Vol. 62: 251–265, 2015
doi: 10.3354/cr01276

CLIMATE RESEARCH
Clim Res

Published online February 26

Climate projections for southern Australian cool-season rainfall: insights from a downscaling comparison

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ABSTRACT: The projected drying of the extra-tropics under a warmer climate has large implications for natural systems and water security in southern Australia. The downscaling of global climate models can provide insight into regional patterns of rainfall change in the mid-latitudes in the typically wetter cool season. The comparison of statistical and dynamical downscaling model outputs reveals regions of consistent potential added value in the climate-change signal over the 21st century that are largely related to finer resolution. These differences include a stronger and more regionalised rainfall decrease on west coasts in response to a shift in westerly circulation and a different response further from the coast where other influences are important. These patterns have a plausible relationship with topography and regional drivers that are not resolved by coarse global models. However, the comparison of statistical and dynamical downscaling reveals where the method and the configuration of each method makes a difference to the projection. This is an important source of uncertainty for regional rainfall projections. In particular, the simulated change in atmospheric circulation over the century is different in the dynamical downscaling compared to the global climate model inputs, related in part to a different response to patterns of surface warming. The dynamical downscaling places the border between regions with rainfall increase and decrease further north in winter and spring compared to the global climate models and therefore has a different rainfall projection for southeast mainland Australia in winter and for Tasmania in spring.

KEY WORDS: Downscaling · Regional climate models · Precipitation · Climate projections

1. INTRODUCTION

The downscaling of global climate models (GCMs) can be useful in making climate projections more locally relevant. There are a number of techniques that fall under the umbrella-term 'downscaling' of GCM projections, from very simple scaling techniques to models of similar complexity to the GCMs themselves. The different types of approaches and their relative merits have been discussed by other authors (e.g. Fowler et al. 2007, Wilby et al. 2009, Maraun et al. 2010). Here, we focus on methods of statistical and dynamical downscaling, techniques that offer the possibility of revealing finer-scale spatial detail in the climate-change signal that is not present in GCMs (Giorgi & Mearns 1999, Wang et al. 2004, Foley 2010, Rummukainen 2010, Feser et al. 2011, Paeth & Mannig 2013). This extra detail is desirable for making locally relevant datasets for use in climate change planning (Maraun et al. 2010). The term 'added value' may be used to describe the ability of the downscaling method to capture regional climate

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characteristics, or the potential to produce regional detail in the climate change signal. Most techniques are able to produce mean current climate states with greater regional detail and lower biases than GCMs, but methods vary in their potential to project a plausible climate change signal at the regional scale. We note that skill in reproducing current climate is a necessary but not sufficient condition to project a plausible regional climate signal. It is possible to assess the presence of a different signal in downscaling than in host models, and this can be given the label of potential added value (Di Luca et al. 2012). However, there is no objective framework to assess the realism of a projected signal, and there will be an element of expert judgment in any assessment.

In this study we examine the projections of cool-season rainfall in southern Australia and examine what affects the projections in each case. We examine the regional detail of rainfall projections for southern Australia from downscaling of climate models compared to the host GCMs, then aim to identify cases of regional detail common to different methods and cases in which the downscaling method has an important impact on the results. We consider how physically plausible each projection may be using qualitative expert judgment. Differences between the 2 methods are considered in the light of finer resolution and in terms of changes in large-scale circulation patterns.

Projections of mean rainfall from a set of simulations using the Bureau of Meteorology analogue-based statistical downscaling method (BOM-SDM) of Timbal & McAvaney (2001) and the dynamical downscaling regional climate model (RCM) Cubic Conformal Atmospheric Model (CCAM) of McGregor (2005) are considered. Both of the methods may have the ability to provide regional detail in the climate-change signal by accounting for local influences on climate with greater fidelity than GCMs. These influences include topography and coastlines and the related regional-scale processes such as orographic uplift, topographic steering, rain shadow effects and land-sea contrasts. CCAM may resolve these effects with a finer grid, and the BOM-SDM may account for them as part of a statistical transfer function. However, CCAM may also differ from the host model at the large scale.

The CCAM model simulates its own global atmosphere and allows bias-correction of the GCM inputs prior to running. In this way, it generates new large-scale atmospheric features compared to the host GCM, and therefore may have different biases and provide its own projection of these features. There are several notable model biases in the circulation simulated by GCMs, as demonstrated by evaluations of models in the Coupled Model Inter-comparison Project phase 3 (CMIP3) archive of Meehl et al. (2007a), such as the position and intensity of a key controller of southern Australia rainfall, the subtropical ridge (Kent et al. 2013). Any correction of circulation through the downscaling process may also provide useful insights regarding the regional climate-change signal. However, the RCM may not have lower biases in these regards. In contrast, the BOM-SDM approach produces a local interpretation of the large-scale atmospheric features produced by the GCMs with no capacity to generate its own large-scale features and only a limited attempt to correct the GCM bias. That attempt is made by using normalised predictors for which the model biases for the first 2 moments (mean and variance) compared to atmospheric reanalyses are removed.

Since both methods achieve higher resolution, but only CCAM alters the large-scale circulation, we can derive insights about the influence of resolution and of circulation by comparing the outputs from 2 methods. Where the results from both methods are similar to each other but distinct from the GCM, we suggest that this pattern indicates an influence of greater resolution. Where the results from BOM-SDM and CCAM are different from each other, we suggest this pattern indicates an influence from an alteration to large-scale circulation in CCAM. If the circulation changes in CCAM are more physically plausible than the host GCMs, then the CCAM results may be preferred, but if they are less physically plausible, then the BOM-SDM results have the advantage of being more consistent with the host model. Previous analysis of CCAM simulations (Grose et al. 2013) found that both higher resolution and a different change to atmospheric circulation compared to the host GCMs affected the regional pattern of winter rainfall change over Tasmania. The present study compares GCMs, CCAM and BOM-SDM outputs for the whole of southern Australia in autumn, winter and spring. In doing so, we provide a qualitative assessment of the possible added value offered by downscaling methods for the production of regional projections for southern Australia in the cool season. As well as the difference between downscaling and GCM hosts, another pertinent issue for climate projections is the sub-sampling of GCMs used in downscaling. Here, we also briefly consider the changes in the small number of models sampled compared to the range of projections in the full set of available CMIP3 GCMs.

The winter-dominated rainfall regime of southern Australia is largely associated with synoptic-scale disturbances in the mid-latitudinal westerlies (Hendon et al. 2007). Many regions within southern Australia have experienced declining cool-season rainfall since the 1970s, particularly in late-autumn and early winter (IOCI 2002, Timbal 2009, CSIRO 2012). This reduction has been largely driven by changes to large-scale circulation, namely the intensification and southerly movement of the subtropical ridge (STR) of high pressure and a poleward movement of the westerly storm tracks (CSIRO 2012, Timbal & Drosdowsky 2013).

The ongoing expansion of the tropics and the associated change to circulation is expected to lead to a further drying of the mid-latitudes at the hemispheric scale, a feature captured by the GCMs of the CMIP3 model archive, but without the emphasis on autumn found in past trends (Bureau of Meteorology & CSIRO 2007, Christensen et al. 2007, Meehl et al. 2007b, Timbal 2009). However, there is regional variation to this pattern in each meridional sector of the southern hemisphere, caused largely by the land–ocean contrast between the continents and oceans and from the asymmetry in the patterns of circulation. For southern Australia, the regional pattern of change in circulation and rainfall is influenced by the contrast between the landmass of Australia and surrounding oceans as well as by specific changes to the split jet structure (Grose et al. 2012). Also, because of Tasmania's position in relation to the circulation change, winter rainfall in Tasmania is projected to stay similar to current, or to increase (Christensen et al. 2007, Grose et al. 2013).

There is further regional variation in projected rainfall change influenced by topography and local drivers of rainfall variability. Downscaling has been used to provide insights on rainfall changes in southern Australia, such as the amplification of rainfall reduction in runoff in the Murray Basin (Austin et al. 2010) as well as the increase in rainfall intensity (Mehrotra & Sharma 2010). Previous comparisons of projected changes in downscaling and GCMs for Australia have found that statistical methods are generally consistent with GCMs, but the particular model configuration has a large influence, and dynamical methods have greater potential for difference from the host models (Charles et al. 2007, Timbal et al. 2008, Chiew et al. 2010, Frost et al. 2011). Also, a high-resolution dynamical model has revealed problems with the host GCM, and the downscaling can produce a different magnitude or even sign of projected rainfall change in some mountainous regions of southeast Australia (Evans & McCabe 2013). Similar to mean changes, downscaling has been used to reveal regional detail in the projection of extremes (Watterson et al. 2008, White et al. 2013); however, Perkins et al. (2014) found that the configuration of the downscaling model had an important influence on the results. Downscaling has revealed that the projected rainfall decline in the cool season is stronger and more consistent among models in south western Victoria compared to further north or on the eastern side of the Great Dividing Range (CSIRO 2012).

The finer resolution of downscaling gives it the potential to better resolve the spatial detail in the climate-change signal of mean rainfall in southeast Australia than coarse GCMs, and to show where the influence from changes to westerly circulation is expressed. This was demonstrated for Tasmania, where the projected change in the mountainous west coast could be distinguished from that on the east coast (Grose et al. 2012, 2013). This difference between these 2 regions was expected since the west-coast rainfall has a very strong relationship to the westerly circulation, but there are a variety of influences on east-coast rainfall (Grose et al. 2013).

2. DATA AND METHODS

This analysis compares the outputs from 5 GCMs from CMIP3 with downscaled outputs from a statistical and a dynamical downscaling technique using these GCMs as input. The GCMs are CSIRO-Mk3.5, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2(medres), MPI/OM-ECHAM5 and UKMO-HadCM3. These models are those used in the Climate Futures for Tasmania project (see Corney et al. 2013) where results were also available from the statistical downscaling model. Rainfall changes between 1980–1999 and 2080–2099 are examined and related to circulation change primarily as change in mean sea level pressure (MSLP).

The statistical downscaling we examine here is the Bureau of Meteorology analogue-based statistical downscaling method of Timbal & McAvaney (2001), referred to as BOM-SDM. This method uses the large-scale circulation and weather systems from a host GCM and adds regional detail via a transfer function from synoptic-scale daily predictors to local conditions. The model was calibrated to, and produced outputs on, the ~5 km resolution grid of the Australian Water Availability Project (AWAP) gridded climate dataset of Jones et al. (2009). Decisions about which predictors are used have an important influence on the results, especially the handling of atmospheric moisture (e.g. Charles et al. 2007, Mehrotra & Sharma 2011). There are different sets of predictors used for downscaling daily rainfall in different sub-regions across southern Australia and in different seasons. The exact combination of predictors used for each calendar season and region in this study are the same as that used by Timbal et al. (2009); see Fig. 1 and Table 4 of that paper for more details. In general, across southern Australia, the optimal combination of predictors are patterns of MSLP combined with either broad-scale daily precipitation or specific humidity at the 850 hPa level and with either the zonal or meridional component of the wind at the 850 hPa level. The domains of the large-scale predictors used in BOM-SDM typically extend beyond the area of interest by a few hundred kilometres (Timbal et al. 2009; their Fig. 3).

The BOM-SDM method uses synoptic-scale weather systems and large-scale features from the GCM with no modification and no 2-way interaction from the small scale back to the large-scale. Therefore, the 'added value' in this downscaling comes entirely from the use of a transfer function from the synoptic scale to the local scale. Timbal et al. (2006) used the statistical downscaling technique to attribute recent trends in the observed climate to anthropogenic external forcings or natural external forcings in the south-western part of Western Australia (SWA). The technique was able to reproduce the rainfall decline in SWA and attribute causes more reliably than the raw output of GCMs, and also to provide insight about the role of MSLP and precipitable water reduction in driving the decline (Timbal 2004, Timbal et al. 2006).

The dynamical downscaling method we show here is that of the Cubic Conformal Atmospheric Model (CCAM) of McGregor (2005). This model uses a 6-sided cubic conformal grid to cover the entire globe. The particular CCAM simulations examined here were performed using a stretched variable global grid for the Climate Futures for Tasmania project (Corney et al. 2013) and are referred to as CFT. The first stage of downscaling was performed with a primary face of the cube covering all of Australia with a uniform resolution of 0.5° (~50 km). A second downscaling was also performed on a global variable grid, with the primary face of the cube covering Tasmania with an even resolution of 0.1° (~10 km). The model was configured to use only sea surface temperature (SST) and sea ice concentration from the host GCM, and to generate an entirely new atmosphere at higher resolution than that of the host GCM. Prior to simulation, a mean SST bias adjustment was applied to the GCM SST input fields, designed to reduce current bias and therefore collapse the model range around the actual climate signal (Katzfey et al. 2009). The climate-change signal from each GCM is incorporated into CCAM primarily through bias-corrected SST fields, meaning the outputs will be more like that of a new simulation than other limited area models with no bias correction. Also, the use of a dynamical model means that there is interaction between processes at a finer scale interacting with the large scale, often termed 'upscaling'. For example, the more resolved effect of topography and coastlines at 50 km will feed back up to the large scale wind fields over the whole region. In summary, the large-scale atmospheric features in CCAM can be different compared to the host model for 3 possible reasons: (1) bias adjustment of SSTs as input, (2) configuration of the new atmospheric and land surface models and (3) the interaction of simulated fine-scale processes with the larger scales ('upscaling'). The CCAM outputs are on a coarser spatial scale than SDM (~50 km compared to ~5 km), so we restrict the analysis to patterns of quite large spatial scale (~100 km and larger).

The current bias in circulation is examined in the GCMs and CCAM simulations primarily through the change in MSLP over the Australasian sector (5–55° S, 100–180° E). Bias in the current MSLP pattern is examined by comparison to ERA interim reanalysis (Dee et al. 2011). Bias in rainfall is examined by comparison to the AWAP rainfall dataset (Jones et al. 2009) over land areas only (ocean cells were not considered because AWAP and BOM-SDM do not extend into the ocean). Area-average bias in rainfall is calculated for the regions of southwest Western Australia (SWA), southern South Australia (SSA), southeast Australia including Tasmania (SEA) and Tasmania alone (TAS), as shown in Fig. 1. Biases in both MSLP and rainfall are similar throughout the cool season, so for simplicity, we examine the single period of May to October.

Projected change in MSLP and rainfall is examined by the difference between 1980–1999 and 2080–2099 under the A2 scenario from the Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000). Changes to zonal and meridional mean MSLP over the Australasian domain are examined in May to October as an indication of the response over the cool season, particularly noting the magnitude and latitude of the maximum response. A detailed examination of the spatial distribution of changes in MSLP and rainfall as well as area-average rainfall change is

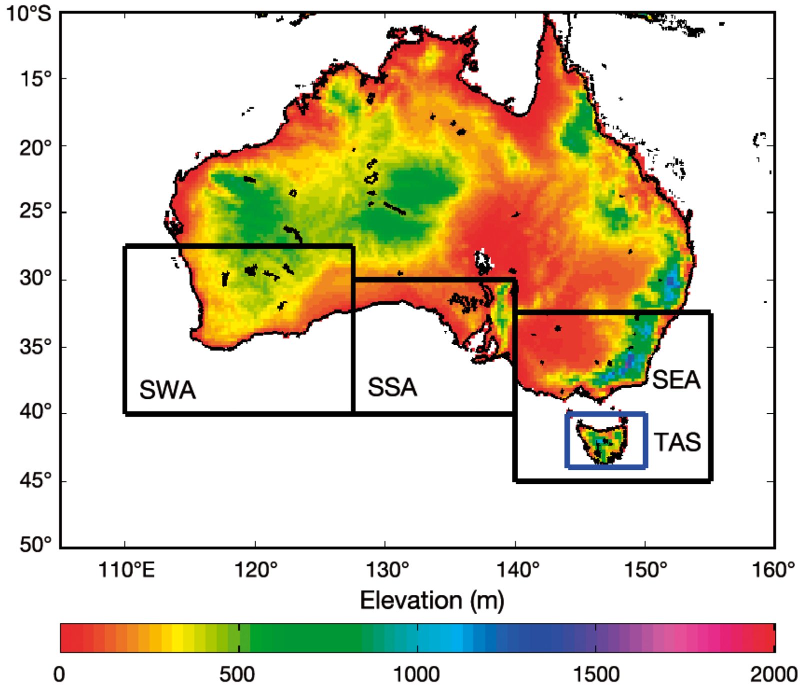

Fig. 1. The Australian region showing surface height (m) and the location of boxes for calculating area-average bias and change in mean rainfall in southwest Western Australia (SWA), southern South Australia (SSA), southeast Australia (SEA) and Tasmania (TAS). Averages use land area only

made for separate calendar seasons because some seasonal distinctions are noteworthy. We examined the seasons of austral autumn (March, April and May [MAM]), austral winter (June, July and August [JJA]) and austral spring (September, October and November [SON]).

For plotting, GCM outputs are regridded to a common 1.5° latitude/longitude resolution, CCAM outputs are shown at native 0.5° latitude/longitude resolution, and BOM-SDM are shown at native 0.05° latitude/longitude resolution and are generated for the land surface only.

3. RESULTS

3.1. Current climate MSLP and rainfall

The multi-model means of both the GCM and CCAM ensembles have some bias in the simulation of MSLP in the current climate compared to ERA interim (Fig. 2). CCAM tends to overestimate MSLP compared to reanalysis, but GCMs tend to underestimate MSLP. The peak value of the zonal average MSLP across 100 to 180° E gives a general indication of the location of the subtropical ridge (STR), shown by dashed lines. The GCMs show a range in the latitude and intensity of the STR in each season that encompasses the observed value. CCAM has a smaller range than the host GCMs and consistently places the high-pressure belt further south than reanalysis. This result shows that the bias correction of SST and the use of a single atmospheric model in CCAM narrows the range in the current climate compared to the host GCMs. Along with these differences in the broad STR position and intensity, there are biases in the specific pattern of MSLP across the Australian sector (100 to 180° E) in all the

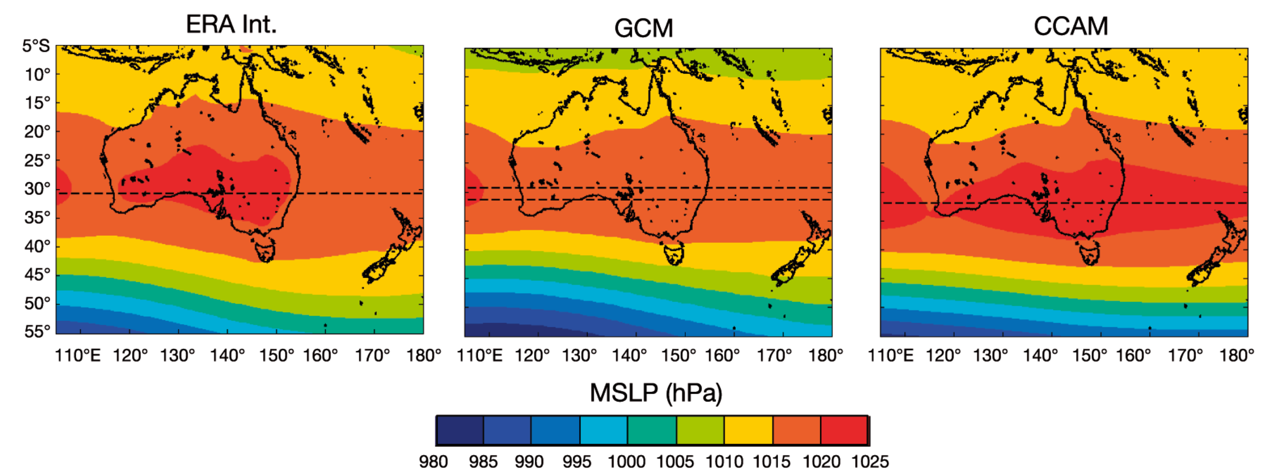

Fig. 2. Mean sea level pressure (MSLP) in ERA Interim reanalysis, mean of 5 global climate models (GCM) and the mean of 5 Conformal Cubic Atmospheric Model (CCAM) simulations in May to October in 1980 to 1999. Dashed lines: latitude of the maximum zonally averaged MSLP across the domain in each model output. Note that for CCAM, all 5 lines overlap

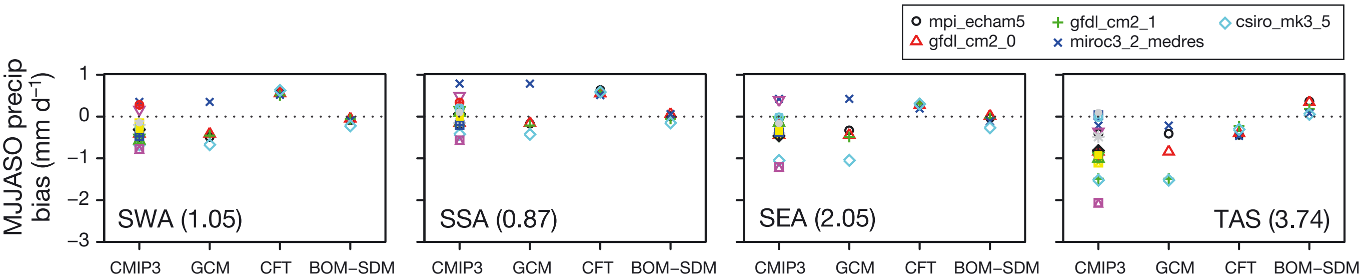

Fig. 3. Area-average bias in mean rainfall in 1980 to 1999 in 4 Australian boxes (areas and acronyms are described in Fig. 1) for May to October. Each plot shows result for 23 CMIP3 global climate models (CMIP3), the 5 global climate models (GCMs) used in this study, 5 CCAM simulations at 0.5° (~50 km) resolution produced for the Climate Futures for Tasmania project (CFT) and 5 Bureau of Meteorology statistically downscaled simulations (BOM-SDM). Values in panels show the current observed mean rainfall (mm d^{-1}). The key shows only the 5 models used in the study (other GCMs are given a coloured symbol but not shown in key). See Fig. 1 for further abbreviations

models, such as the strength of the trough at the Western Australian coast and the curvature of the isobars over the Tasman Sea. There is a difference between CCAM and the GCMs in their simulation of the intensity and direction of the gradient at the southern edge of the STR to the Southern Ocean (Fig. 2). Biases are similar in strength and direction in the calendar seasons of MAM, JJA and SON (not shown).

Area-averaged rainfall biases in respect to AWAP in 1980 to 1999 for CMIP3 (land only) tend to be <1 mm d^{-1} in the large regions examined, with some larger biases for the smaller region of Tasmania (Fig. 3). Some of the biases, however, are large relative to the average observed rainfall amount (see values in panels). The 5 models selected for this study generally provide a reasonable sampling of the typical biases observed across the full CMIP3 dataset. Both downscaling approaches show a smaller range of biases compared to the host GCMs, and are comparable to the lowest biases in GCMs in most cases, except for a wet bias in the SWA and SSA in the CCAM simulations. The statistical downscaling consistently provides the smallest rainfall biases because, while it establishes a link between daily weather systems and local rainfall, it is in effect re-sampling observations, and is therefore anchored to the observed dataset against which it is being evaluated.

3.2. Projected change in MSLP

The zonally averaged MSLP in May to October over this sector (100 to 180° E) is projected to increase at ~40° S between 1980–1999 and 2080–2099 in all GCM and CCAM simulations (Fig. 4). The increase is

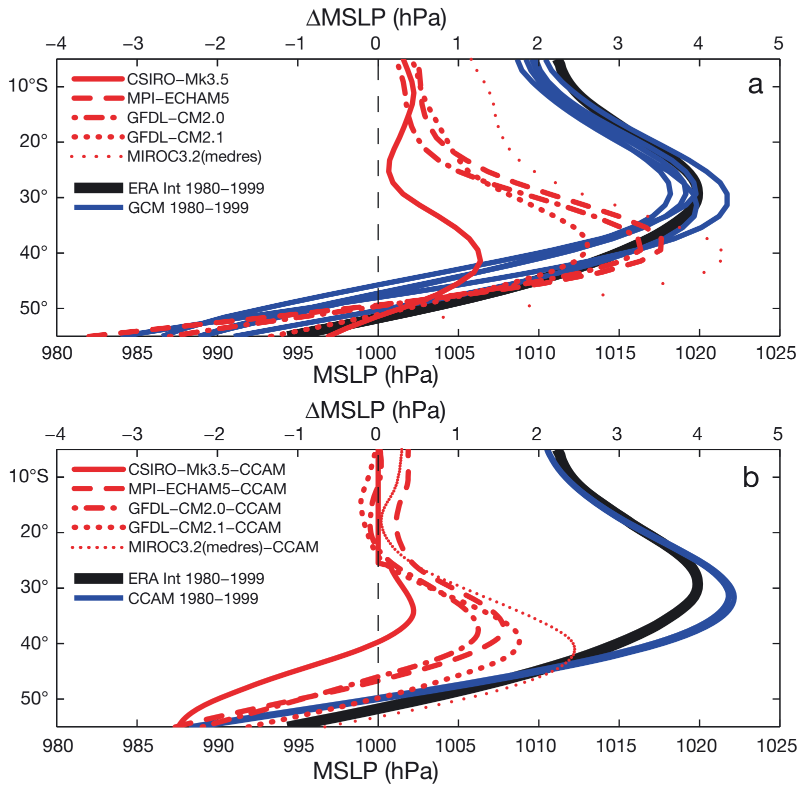

Fig. 4. Zonal average mean sea level pressure (MSLP) for May to October in the Southern Hemisphere in the Australian sector (100 to 180° E), showing mean in ERA Interim in 1980–1999 (black), in each model in 1980–1999 (blue) and change between 1980–1999 and 2080–2099 under the A2 scenario in each model (red) in (a) 5 GCM simulations and (b) 5 CCAM simulations. Mean is shown on the bottom axis and change is shown on the top axis

at the southern edge of the current high-pressure belt (Fig. 4), indicating the MSLP increase represents a projected strengthening and pole-ward expansion of this high-pressure belt. This pattern is common to all GCM and CCAM simulations, but the specific magnitude and latitude of the MSLP increase differs between the models.

The GCMs show a range of intensity changes, but a consistent latitude of peak MSLP increase at 37 to 41° S (Fig. 4a). The magnitude of this intensification is partly related to climate sensitivity (i.e. the magnitude of global warming response by any single model to a common external forcing), with the most sensitive model, MIROC3.2(medres), showing the greatest change. There is no strong relationship between the increase in intensity and the latitude of the maximum increase between the 5 GCMs ($R^2 < 0.5$), showing that a greater increase in intensity is not linked to a greater shift south (Fig. 4a). The MSLP increase in this region is consistently weaker in each CCAM simulation compared to its host model (Fig. 4b). The inter-model range in the peak MSLP change in the 5 CCAM simulations shows a linear relationship between intensity and location ($R^2 > 0.95$), where the smallest change is the furthest north (~0.5 hPa, 34° S) and the largest is the furthest south (~2.5 hPa, 41° S). Across all the GCM and CCAM simulations, there is a weak relationship between the size of the bias in the current climate and the magnitude of the projected change ($R^2 = 0.6$), where the models with the largest positive bias have the smallest projected change. This relationship may partly account for the smaller projected change in CCAM compared to GCMs (Fig. 4b).

The maximum MSLP of the subtropical ridge in May to October varies between 1017 and 1022 hPa at the longitudes across the Australian sector in ERA Interim in 1980 to 1999 (Fig. 5). Each GCM has a dif-

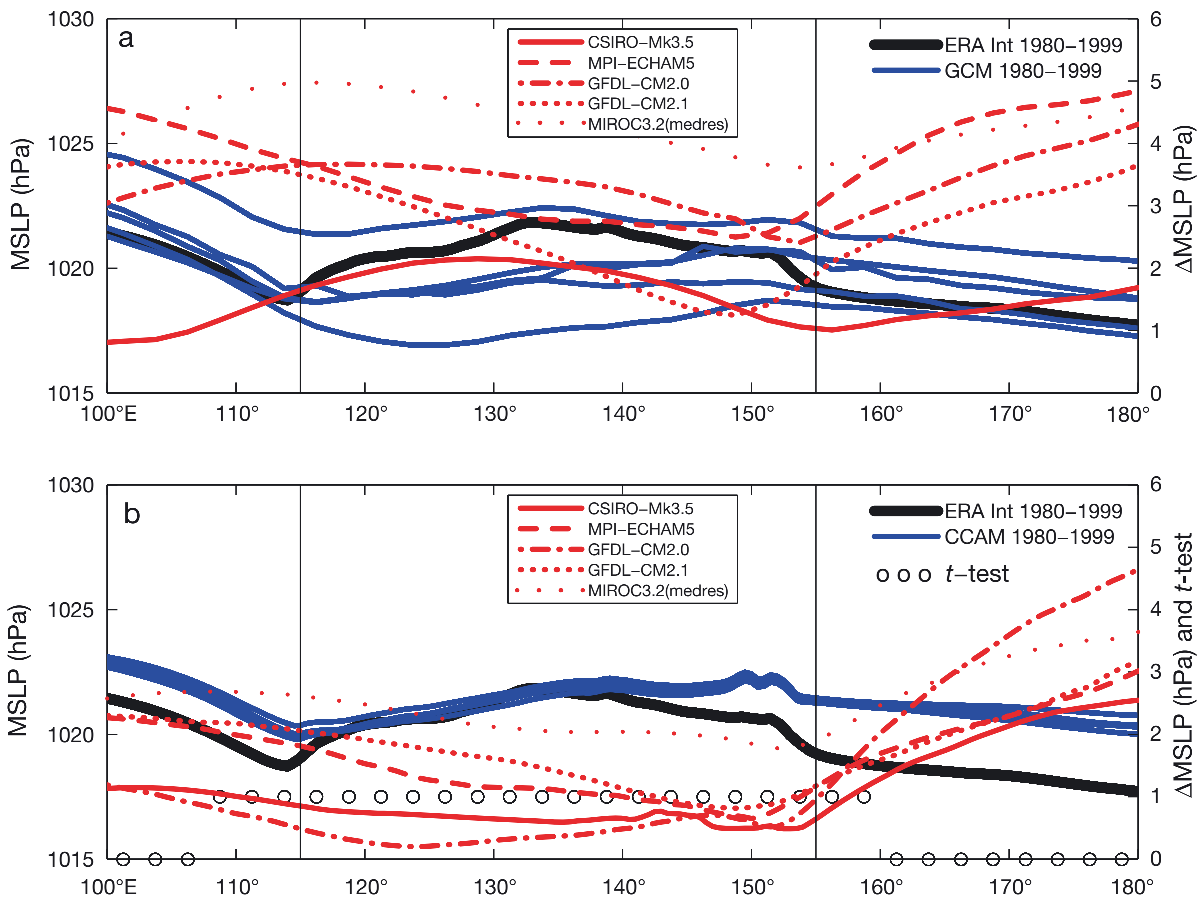

Fig. 5. Maximum mean sea level pressure (MSLP) by longitude for May to October in the Australian sector of the southern hemisphere (100–180° E, 5–65° S), showing means for 1980–1999 and change to 2080–2099 under the A2 scenario, with (a) maximum MSLP in ERA Interim climatology (black) and in 5 Global Climate Models (blue) as well as the maximum MSLP change in those models between 1980–1999 and 2080–2099 (dashed red, right hand axis) and (b) as for (a) but for CCAM outputs. Also included in bottom panel is the Student's *t*-test result of the comparison of the GCM and CCAM change populations at 2.5° longitude intervals (1 shows significant difference, 0 no significant difference). Vertical lines: extent of Australian continent

ferent bias in the simulation of the strength of the STR (Fig. 5a). The CCAM simulations are fairly similar with a positive bias over the Tasman Sea and over the Indian Ocean but lower bias over the Australian continent (Fig. 5b). There is a projected increase in MSLP across the entire sector in all model simulations, and this increase is generally lower in CCAM than in the GCMs. The difference in MSLP change between the 5 GCMs and 5 CCAM simulations is significant at the longitude range of the Australian continent (Student's 2-tailed *t*-test of the 2 populations of 5 at a 0.05 significance level) but is not significantly different east of 160° E or west of 110° E (Fig. 5b).

There are some noteworthy differences in the spatial pattern of MSLP change in individual seasons (Fig. 6). The weaker response of MSLP in CCAM compared to GCMs directly to the south of the Australian continent is reflected in all 3 seasons (Fig. 6). In each season, the general sharpness and latitude of the band of increase in MSLP is similar between CCAM and the GCMs, but there are several notable differences in the magnitude and shape of the band. The weaker increase in MSLP in CCAM at the longitude of the Australian continent compared to the GCM mean is particularly noticeable in JJA, as discussed by Grose et al. (2013), but it is also seen in SON.

The combination of bias in the current climate and differences in response across the continent of Australia lead to a different circulation change in CCAM compared to the GCMs. There is a direct relationship between rainfall and MSLP across southern Australia during the cool part of the year (Allan & Haylock 1993, Hope et al. 2010). Therefore, the difference in circulation change in CCAM compared to GCMs is expected to have an important influence on the projected rainfall change, and this is explored in the next section.

3.3. Projected change in rainfall

There are some notable differences in the patterns of mean rainfall change in the downscaling compared to the host GCMs, indicated in the multi-model mean of each ensemble (Fig. 6), and in area-averaged changes over land (Fig. 7). An increase in MSLP implies a reduction in westerly circulation and a reduction of rainfall in southern Australia. While there is a general projection of increased MSLP and reduced rainfall in southern Australia as a whole for the entire cool season, as discussed above, the latitude of the MSLP increase and regional rainfall projection vary by season. Therefore, we discuss the calendar seasons of MAM, JJA and SON in turn.

In MAM, the overall rainfall change pattern is similar in all the projections, with a large area of rainfall reduction over the ocean south of Australia encroaching onto the continent in SWA, SEA and Western Tasmania. There is a transition to an inland trough, with a rainfall increase area further north and east (i.e. away from the reduction of the westerlies implied by the MSLP changes described in the previous section). However, there is no strong model agreement on the sign of change here.

Differences in the amplitude of the rainfall change across southern Australia in MAM are notable, where BOM-SDM projects a rainfall decline in excess of 30% along the coast in Western Victoria and southern South Australia. In comparison, the host GCMs do not project a rainfall decline exceeding 20% (Fig. 6a). The large rainfall decrease projected by BOM-SDM is contrasted by a rainfall increase further inland, and thus, the regionally averaged rainfall projection across the entire SEA region is on par with the other models in MAM (Fig. 7). This greater contrast between rainfall decline and increase in the BOM-SDM results is of particular interest as it better matches what has been observed in recent times in the region (Timbal 2009). The rainfall increase to the southeast of the continent is coincident with the projected increase in the strength and extent of the East Australia Current, and the rainfall response is far greater in CCAM compared to the GCMs. This feature is mainly over the ocean, but both downscaling methods indicate that the influence encroaches slightly over the continent (e.g. eastern Tasmania in the inset in Fig. 6a). Also, both the BOM-SDM and CCAM projections show a rainfall decline in SWA that is more restricted to the west coast compared to the GCM hosts.

In JJA, the major difference in the precipitation response between CCAM and the other datasets is in the location of the border between areas of rainfall increase and decrease (Fig. 6b). The GCMs and BOM-SDM show that the area projected to become wetter is restricted to the latitude of Tasmania, but CCAM places this boundary further north, and hence a section of the southeast Australian mainland is projected to become wetter in the multi-model mean. The difference in rainfall projection between the CCAM and GCMs simulations is closely related to their respective MSLP changes. Since an increase in MSLP infers a reduction in rainfall in southern Australia (Allan & Haylock 1993, Hope et al. 2010), the GCMs have a larger MSLP signal and therefore a

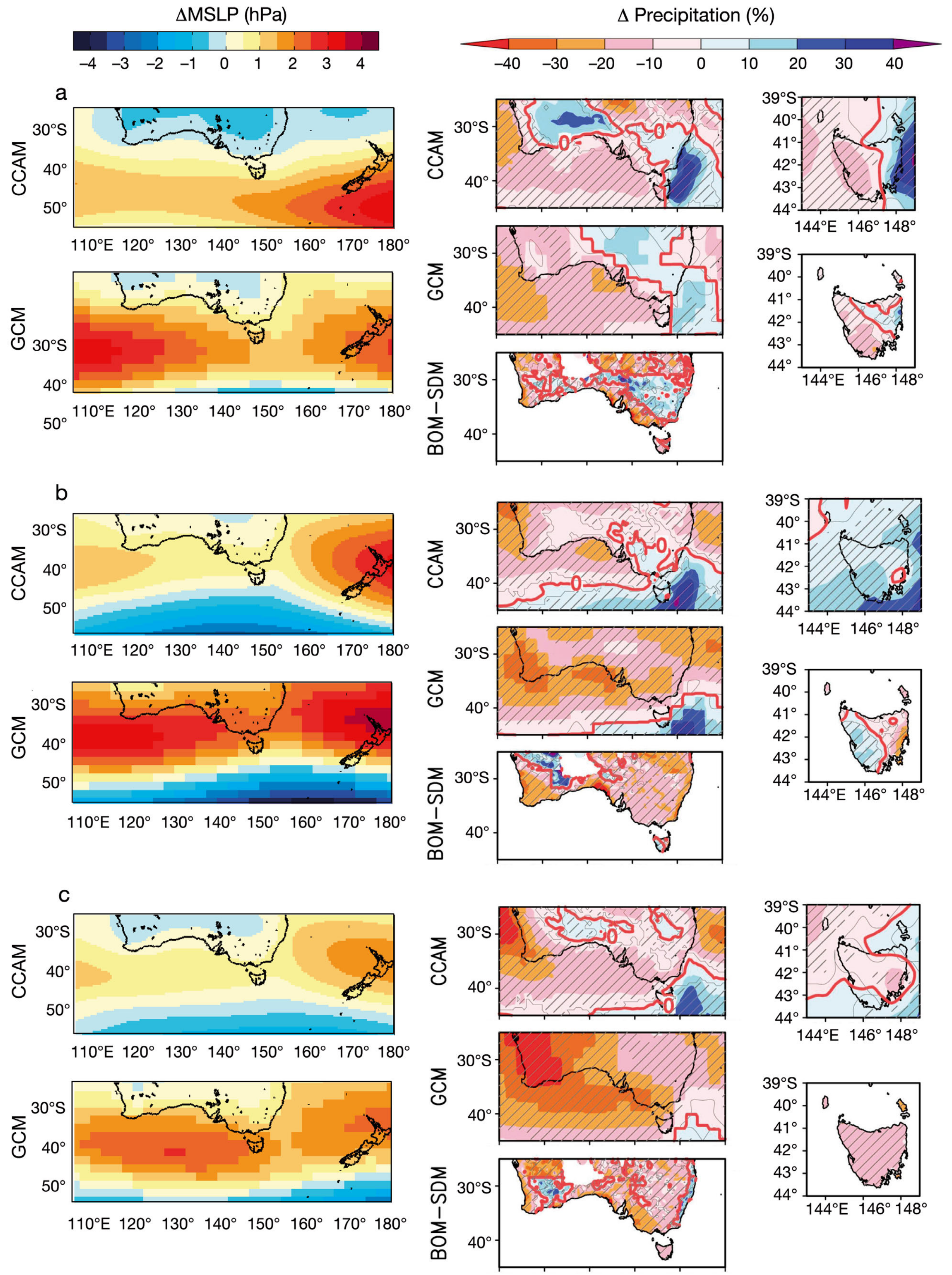

Fig. 6. Mean sea level pressure (MSLP, left) and precipitation change (right) in (a) austral autumn (March–May), (b) winter (June–August) and (c) spring (September–November) between 1980–1999 and 2080–2099 under the SRES A2 scenario over the southern Australian region and Tasmania. Shown are the multi-model mean in 5 CCAM downscaling simulations (top row), 5 CMIP3 global climate models (GCM, centre row), and Bureau of Meteorology analogue-based statistical downscaling (BOM-SDM, bottom row). Diagonal shading in the precipitation panels is where 4 or 5 models agree on the sign of change

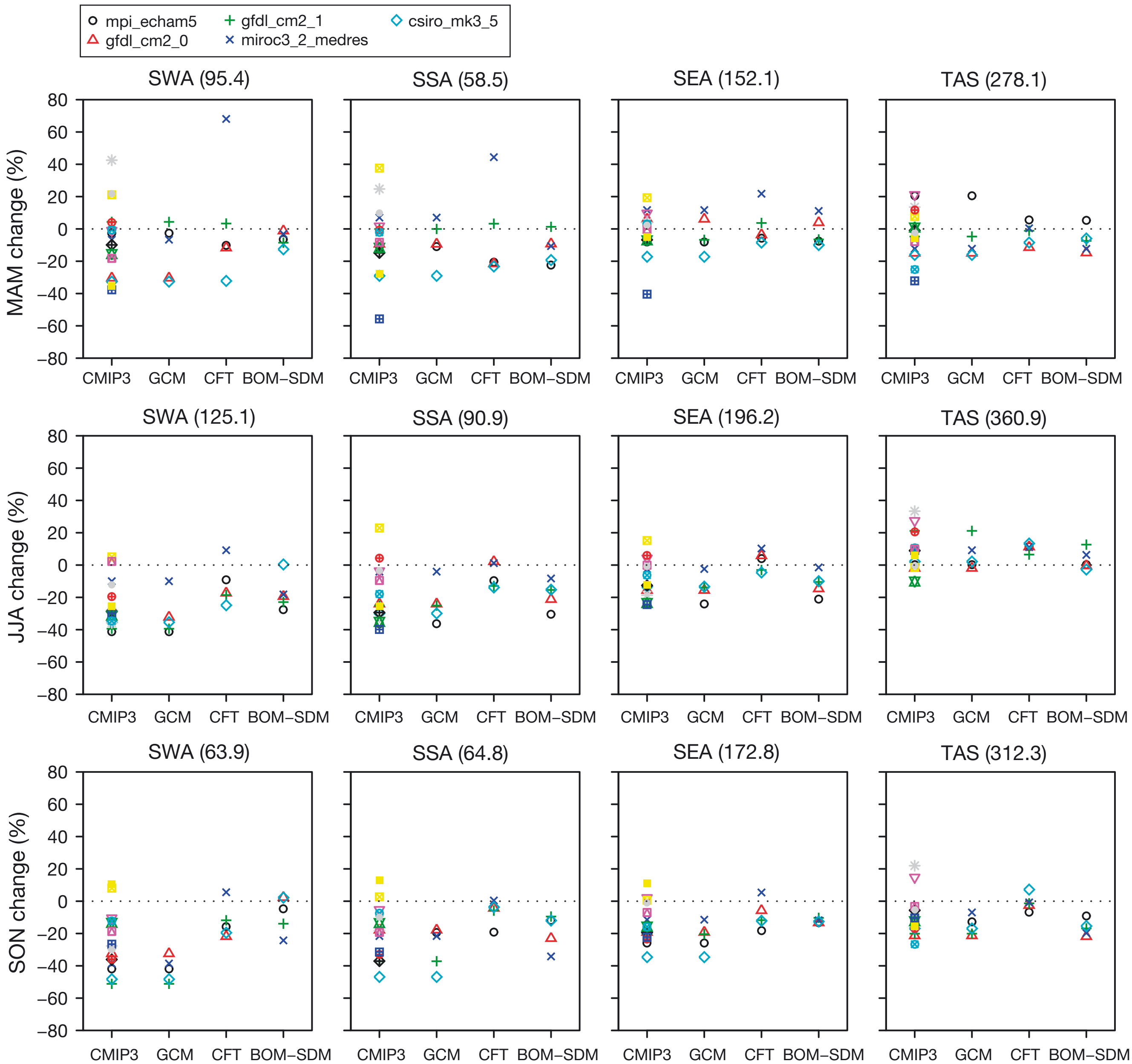

Fig. 7. Area-average change in mean rainfall (%) between 1980–1999 and 2080–2099 under the A2 scenario in 4 boxes (area codes are described in Fig. 1) for March-April-May (MAM, June-July-August (JJA) and September-October-November (SON). Each plot shows results for 23 CMIP3 global climate models (CMIP3), the 5 global climate models (GCMs) used in this study, 5 CCAM simulations produced for the Climate Futures for Tasmania project (CFT) and 5 Bureau of Meteorology statistically downscaled simulations (BOM-SDM). Values above each plot show the current observed mean rainfall (mm d^{-1}); the key shows only the 5 models used in the study (other GCMs are given a coloured symbol but are not shown in key)

large negative rainfall projection over mainland Australia, while in the CCAM model, the lower pressure increase corresponds with a weaker rainfall decline. The boundary between rainfall decline and increase appears to be approximately congruent to the +0.5 hPa increase line in both results.

There are a few noteworthy regional features in the downscaling that were absent from the host models in JJA. (1) The rainfall decrease or low level of change in eastern Tasmania in contrast to western Tasmania in BOM-SDM. Topography and other factors mean that western Tasmanian rainfall responds primarily to changes in westerly circulation and embedded weather systems, but eastern Tasmanian rainfall response is driven by other factors such as the incidence of cutoff lows. The statistical model may account for these differences in producing this regional projection. This difference is not clearly present in the CCAM simulations, and this result may be related to the boundary between rainfall increase and decrease being further north. However, a similar distinction between west and east Tasmania was found in summer rainfall projections in these CCAM simulations, congruent with the relationship to westerly circulation (Grose et al. 2013). (2) The sharp rainfall decrease in a small area of South Australia in BOM-SDM projections. A rainfall decrease is also seen in the host GCMs but mostly over the ocean rather than over the continent. This feature is similar to the large signal in autumn across the western part of SEA. Again, it appears that the BOM-SDM provides a sharper local signal in an area where westerly airflow meets the continental edge, a feature which cannot be represented precisely by GCMs that typically have a grid box resolution of 100 to 200 km. (3) There is an enhancement of the projected rainfall decrease across the eastern side of the Australian continent on the coastal plain east of the Great Dividing Range in BOM-SDM. The sign of change is consistent with the GCMs, but the magnitude is markedly increased. The CCAM projections do not include these last 2 regional features, but the signal here is likely to be affected by the larger-scale differences related to MSLP change described above. (4) There are different regional patterns of rainfall change in Western Australia in the downscaling compared to the GCM hosts. The BOM-SDM projections show a rainfall decline in SWA, but rainfall increase inland and the CCAM projections indicate a weaker rainfall decrease in the southwest and then little change in rainfall inland.

In SON, the border between regions of projected increase and decrease in rainfall is further north in CCAM compared to the host models (Fig. 6c), as it was as in JJA. This strongly affects the projected rainfall response for parts of Tasmania (Figs. 6c & 7). There is a large and consistent projected decrease in GCMs and BOM-SDM, but Tasmania sits on the borderline between increase and decrease in CCAM. This means that CCAM projects rainfall increases in some regions of Tasmania (Fig. 6c) and little change in the state-wide mean (Fig. 7). Also, there is a projected rainfall increase in BOM-SDM along the narrow eastern seaboard of mainland Australia, in contrast to the decrease in the host models and the CCAM projections (Fig. 6c). The CCAM output shows a rainfall increase over the ocean next to the east coast, but does not show a projected rainfall increase over land. The eastern seaboard is relatively narrow (100 to 200 km) and hence is difficult to capture for GCMs and even for a climate model run at higher resolution (50 km for CCAM); this limitation could explain the differences between the BOM-SDM projections and the other approaches. It is also worth noting that this feature is stronger in the subset of the CMIP3 downscaled models considered in this study compared to a larger set described by Timbal et al. (2011, their Fig. 10).

In SON, there are differences in the regional pattern of projected rainfall change in the downscaling compared to the GCM hosts in Western Australia. The BOM-SDM projections show a rainfall reduction not exceeding 40% restricted to near the west coast contrasting to rainfall increase inland. The CCAM projections show a rainfall reduction not exceeding 40% near the coast and a region of little projected change inland. It should be noted that the sharp boundary between the area of rainfall increase in SWA and further north is an artefact of the BOM-SDM. It describes 2 very different projections based on different configurations of the BOM-SDM that are utilised for the climate regions SWA and the region to the north (see Timbal et al. 2009 for details on these regions and the boundary issues arising from the methodology). A similar boundary can be seen at the same latitude across the rainfall projections in SEA in SON.

The area-average projected rainfall change in the 5 selected GCMs (Fig. 7) covers the range of projected change in the entire CMIP3 archive except for outliers in several cases (e.g. SEA in MAM) but samples mainly the dry end in other cases (e.g. all regions in SON). These models were chosen primarily on simulation of the current climate and were not explicitly chosen to be representative of the full range of the GCM archive, so some biases in sampling are inevitable.

4. DISCUSSION

The results presented here show several cases in which the projected rainfall response differs between each downscaling model and the host GCMs. Differences between BOM-SDM and the host models are created through the statistical model that links the synoptic-scale processes to local rainfall at a ~5 km scale. For the CCAM results, some of the differences to the host may also be due to accounting for finer-scale processes, while others are due to a difference in the broader-scale circulation response.

The typical GCM resolution (100 to 250 km) means that sub-synoptic scales are not well resolved, and GCMs produce rainfall at their grid scale using various parameterisations. The BOM-SDM uses a transfer function that characterises the relationship between weather systems and rainfall including the effect of topography and other surface factors and produces output on a fine grid. For effects such as orographic uplift, the BOM-SDM can implicitly include relationships between synoptic-scale fields and local rainfall into the transfer function. BOM-SDM produced some notable regional detail in the rainfall projections, including a greater rainfall decline in southwest Victoria in MAM, a different response in the eastern seaboard compared to inland in SON and a different response in each half of Tasmania in JJA. These fit the 'potential added value' framework of extra detail in the climate-change signal (Di Luca et al. 2012). The extra regional detail appears to be related to topography and coastal effects, and the regional patterns of change might be more physically plausible than the host models.

The BOM-SDM uses the broad-scale climate-change signal as the driving GCM, including the same weather systems as the host model, but produces a different regional pattern of rainfall change. The cases in which BOM-SDM produced distinct trends in regions of high surface forcing (topography, coastlines) that are poorly resolved in GCMs suggest that the downscaling is producing plausible 'added value'. However, the expression of the climate-change signal in local rainfall is also affected by the choice of predictors and the configuration of the model.

Some of the changes in CCAM can also be related to the effect of higher resolution, including the contrast between east and west Tasmania in MAM and the projections for SWA in SON. However, some of the differences between CCAM and the host are due to a different circulation response and are not as easily contextualised by 'potential added value' at the regional scale. The rainfall changes affected here are primarily the different placement of the boundary between rainfall increase and decrease, affecting the sign of change over SE Australia in JJA and over Tasmania in SON. In these cases, CCAM is showing many aspects of a new simulation at the large scale, so to gauge how physically plausible the projected changes are in some respects, they need to be evaluated as a new model.

In the results shown here, CCAM and the GCMs both show a band of increasing MSLP over the southern Australian region, associated with a poleward movement of the STR and storm tracks. However, the band is weaker in the Australian sector in CCAM compared to the hosts (Figs. 4–6). This can be related to at least 2 differences between the CCAM configuration and the host GCMs, which we discuss here: a different bias in the current climate and a different sensitivity to the presence of the Australian continent.

Biases in MSLP are very consistent in every CCAM simulation and are fairly distinct from the GCM hosts (Figs. 4 & 5). The high bias of MSLP in the current climate may contribute to the weaker MSLP response over the Australian sector. Across all GCM and CCAM simulations, there is a weak relationship (R^2 = 0.6) between the model spread in MSLP bias and the model spread in projected change in just the Australian sector (Fig. 4). A relationship between bias and projection exists in the latitude shift of the westerly jet for the entire hemisphere in CMIP3 GCMs (Kidston & Gerber 2010) where the current bias has an influence on the projection. A similar relationship may be present here; however, the relationship is fairly weak and only calculated from 6 samples (5 GCMs and CCAM).

Apart from the effect of bias, there appears to be a different response to land and ocean in CCAM compared to the GCMs. There is a model spread in the degree of land–ocean contrast and the atmospheric response to this contrast between different climate models (e.g. Fasullo 2010), and it appears that the CCAM configuration used is a particularly strong responder in this regard. There are at least 3 aspects of the model simulation that can potentially lead to this different response: (1) bias adjustment of SSTs as input, (2) the configuration of the atmospheric model and (3) upscaling of processes at small spatial scales to the large scale. The SST bias adjustment is not expected to be the dominant influence here, as the corrections in this region were generally small, and the effect is greater in the region of land–ocean contrast than over the open Tasman Sea. Also, the CCAM simulations have a stronger response to SST increases over the East Australia current region in MAM (Fig. 4), showing they may have a stronger response to SST patterns than the GCM. This pattern indicates that the difference between CCAM and GCMs is mainly in the response to SST rather than a large correction of the SST itself.

Aspects of CCAM model configuration and upscaling will be inter-related, particularly through processes such as convection at different length scales. Land–ocean contrast is influenced by the greater warming over land compared to the ocean, which is in turn influenced by changes in lapse rates related to convective equilibrium (Byrne & O'Gorman 2013). These CCAM simulations were made with a stretched grid and a particular convection scheme, land-use scheme and radiation scheme that are subject to development. A different configuration of CCAM can give different results (e.g. Perkins et al. 2014). Indeed, the particular configurations of all GCMs, RCMs and statistical models have important effects on the results that need to be taken into account when making regional climate projections.

There is no objective framework to evaluate the plausibility of each output and to reconcile the differences between the results. However, the most compelling cases for considering the downscaling in particular are regions where the downscaling methods agree on a regional pattern of change, such as in Tasmania. For the regions where the results from different downscaling methods disagree and there is no clear reason to reject one or the other method, the results suggest widening the range of plausible future change to consider all results.

5. CONCLUSIONS

Downscaling gives finer resolution, and this leads to a few cases of potential added value in the climate-change signal for southern Australia in the cool season. These regional features of change appear to be physically plausible. However, the results are also influenced by several other factors that make identifying the added value of downscaling not completely clear and unequivocal. These factors include the effect of circulation bias in the current climate (inherited from the GCM in the BOM-SDM and a new bias simulated in CCAM) and the effects of the configuration of the model (e.g. response to the land–ocean contrast in CCAM).

The clearest regional detail in the rainfall signal that is consistent in both the BOM-SDM and CCAM is a different response in rainfall trend on each side of Tasmania in MAM and to some extent in JJA. Both downscaling methods also indicate gradients of change that are greater than in GCMs in Western Australia in SON. The BOM-SDM also indicates a greater gradient between rainfall decreases at the southwest Victorian coast and increases further inland in MAM. These changes appear to be a greater differentiation of regions where the weakening of westerly circulation would cause a rainfall reduction and of areas further from coasts where other effects are important. Better definition of these regions in downscaling is eminently plausible due to finer resolution. These steeper gradients and regions of different sign of change appear to be physically plausible responses and candidates for added value in the climate-change signal.

The different placement of the border between rainfall increase and rainfall decrease in southeast Australia in the CCAM results appears to be strongly influenced by the particular configuration of CCAM used, which shows a particularly strong response to the spatial pattern of surface warming compared to the host models. This has a conspicuous effect on the resulting projections for SE mainland Australia in JJA and for Tasmania in SON. This highlights the influence of the atmospheric model in creating aspects of a new atmospheric simulation when using dynamical downscaling from a host model.

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Editorial responsibility: Balaji Rajagopalan, Boulder, Colorado, USA

Submitted: March 4, 2014; Accepted: November 15, 2014
Proofs received from author(s): February 19, 2015