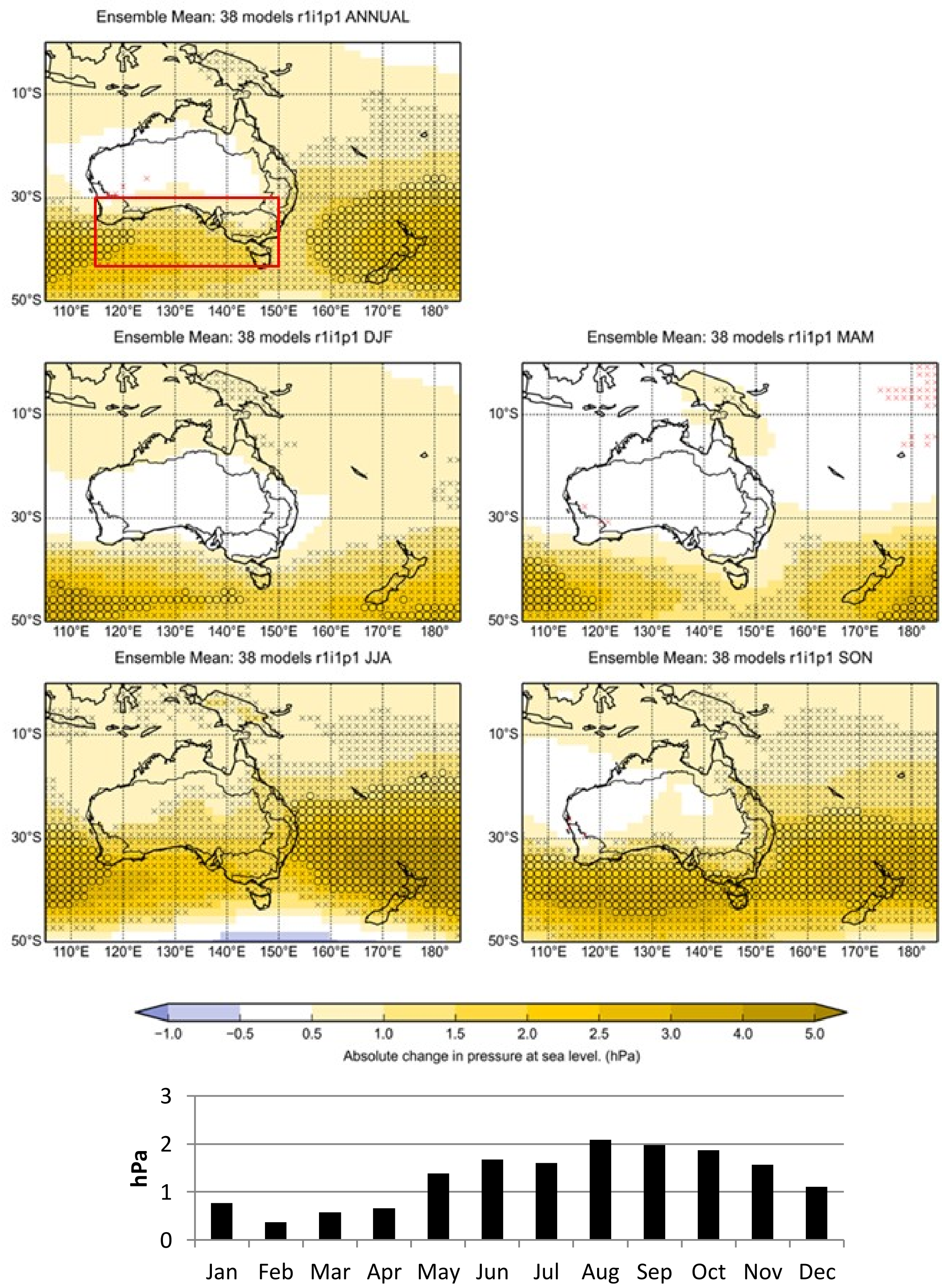
Figure 3 As Figure 2, but change is expressed as a percentage of 1986-2005 rainfall.



Projection of pressure, winds and zonally consistent features

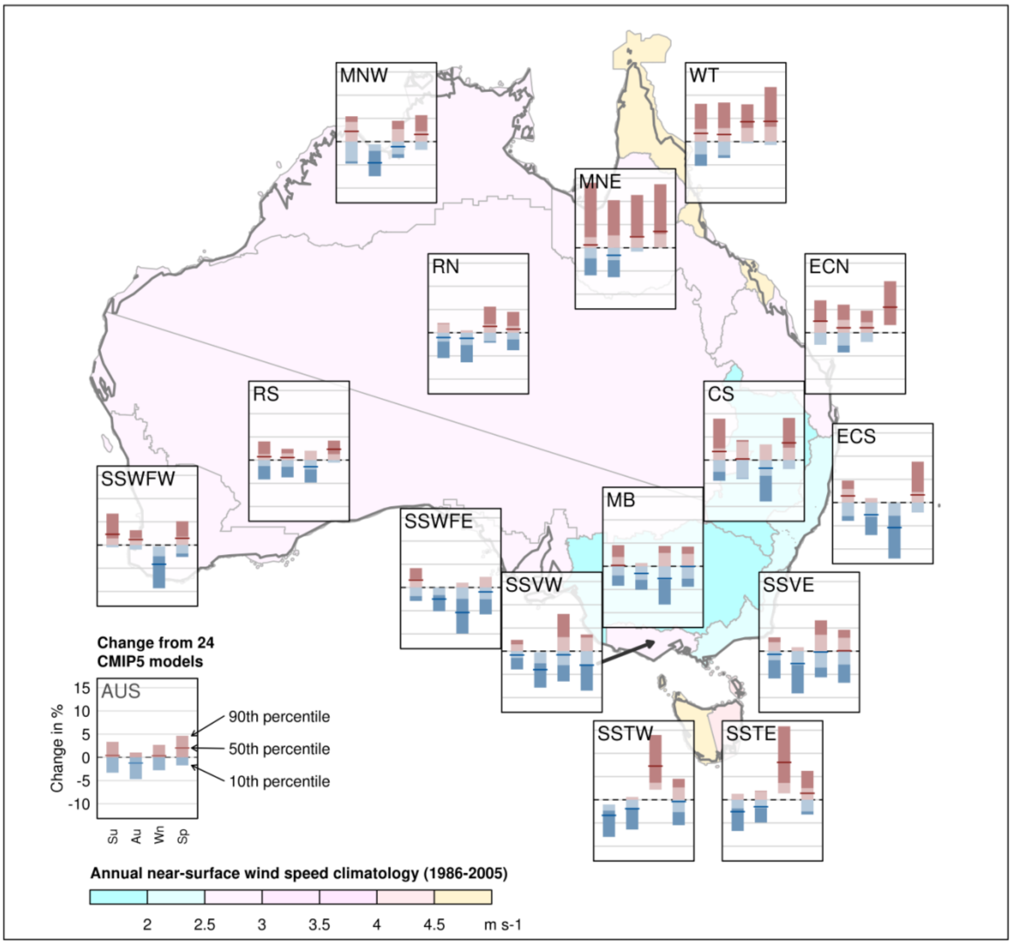
There is a strong seasonal cycle in MSLP and mean winds over southern Australia. The band of high MSLP known as the subtropical ridge (STR) ranges in latitude from about 39 °S in summer to about 30 °S in winter and marks the boundary of mean westerly and easterly winds. There is also a seasonal cycle in the dominant westerly circulation and storm track, being furthest north over southern Australia in winter and furthest south in summer. These large-scale features influence both the west and the east of southern Australia (Hope et al., 2010), and their latitudinal variation is explored in this section.

Figure 4 Ensemble mean changes in mean sea level pressure (in hPa) under RCP8.5 (period 2080-99 minus period 1986-2005) for annual (top left) and all 4 seasons. The black stippling denotes model agreement on changes greater than 0.5 hPa (increases or decreases) at the level of >90% (black circles) or >67% (black crosses) of models. The equivalent model agreement on changes less than 0.5 hPa are stippled in red (source: CSIRO and Bureau of Meteorology, 2015). The bar graph shows the month-by-month difference in MSLP between 2080-2099 and 1986-2005 averaged over the region 115 to 150 °E and 30 to 45 °S.



In general, the STR is projected to strengthen over the course of this century in each month of the year, and move poleward in many months of the year (see Grose et al. (2015)). This is reflected in the projected changes to MSLP in 38 models examined here (Figure 4), with a belt of MSLP increase to the south of the current location of the STR in all seasons in the model mean (the STR is currently located at ~30 °S in August through to ~39 °S in February). There is high model agreement for an increase in MSLP over Tasmania in summer and spring and over much of southern Australia in winter and spring (Figure 4). Little change is projected over southern Australia in autumn. The MSLP for the southern region (115-150 °E and 30-45 °S) is projected to increase in all months, with the largest increases between May to November (ensemble mean shown in the bar graph in Figure 4). Concurrently, the large-scale circulation is projected to shift, with the mid-latitude westerlies projected to move further south in winter and spring, implying a change in the incidence of rain-bearing weather systems that impact upon southern Australia. This is shown by changes to mean near-surface wind speed (Figure 5), with projected reductions in westerly wind speeds in southwest and southeast Australia in winter. The westerly circulation is projected to strengthen to the south of the STR in winter, implying increased rainfall in winter in Tasmania (Figure 5). Most models also project a reduction in wind speed across parts of southeast Australia in autumn and spring. The median reduction in wind speed in autumn is greater than in spring across the clusters of southeast Australia. In many clusters all models project a reduction in autumn wind speed (SSWFE, SSVW). The lack of a reduction in wind speed in spring in southwest Western Australia does not align well with the rainfall reductions projected there, and suggests another process at work.

Figure 5 As for Figure 2, but showing 10-m westerly wind speed change (percent), and showing 3-month seasons. (Source: CSIRO and Bureau of Meteorology, 2015).



In summary, the projected large-scale changes for winter are consistent with both past changes and observed and projected rainfall declines. However, the models tend to underestimate the observed changes and, by implication, may underestimate future changes. Projected MSLP changes are consistent with the seasonal expression of projected rainfall change; increases in spring are consistent with projected rainfall declines, with little change in autumn.

Blocking and other longitudinally-varying features

Large-scale circulation features in the Australian region that vary by longitude include atmospheric blocking, the splitting of the subtropical jet and the long wave pattern. An evaluation of the simulation of these features by models, and the physical plausibility of their projections, can also affect the confidence in CMIP5 projections.

As in CMIP3, CMIP5 models have been found to significantly underestimate blocking in the northern hemisphere (Dunn-Sigouin and Son, 2013; Masato et al., 2013). In the Australian region, Ummenhofer et al. (2013) found that, while an atmospheric GCM (with no coupled ocean) could reproduce the preferred location and seasonal cycle of blocking, it also underestimated the magnitude, especially in late winter and spring. Grose et al. (2012) showed that dynamical downscaling of CMIP3 models only partly improved the representation. Many CMIP5 models also show a connection between rainfall and blocking over southeast Australia that is too weak, with almost half of the models showing a correlation approaching that of observations but many models showing very low correlation (CSIRO and Bureau of Meteorology, 2015).

In the northern hemisphere, blocking is projected to decrease in frequency and possibly undergo shifts in its location (Masato et al., 2013). In the Australian region, Grose et al. (2012) found that while blocking is underestimated in the current climate, a decrease in blocking is projected for the period from June to November. In addition, a decrease in the frequency but an increase in intensity of cutoff lows was also noted. Autumn and spring rainfall in western Tasmania is negatively correlated with blocking while much of southeast Australia shows a positive correlation to blocking through its association with cutoff lows (Risbey et al., 2009b). As a consequence, the projections imply a reduction in cutoff rainfall in winter and spring, but an increase in heavy rainfalls. However, the underestimation of blocking frequency and the poor connection of blocking to rainfall in the current climate lowers the confidence in the associated rainfall projections.

Comparison of model and observed trends in the recent past

We compare the model simulations to recent observed rainfall changes in order to understand if there is already a signal of a changing climate, and if so, how the models' interpretation of this compares with what has been observed.

As in previous generations of models, the CMIP5 models tend to simulate a reduction in winter and spring rainfall across southern Australia from 1956 to 2005 but little change in autumn (Figure 6). This distinction is highlighted with averages across mainland southern Australia (bar graph in Figure 6). Upward trends are significant in the model mean in summer, right through to March, which has an opposite, declining trend in the observations. The strong observed declines in April and May are not simulated by most models. The observed trends in September are again at odds with the multi-model mean direction of rainfall.

Trends in MSLP from 1956 to 2005 in the model mean exemplify the seasonal paradox, with greater increases in spring compared to autumn, contrary to observed trends (Figure 7). These circulation changes are consistent with the seasonal paradox, but do not explain the cause of it.

Another factor that influences rainfall formation in climate models is the moisture content of the air. Figure 8a shows the trends in relative humidity from NCEP/NCAR reanalyses at 850 hPa, HadCRUH and the CMIP5 multi-model mean. Data over the region 115-150 °E and 30-45 °S are included. Note that specific humidity is rising as temperatures rise, but relative humidity provides an appreciation of how saturated the air is. There are known concerns with the NCEP/NCAR humidity fields (Dessler and Davis, 2010), and a reversal of NCEP/NCAR trends with height from the surface to 850 hPa (Paltridge et al., 2009), thus the shorter record from HadCRUH is included for comparison. Over the last 50 years, NCEP/NCAR suggests that the air is drying across the region through autumn, winter and spring, with the most drying in winter. In the model mean, the simulated trend of near-surface relative humidity aligns with the direction of rainfall change shown in the bar graph in Figure 6, with small but significant declines in September and October, and an increasing trend in autumn. This disparity in autumn suggests that although MSLP and wind changes drive part of the signal, shifts in the local humidity may also be involved (although cause and effect may be difficult to disentangle in this case). The same seasonality is seen in the projections (Figure 8b), with the strongest declines in late winter and spring. The contribution from large-scale drivers compared to local humidity responses is not clear, and is beyond the scope of this study. It is also unclear what is driving the local humidity response and the level of influence from external forcings compared to natural variability. It may be that natural variability is 'masking' the changes in spring in the observed record.

Model weightings and downscaling

Climate models have known biases and limitations, and it is possible that weighting the output from one over another would improve the seasonal paradox outlined above. However, there is relatively little difference in the projected changes to southern Australian rainfall using all models compared to models weighted by their simulation of the mean climatology and recent trends using either Bayesian Model Averaging or Ensemble Regression (CSIRO and Bureau of Meteorology, 2015). This shows that there is no simple and clear basis to weight or reject models to derive more reliable rainfall projections. In particular, there is no subset or weighting scheme that gives a seasonal projection similar to recent observed trends, so weighting does not resolve or provide insights on the 'seasonal paradox' issue.

Figure 6 Observed trend in seasonal mean rainfall (mm per decade (mm/10a)) from 1956 to 2005 (a-d) and median of trends simulated by 42 CMIP5 models over the same period (e-h). Stippling in a-d denotes areas where the observed trend is significantly different from zero at the 10% level. Plus and minus symbols in e-h denote areas where less than 10 per cent of the simulated trends are as large as the observed trend. (Source: CSIRO and Bureau of Meteorology 2015). The bar graph shows the month-by-month trends from land points across southern Australia (not including Tasmania to allow the winter declines across continental southern Australia to be most evident) from AWAP and the multi-model mean of 39 models (note that the observed trend contains both the forced response and natural variability, and may thus be larger than the model mean response). Trends that are significantly different from zero at the 10% level are marked with an '*' for the model mean and '+' for the observations.

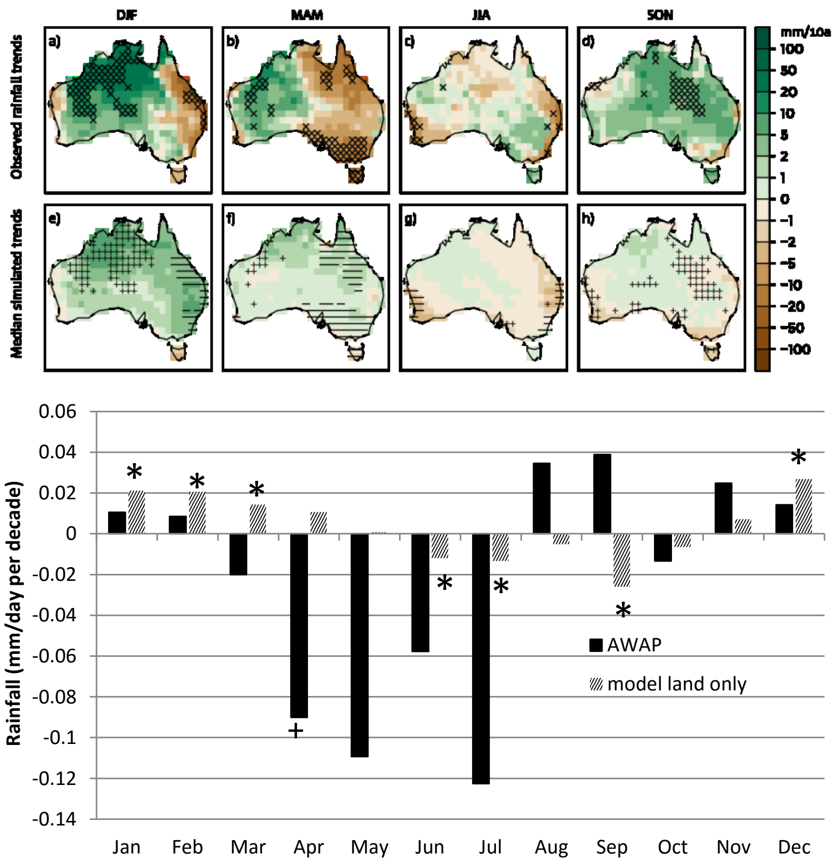


Figure 7 Month-by-month trends in MSLP over the region 115 °E to 150 °E and 30 °S to 45 °S for the years 1956 to 2005 from two reanalyses and the multi-model mean of 39 CMIP5 models. Trends that are significantly different from zero are marked with 'x' and '+' for NCEP/NCAR and 20C reanalyses respectively and '*' for the CMIP5 multi-model mean

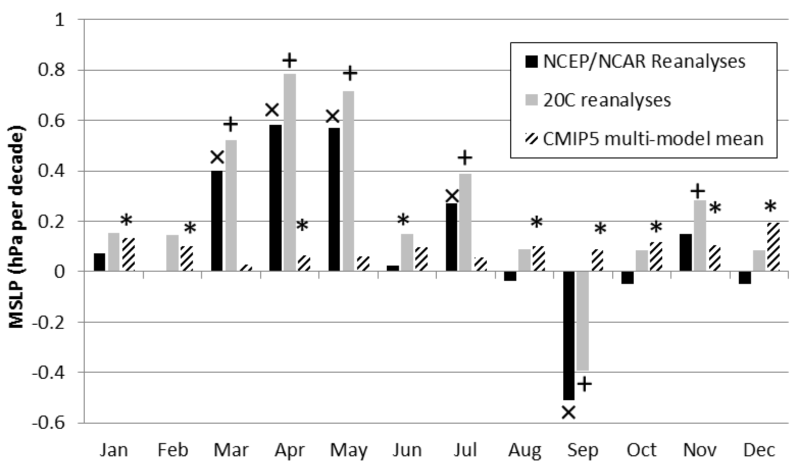
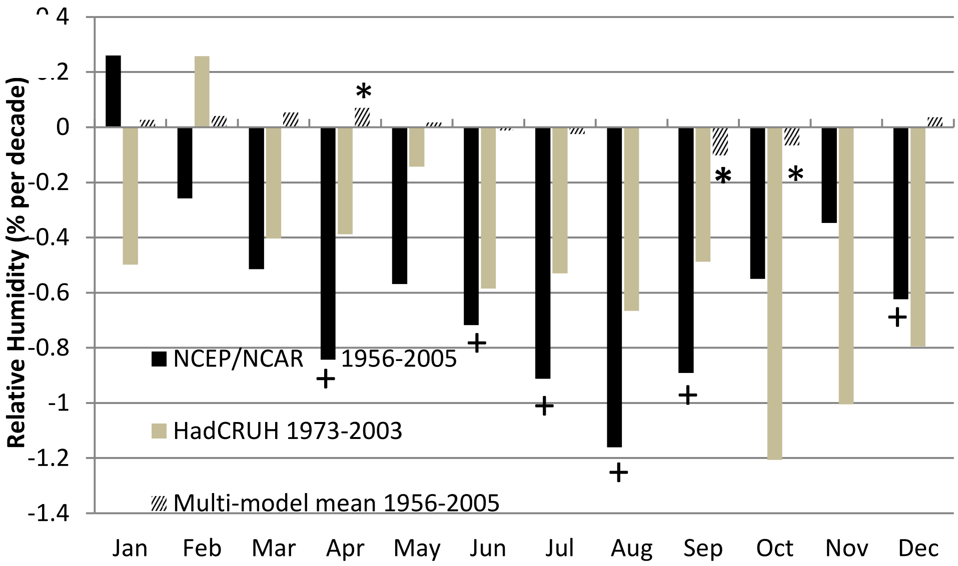


Figure 8. Month-by-month change in near surface relative humidity (RH). (a) Linear trend per decade from 1956 to 2005 in NCEP/NCAR reanalyses and multi-model mean. Trends significantly different from zero at the 10% level are marked with '+' for NCEP/NCAR and '*' for multi-model mean. The shorter trend from HadCRUH 1973-2003 is also included for comparison. (b) Change between 2080-2099 average and 1986-2005 average

a.



b.

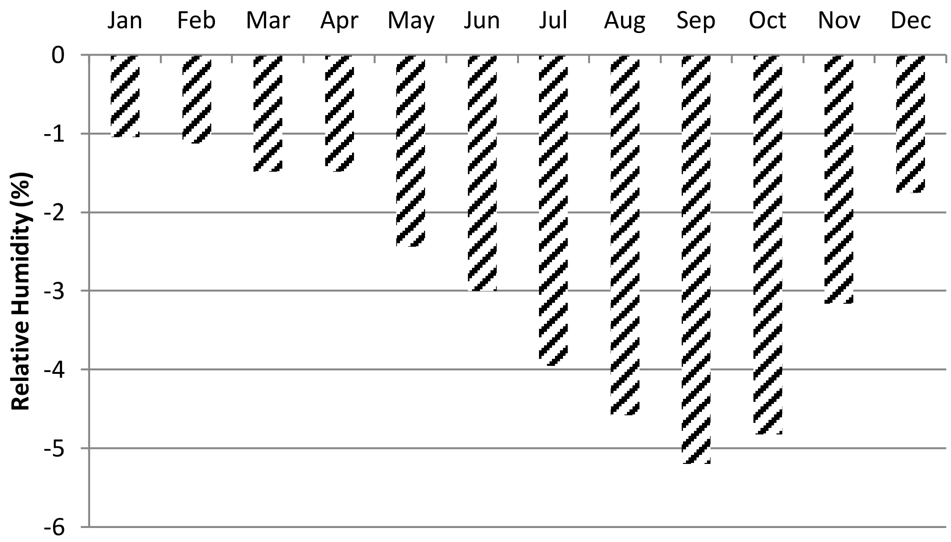
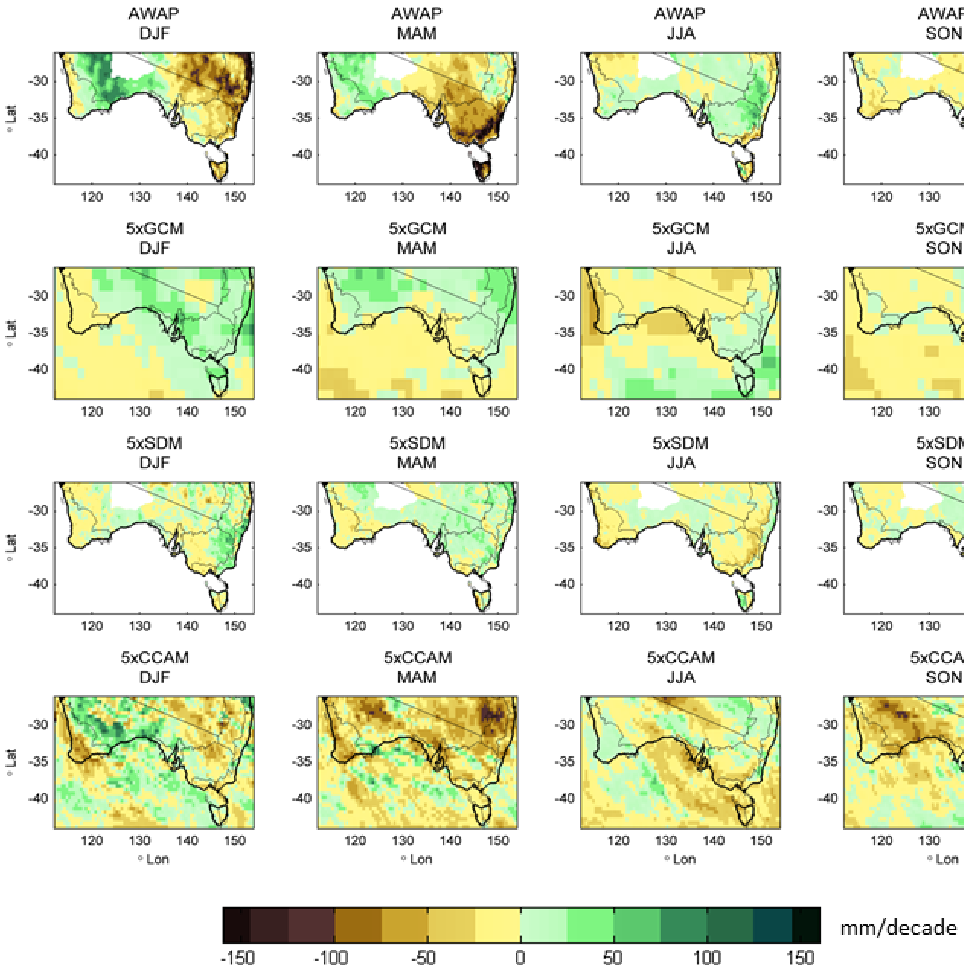


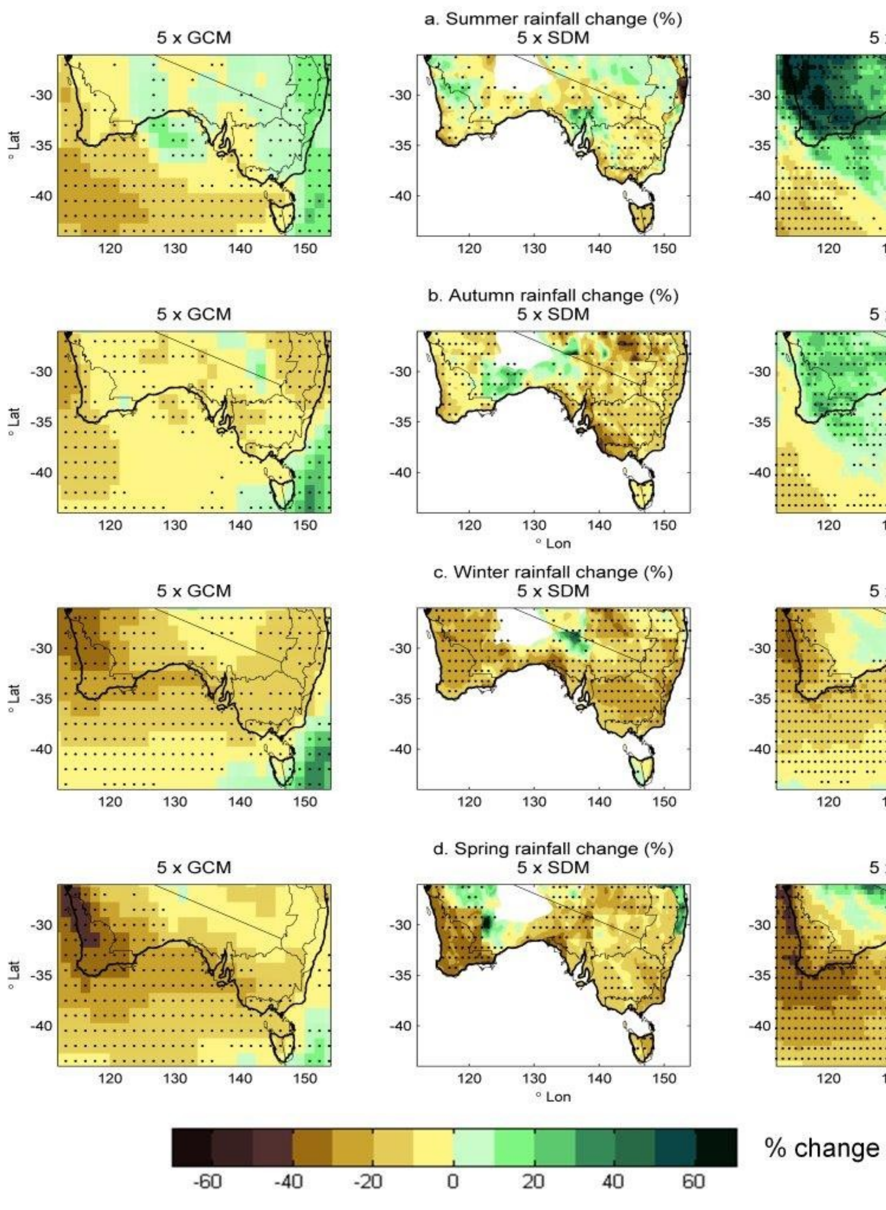
Figure 9 Rainfall trend (mm per decade) from 1970 to 2005 using AWAP data for each season (top row). Seasonal rainfall trend, 1970 to 2005, from the model mean of five CMIP5 GCMs, and the model mean from those same GCMs downscaled using BOM-SDM and CCAM downscaling methods. The white regions in BOM-SDM results indicate an area with insufficient observed data coverage to use in the model. The columns (from left to right) represent summer (DJF), autumn (MAM), winter (JJA) and spring (SON).



Downscaling provides another means by which to reduce biases arising from low resolution or parameterisation methods. Five GCMs were used as common input to both BOM-SDM and CCAM downscaling methods, and a comparison of the observed trends using the full GCM output and downscaled output by season is shown in Figure 9. CCAM outputs are available from 1970, so observed trends from AWAP and trends in each model output are shown for 1970-2005. The observed rainfall decline in southeast Australia is dramatic and spatially extensive in autumn (MAM) over this period, and it is not matched in any model output. The trends in downscaling can differ from the host GCMs; some of these trends more closely match the observed trend (e.g. east and west Tasmania in JJA in the BOM-SDM results), but others appear further from observations. However, these differences may not be significant because the short period (36 years) and small sample (5 models) mean that there is likely to be more noise. Interestingly, in southwest Australia, strong winter rainfall declines seen from 1956 have weakened and declines in spring have strengthened.

The projected rainfall change after downscaling reveals some telling differences for southern Australia and also for sub-regions of southern Australia (Figure 10). Regional detail of projected changes in the downscaling that didn't appear in the GCMs include a different sign of change in the west of Tasmania compared to the east in summer and autumn in CCAM, and in winter in BOM-SDM. This is consistent with previous downscaling, and coincides with a climatological boundary in the current climate where rainfall in the west relates very closely to westerly circulation but rainfall in eastern Tasmania has other influences (Grose et al., 2013). Another regional feature present in the BOM-SDM downscaling relates to the question of the seasonal paradox. A projected rainfall decrease that is stronger in spring than in autumn can be seen in the 5 GCM mean, which is in contrast to the recent trends. However, in the BOM-SDM results there is a strong projected decrease in autumn rainfall near the coast in parts of Murray Basin, SSVW and SSWFE, while the projected change for spring is similar to the host models (Figure 10b, 10d). This means that for these regions, the 'seasonal paradox' is reduced. The BOM-SDM adds the known statistical relationship between the large-scale predictors of fields such as MSLP, atmospheric moisture and wind to rainfall. These elements are the ingredient used by physical parameterisations within climate models to generate rainfall but in the case of the application of the BOM-SDM the relationship is built empirically using past observations and thus bypasses the model parameterisations. It therefore provides a possibility to correct some model limitations in rainfall generation. Thus, for this region of southeast Australia, the seasonal projections from BOM-SDM may not be as far from recent trends as the GCMs projections are, reducing the seasonal paradox somewhat. Given that BOM-SDM inherits the same circulation and weather systems as the GCM hosts, the cause of the difference in rainfall trend may be due to the projected reductions in autumn wind (Figure 5) or local interactions with model rainfall parameterisations that influence rainfall in autumn more than in spring. CCAM produces a greater tendency for rainfall increase across much of southern Australia in summer and autumn than the GCMs used. This may be in response to the warming of the surrounding oceans; it is not necessarily a superior projection, just a different and additional possible projection at the wetter end of the CMIP5 range of projections.

Figure 10 Projected rainfall changes (%) in southern Australia from 5 CMIP5 GCMs, and BOM-SDM and CCAM downscaling using those same five GCMs as input (see Table 1) for 1986-2005 to 2080-2099 under RCP8.5. Stippling indicates where four or five models agree on the sign of change. Note that summer is in the top row, then autumn etc. unlike Figure 9. The white regions in BOM-SDM results indicate an area with insufficient observed data coverage to use in the model.



Discussion and Synthesis

Most models project rainfall to decrease in much of the cool season across most regions of southern Australia, consistent with atmospheric circulation changes. Despite the good level of consistency amongst the models, limitations in the simulation of some important climate processes in the current climate lowers confidence in the projected change of these processes and also the associated rainfall. In addition, the 'seasonal paradox' in CMIP5 projections compared to recent observed trends is present as for previous projections.

In order to accurately represent long-term change, climate models must be able to simulate the influence from large-scale influences on climate and also the correct local rainfall processes. At the broad scale, pressure increases across southern Australia are projected, consistent with physical understanding. For example, these changes are consistent with projected increases to SAM under greenhouse gas forcing by the end of the century, with a contraction of the polar jet towards Antarctica, although increasing levels of stratospheric ozone through the course of the century might reduce trends at mid-century in summer (Arblaster et al., 2011). These changes to pressure and wind are consistent with the projected rainfall changes presented above, and conform to the general principle of expanding local STR and southerly movement of cyclones in much of the cool season.

However, changes in some MSLP indices may be underestimated. For example, CMIP5 models produce a trend in the intensity of the STR and the STR-rainfall connection that are both too weak, and this suggests that the rainfall projection associated with changes in the STR may be underestimated (Grose et al., 2015).

To have confidence in models at the local scale, they need to simulate the appropriate rainfall amount from such systems as fronts and cutoff lows. They also should simulate the relative rainfall contributions from convective and stratiform (e.g. fronts) processes. The separation between the two processes is largely dependent on the model and which parameterisations are used for both types of rainfall. It is well established that many climate models do not do this well, forming too much 'drizzle' by simply precipitating from the column when humidity is high (Dai, 2006). Although many CMIP5 models have higher resolution than CMIP3, the resolution is still too large to allow a direct calculation of rainfall processes and these must be parameterised. This, among other factors, means that the modelled association between large-scale weather features and rainfall may not reflect the observed association. In one CMIP5 model (ACCESS1.0) it was found that, although the model captured the structure and frequency of observed synoptic patterns, it simulated the rainfall intensity and frequency less well (Brown et al., 2010).

The 'seasonal paradox' issue may be due to natural variability in recent observations or could be due, at least in part, to biases and deficiencies in the model simulation of the large-scale circulation and their association with rainfall. Some difference between any single model simulation and observations are expected because natural variability is not in phase, including phases of multi-decadal modes of variability. However, the multi-model mean provides an estimate of the underlying forced climate response, since the different phases of natural variability are likely to cancel each other out in most instances. Trends in the multi-model mean are not expected to be identical to observations either, since there is still natural variability in the observations. However, amongst the diverse individual responses of climate models to the same forcings, it would be expected that by chance some will be similar to the observed trend if the forced response is correctly simulated, which is not the case here (Figure 6a-d shows where there is a significant trend, Figure 6e-h shows where less than 10% of models show a trend that is of the same magnitude). Therefore, the presence of the seasonal paradox must be taken as a sign of reduced confidence in model projections of the seasonal expression of rainfall changes in southern Australia

The representation of rain-bearing features in climate models goes some way to explaining the seasonal paradox. Catto et al. (2013) found that although rainfall associated with fronts was underestimated, the major precipitation errors were associated with non-frontal rainfall, which might derive from systems such as cutoff lows. Since cutoff lows are important for rainfall across southern Australia, and their decline in number have contributed to the autumn rainfall reduction in the southeast (Pook et al., 2009), the poor representation of cutoffs in models (Grose et al., 2012) might explain that, even if the observed autumn rainfall decline is a forced signal and not simply driven by natural variability, models are less likely to capture it. Thus it remains a possibility that the observed autumn rainfall decline is a forced response and therefore we might expect further autumn rainfall declines in the future. Statistical downsclaing may produce a more realistic relationship between large-scale predictors and local rainfall, so may overcome the problems with GCM simulations. Statistical downscaling projects greater decreases in autumn rainfall than the host models for some regions of southeast Australia, whereas subsets of GCMs selected by their simulation of the current climate do not give a different projection than CMIP5 as a whole. This suggests that deficiencies at the synoptic and local scale are playing a role in the 'seasonal paradox' in the CMIP5 results, as shown by the seasonal differences between observed and simulated trends in the MSLP and humidity explored here.

The wide range of information presented in this study, including GCM and downscaling projections and a review of physical processes influencing southern Australian rainfall, is used here to assess the degree of confidence in the rainfall projections. Following the method used by IPCC (2013), confidence is assessed based on a combination of the amount of evidence (ranging from *Limited* to *Robust*) as well as the level of agreement between the different lines of evidence (from *Low* to *High*), leading to a range of confidence descriptors as shown in Table 2. The assessment is presented individually for each season, as well as for cases where eastern or western Tasmania is notably different to continental southern Australia.

Table 2. Confidence assessment in relation to projected changes in future rainfall for Southern Australia sub regions ('Southern continent' excludes Tasmania). Confidence is assigned for each season based on the degree of evidence and its level of agreement, where good evidence or agreement is in green and poor evidence or disagreement is in red (refer to text and references therein). Confidence on factors of atmospheric circulation, climate drivers and past trends come from this study and CSIRO and Bureau of Meteorology (2015).

Season	*Region*	*Projection*	*Evidence*	*Agreement*	*Confidence*	*Notes*
Autumn	Sthn continent	Moderate decrease	Medium	Medium Past trends Downscaling	Medium	Magnitude of decrease may be underestimated. Downscaling may add value
	Western Tas	Moderate decrease	Medium	Medium Past trends Downscaling	Medium	Magnitude of decrease may be underestimated
	Eastern Tas	Little change or increase (based on downscaling)	Medium	Medium	Medium	Downscaling may add value
Winter	Sthn Continent	Decrease	Robust SAM STR Blocking Circulation ENSO	High	High	Future changes to ENSO are uncertain
	Tasmania	Little change or Slight increase	Medium Circulation SAM	Medium	Medium	The latitudinal positioning of the westerlies varies across models
Spring	Sthn Continent	Decrease	Robust Circulation ENSO IOD	Medium Past trends	Medium-High	Changes in tropical processes and their teleconnection to Australia are not certain
	Tasmania	Decrease	Robust Circulation ENSO IOD Blocking	Medium Past trends	Medium-High	Model representation of blocking and rainfall from cutoff lows is important
Summer	Sthn continent	Little change	Medium	Medium Downscaling	Medium	Model spread is high
	Western Tas	Moderate decrease	Medium-Robust	Medium	Medium-High	
	Eastern Tas	Little change	Medium	Medium Downscaling	Medium	

Meaning of terms used in table - Circulation: changes to atmospheric circulation, primarily changes to the subtropical ridge and westerly storm tracks; SAM: Southern Annular Mode; ENSO: El Nino Southern Oscillation; IOD: Indian Ocean Dipole; Blocking: Atmospheric Blocking

As there is some uncertainty associated with projected future changes to large-scale modes of variability such as ENSO and IOD (as discussed in CSIRO and Bureau of Meteorology (2015)), this adds uncertainty to the projections in seasons where these modes have a strong relationship to rainfall in this region (e.g., Risbey et al., 2009b). In cases where there is strong supporting evidence relating to physical processes associated with rainfall in this region (e.g. projected changes to SAM and the STR), this can add confidence to projections. Factors such as these are considered in the confidence assessment (Table 2).

Conclusions

CMIP5 models confirm previous findings of a projected decline in cool season rainfall in southern Australia under a warming climate, with some regional exceptions such as wetter winters in Tasmania. In southwest Western Australia, this rainfall reduction represents a continuation of observed trends since the 1960s, driven by large-scale circulation changes. Across southeast Australia, the recent and projected rainfall decline is also linked to an increase in the persistence of highs and a growing intensity and expansion of the STR. The exception to this trend is Tasmania, where rainfall may undergo little change or a small increase at the height of winter due to an increase in westerly winds to the south of the STR.

The so-called seasonal paradox in autumn and spring is present in CMIP5, as it was in CMIP3, although statistical downscaling suggests the issue may not be as large as the GCMs suggest, at least for some restricted regions of southeast Australia. The cause of the seasonal paradox is likely a combination of variability within the observed record and an underestimation of the response to forcing by climate models. This underestimate may be due to climate models' representation of features such as cutoff lows, their association to rainfall and the model rainfall parameterisations.

An assessment of confidence in the projections (as summarised in Table 2) represents a synthesis of information presented throughout this study. The resultant confidence estimates range from *Medium* to *High*, depending on season and region, and is generally higher than for other regions of Australia (such as the eastern seaboard: Dowdy et al. (2015)) due to the relatively high degree of evidence and agreement for the southern Australia rainfall projections.

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