The simulation of cutoff lows in a regional climate model: reliability and future trends

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Abstract Cutoff lows are an important source of rainfall in the mid-latitudes that climate models need to simulate accurately to give confidence in climate projections for rainfall. Coarse-scale general circulation models used for climate studies show some notable biases and deficiencies in the simulation of cutoff lows in the Australian region and important aspects of the broader circulation such as atmospheric blocking and the split jet structure observed over Australia. The regional climate model conformal cubic atmospheric model or CCAM gives an improvement in some aspects of the simulation of cutoffs in the Australian region, including a reduction in the underestimate of the frequency of cutoff days by more than 15 % compared to a typical GCM. This improvement is due at least in part to substantially higher resolution. However, biases in the simulation of the broader circulation, blocking and the split jet structure are still present. In particular, a northward bias in the central latitude of cutoff lows creates a substantial underestimate of the associated rainfall over Tasmania in April to October. Also, the regional climate model produces a significant north–south distortion of the vertical profile of cutoff lows, with the largest distortion occurring in the cooler months that was not apparent in GCM simulations. The remaining biases and presence of new biases demonstrates that increased horizontal resolution is not the only requirement in the reliable simulation of cutoff lows in climate models. Notwithstanding the biases in their simulation, the regional climate model projections show some responses to climate warming that are noteworthy. The projections indicate a marked closing of the split jet in winter. This change is associated with changes to atmospheric blocking in the Tasman Sea, which decreases in June to November (by up to 7.9 m s^{-1}), and increases in December to May. The projections also show a reduction in the number of annual cutoff days by 67 % over the century, together with an increase in their intensity, and these changes are strongest in spring and summer.

Keywords Cutoff low · Atmospheric blocking · Split jet · Climate models · Climate change · Regional climate models

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1 Introduction

Cutoff lows are cold-cored extra-tropical cyclones that have been displaced or have formed equatorwards of the prevailing westerly flow of the mid-latitudes. They typically develop in the mid to upper troposphere and frequently, but not always, extend down to the surface (Pook et al. 2006). A ridge of high pressure is commonly located polewards of the low. The diameters of cutoff lows can range from the mesoscale to the synoptic scale (Reeder and Smith 1998), but the majority of the systems examined by Pook et al. (2006) are synoptic-scale systems. Cutoff lows are important weather systems because they are capable of

stratosphere-troposphere exchange, they can lead to deep moist convection and heavy rainfalls, and can bring an important fraction of the total rainfall in many regions. This study aims to evaluate the simulation of cutoff lows and the wider circulation in a regional climate model (RCM) for the southeast of Australia and Tasmania, and to examine the changes to these features that the RCM projects with a warming climate.

Models of the climate system need to simulate current rainfall with some fidelity before their projections of rainfall can be used with confidence (Meehl et al. 2007a). Regional model simulations of the rainfall climate depend on the realistic simulation of the mean synoptic climatology of the systems that bring rain. This includes realistic simulation of cutoff lows. If the simulated total rainfall compares well with observations but the synoptic climatology differs, then this may indicate a set of compensating errors within the model. These compensating errors may not balance out in the future as the dynamics of the climate changes, and the model may give an inaccurate representation of future rainfall. In this way, a bias in the simulation of the important systems can lead to a reduction in confidence in the rainfall projection from the climate model. For regions where an important source of rainfall is episodic systems that are distinct from the mean circulation, biases in the simulation of those episodic systems and their wider context may lead to considerable problems in making rainfall projections.

1.1 Cutoffs in southeast Australia and Tasmania

Episodic cutoffs lows are an important source of rainfall in some regions within the mid-latitudes of southern Australia, including some areas of eastern Australia and northeast Tasmania. In southeast Australia, cutoffs can bring over 50 % of the rainfall to the cropping region in northwest Victoria (Pook et al. 2006), so seasonal forecasts must include the incidence and strength of cutoff lows to be of value in this region (McIntosh et al. 2007). In northwest Victoria, cutoff rain is highly correlated with total rainfall in the growing season (April to October) and hence inter-annual rainfall variability (Pook et al. 2006). Also, the first significant rainfall of the winter growing season in southeast Australia is predominantly associated with cutoff lows (Pook et al. 2009). Even in El Niño years, several intense cutoffs can create a high rainfall season, masking the effect of El Niño conditions (Brown et al. 2009). Cutoffs bring almost 50 % of April to October rainfall in parts of northeast Tasmania and a slightly smaller proportion in the southeast (Pook et al. 2010). These systems bring a much smaller proportion of west coast rainfall, however the total rainfall in the west is much higher in this region so this still represents a considerable absolute amount of rainfall.

Cutoffs are also a very important source of the heavy and extreme rainfalls in northeast Tasmania. The importance of cutoffs to Tasmania and the spatial variation across a relatively small area make it a relevant case study for the evaluation of this type of system in climate models, including the effect of horizontal resolution, and to examine trends with climate warming.

Cutoffs are significantly correlated with blocking highs in the Australian region in the growing season of April to October (Pook et al. 2006). Blocking in the Australian region can be estimated using the Blocking Index employed by the Bureau of Meteorology (Pook and Gibson 1999). The blocking index at 140°E is positively correlated with rainfall over northeast Tasmania in all seasons and negatively correlated with rainfall in the southwest in all seasons except summer (Risbey et al., 2009). Blocking in turn has a role in modulating the intensity of the split jet in the upper atmosphere (Trenberth and Mo 1985). In Australia, the split jet refers to the shape of the time-mean flow, where the subtropical jet splits into two distinct branches over eastern Australia. The two distinct branches are the equator-ward subtropical jet at approximately 25–30°S, and the polar front jet at around 55–60°S (Bals-Elsholz et al. 2001). Also, Ndarana and Waugh (2010) suggest that the majority of mid-latitude cutoffs in the southern hemisphere can be linked to Rossby wave breaking events. Therefore, models must simulate blocking, the split jet structure of the region and the Rossby wave breaking at a hemispheric scale with some reliability in order to simulate cutoff lows.

1.2 The simulation of cutoffs in models

Problems have been uncovered in the simulation of mean circulation, the split jet, blocking and cutoffs in coupled general circulation models (GCMs). The current generation of GCMs have a typical horizontal resolution of 1°–3° latitude and longitude. The cause of the problems can be placed into two main categories: problems with insufficient resolution, and problems from model parameters and physics that are not improved by finer resolution. Problems that are not solved by higher resolution may include omission of relevant physical processes from the model or inaccurately simulated physical processes (e.g. from poor parameterisation of physical processes). Some persistent biases in the simulation of mean sea level pressure (MSLP) and mean circulation by GCMs are not related to spatial resolution (Randall et al. 2007). The persistent low bias in the simulation of blocking in both the northern and southern hemisphere by climate models is at least partly linked to the mean climatological biases in models. Some studies have shown that higher horizontal resolution leads to an improvement in the simulation of blocking frequency

(Matsueda et al. 2009), but much of the blocking error in climate models can be directly attributable to the climatological bias of the model, rather than coarse horizontal resolution (Scaife et al. 2010). Vertical resolution and the representation of the stratosphere, and the troposphere-stratosphere connection, are also likely to have an effect on the simulation of the split jet, blocking and cutoff lows.

Increasing horizontal resolution generally leads to better simulation of synoptic scale features the size of cutoffs. For example, the characteristics and structure of hurricane vortices are simulated with more accuracy in higher resolution models (Bengtsson et al. 1995). The synoptic-scale exchange between troposphere and stratosphere is an indication of tropospheric folds such as upper level troughs or cutoffs, and these features are significantly more realistic at higher resolution (Kentarchos et al. 2000). In the Australian region, small-scale physical processes play a key role in the development of cutoffs, and higher resolution improves intensity and track forecasts in weather models (Leslie et al. 1987). Regional scale numerical weather prediction models run at a horizontal resolution of 75 km are capable of reliably simulating the location and intensity of cutoffs (Qi and Leslie 2001; Qi et al. 2000) as well as the heavy rains and gale-force winds associated with them (McInnes et al. 1992). However, there is an influence from the model run time after initialisation, and numerical weather prediction models are expected to simulate cutoffs in the near period more reliably compared to observations than models run freely in climate mode.

An evaluation of the CSIRO-9 GCM showed that cutoffs developed in a manner similar to observed lows, but are distorted: the cutoff low is further east at the surface than at the upper levels (Katzfey and McInnes 1996). Low resolution was suggested as a possible cause of this bias, and Katzfey and McInnes (1996) suggest that the simulation could be improved by higher resolution. The GCM simulations also indicated that latent heat release had an important role in the formation of cutoff lows, so the atmospheric response to latent heat release at the surface may also be improved in finer scale simulations. Degradation of ECMWF Reanalysis to a 500 km scale by interpolation shows that the thermal structure is retained but the potential vorticity is significantly degraded and shows similarity to GCMs (Katzfey and McInnes 1996). Katzfey and McInnes suggest that biases in the simulation of vorticity in GCMs can be attributed to coarse resolution, but the north–south thermal structure in GCMs has a bias that is larger than can be explained by coarse resolution alone. This implies that simulation of the split jet may not be improved through finer resolution.

Another deficiency in GCM simulation of cutoff lows is that GCMs under-predict the frequency of cutoffs (Lambert 1988). The CSIRO-9 GCM under-estimated the number of cutoffs per year in the Australian region by approximately 45 %, with the greatest under-prediction in autumn and winter (Katzfey and McInnes 1996). There is also a marked under-prediction of the frequency of cutoff days in several other GCMs including CSIRO-Mk3 (McIntosh et al. 2008; Pook et al. 2010). The underestimation of the number of cutoff days is possibly linked to a poor simulation of the split jet (Katzfey and McInnes 1996). The under-prediction of the number and character of cutoff lows reduces the confidence in the model simulation of rainfall processes, and therefore in the projection of rainfall trends. The under-prediction of the frequency of cutoffs may be partly improved by finer spatial resolution, but the deficiency of the simulation of features such as the split jet may mean that problems remain in climate simulations even if they are run at fine resolution.

While the various biases in climate models compared to observations described above may reduce the confidence in using model projections of rainfall quantitatively, the projected change in processes with a warming climate are still of interest from a dynamical point of view. There is a reduction in the number of cutoffs over eastern Australia in $2\times CO_2$ GCM simulations compared to control simulations, probably caused by the reduced baroclinicity caused by the greater warming of the polar regions compared to the mid-latitudes and smaller split jet (Katzfey and McInnes 1996). Sea surface temperature (SST) sensitivity experiments in weather models by McInnes et al. (1992) illustrate the response of cutoffs to surface warming. An increase of SST of 2–3 °C caused a deepening of the central pressure of simulated cutoffs of generally 1–2 hPa, but up to 7 hPa. Also, the peak cutoff rainfall was increased by 45–80 %, and the mean rainfall from cutoffs also increased. Peak surface winds increased by 10 %, but the areal extent of gale force winds increased by 50–70 %. Fewer cutoffs accompanied by an increase in cutoff depth and rainfall brought by cutoffs, along with a less distinct split jet may represent a plausible response to surface warming, despite the deficiencies in the simulation. Changes to the split jet, blocking and cutoffs with surface warming have already occurred in recent decades, and these changes may be partly related to the surface warming already occurring. The strength of the subtropical jet and the polar front jet increased slightly, and the split between them slightly decreased in size over the period 1958–2000 (Bals-Elsholz et al. 2001).

This study aims to examine the simulation of mean circulation, the split jet, blocking and cutoff lows in an RCM to examine the effect of finer spatial resolution on these features in a climate simulation. After an evaluation of the simulation of these features, the projected trends with climate change will be examined.

2 Methods

Coupled general circulation model (GCM) output was dynamically downscaled using the CSIRO stretched grid RCM named Conformal Cubic Atmospheric Model (CCAM) (McGregor 2005; McGregor and Dix 2008; Thatcher and McGregor 2011). The downscaling used only SST anomalies and sea-ice concentrations from each host GCM as inputs. Prior to modelling, the SSTs from the GCM were bias-adjusted against Reynolds SST (Reynolds 1988) and interpolated to the relevant grid scale. A suite of six GCMs from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP-3) multi-model dataset (Meehl et al. 2007b) was used as input to CCAM, five of which were chosen for their performance in reproducing observed rainfall in the southeast Australian region (Smith and Chandler 2009). The other GCM was the most recent version of the Australian GCM (CSIRO-Mk3.5) available at the time of the study. The GCMs used as input were: CSIRO-Mk3.5, GFDL-CM2.0, GFDL-CM2.1, ECHAM5/MPI-OM, UKMO-HadCM3, MIROC3.2(medres). We examine simulations performed using the A2 emissions scenario from the special report on emissions scenarios (Nakićenović and Swart 2000), which describes a heterogeneous world through the twenty-first Century, resulting in ongoing high greenhouse gas emissions.

The downscaling was done in two stages. The first stage used a stretched grid with a grid resolution of approximately 0.5° lat/lon over the Australian continent. These model outputs are used for the analysis of circulation, the split jet, blocking and cutoff lows. The second stage of the downscaling used SST from the GCM as well as spectral nudging of the atmosphere from the intermediate model (Thatcher and McGregor 2009) to force a stretched grid with a grid resolution of approximately 0.1° lat/lon over Tasmania. These model outputs are used for analysis of rainfall. The methods are fully detailed by Corney et al. (2010).

The RCM outputs were compared to an example GCM (CSIRO-Mk3) taken from the CMIP3 archive (Meehl et al. 2007b) and also to NCEP/NCAR Reanalysis 1 (Kalnay et al. 1996; Kistler et al. 2001). NCEP Reanalysis 1 is at a horizontal resolution of 2.5° lat/lon grid resolution. The split jet is examined in the pattern of mean zonal wind at the 500 hPa pressure surface. NCEP Reanalysis 1 winds are compared to the RCM simulations for the end of the twentieth Century, and the change over the century is examined by comparing the difference in patterns by the end of the twenty-first Century. Blocking is investigated using the Blocking Index in both NCEP Reanalysis 1 and the RCM simulations (baseline and future).

For the analysis of cutoff lows, a specialised analysis toolbox was used named Synview. This software uses an algorithm based on MSLP, the 500 hPa geopotential level, and the 500–1,000 hPa geopotential thickness. It detects lows that are closed at the surface or at the 500–1,000 hPa levels using the rules developed by Pook et al. (2006). Cutoff lows were detected in 6-hourly output of the downscaled model simulations. The 0.5° lat/lon grid resolution model output was linearly interpolated to 2.5° lat/lon grid resolution to match the NCEP Reanalysis 1 and suit Synview. This interpolation means that the fine spatial structure of the lows is lost, but the basic features of the low are retained, so the analysis still measures the outcome of the dynamic development of lows in the RCM. Cutoffs in the RCM were compared to NCEP Reanalysis 1 and also ECMWF ERA40 Reanalysis (ECMWF 2010) for another perspective. The latitude, longitude, areal extent and depth of lows are reported at the surface level in this paper, except where marked.

To evaluate the simulation of lows in the entire extra-tropical region, the Synview software package was applied using an analysis window of 135–170°E and 45–20°S, the region of eastern Australia between the tropics and high latitudes (shown in Fig. 1). The bounds of the analysis box were loosely based on Katzfey and McInnes (1996), but were modified to meet the features of the Synview system such as the limit of reliable detection. Cutoffs that can bring rainfall to Tasmania were analysed using a smaller analysis box of 135–155°E and 35–50°S. This region was identified as appropriate to Tasmanian rainfall through careful manual analysis (Pook et al. 2010). An example
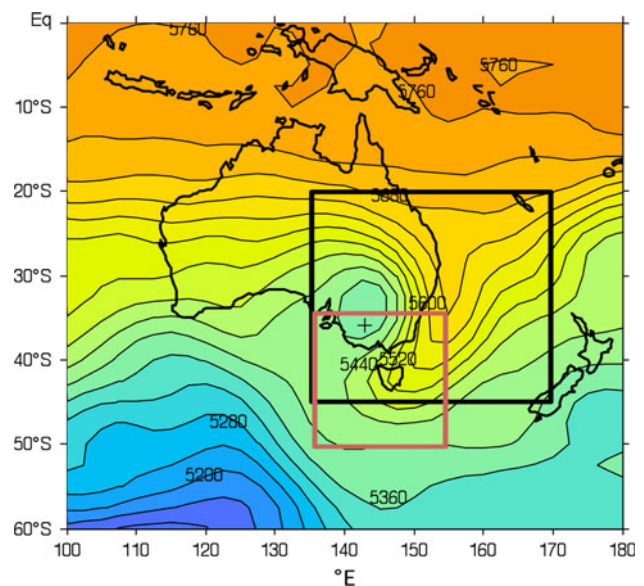

Fig. 1 Geopotential thickness of the 500–1,000 hPa layer on 23 August 2003 from NCEP Reanalysis 1, showing the position of a cutoff low (*plus symbol*), the analysis window for the RCM evaluation (*black box*) and the analysis window for Tasmanian rainfall from cutoffs (*red box*)

chart of 500–1,000 hPa geopotential thickness in NCEP Reanalysis 1 over the Australian region on 23 August 2003 (Fig. 1) indicates the position of a cutoff low automatically detected in southeast Australia by Synview. Also shown on the figure are the dimensions of the two analysis windows used in this study.

3 Results

3.1 Mean circulation

There are some differences between the GCM and RCM simulations, some of which indicate an improvement with higher resolution compared to NCEP Reanalysis 1, others that don't. In common with GCM simulations, the RCM shows a markedly steeper pressure gradient in the mid-latitudes than is found in observations (Fig. 2). This is caused by both a high bias in the pressure of the subtropical ridge and a low bias in the circumpolar trough. This effect is the most obvious in winter (Fig. 2, bottom row) where the RCM ridge extends well into the Tasman Sea. The RCM also shows a weaker trough near Western Australia compared to NCEP Reanalysis 1, especially in winter.

The simulation of the mean 850 hPa zonal wind speed field over Australia is less biased in the RCM compared to

the example GCM in several ways, but some of the same problems remain (Fig. 3). The northward bias of the mid-latitude westerlies in winter is less pronounced in the RCM compared to the example GCM (Fig. 3, bottom row). The bias in the shape of the wind speed contours over the Tasman Sea and New Zealand are reduced in the RCM compared to the example GCM, but is not eliminated. The pattern of mean flow over the Tasman Sea region in winter is particularly relevant to this study, as it is linked to the split jet structure, blocking and therefore cutoffs.

Global climate models project that greenhouse warming causes the westerly jet to move poleward in the summer half-year and to generally get stronger year-round (e.g. Kushner et al. 2001). These changes are also present in the RCM simulations, including a strengthening of the westerly jet to the south of Australia in winter, which has particular relevance to the split jet, blocking and cutoffs (see below).

3.2 Split jet

The structure of the split jet over the Australian region is indicated by the mean zonal wind speed at the 500 hPa pressure surface (Fig. 4). Compared to NCEP Reanalysis 1 (Fig. 4a), output from the example GCM CSIRO-Mk3 shows some marked biases in the simulation of the split jet
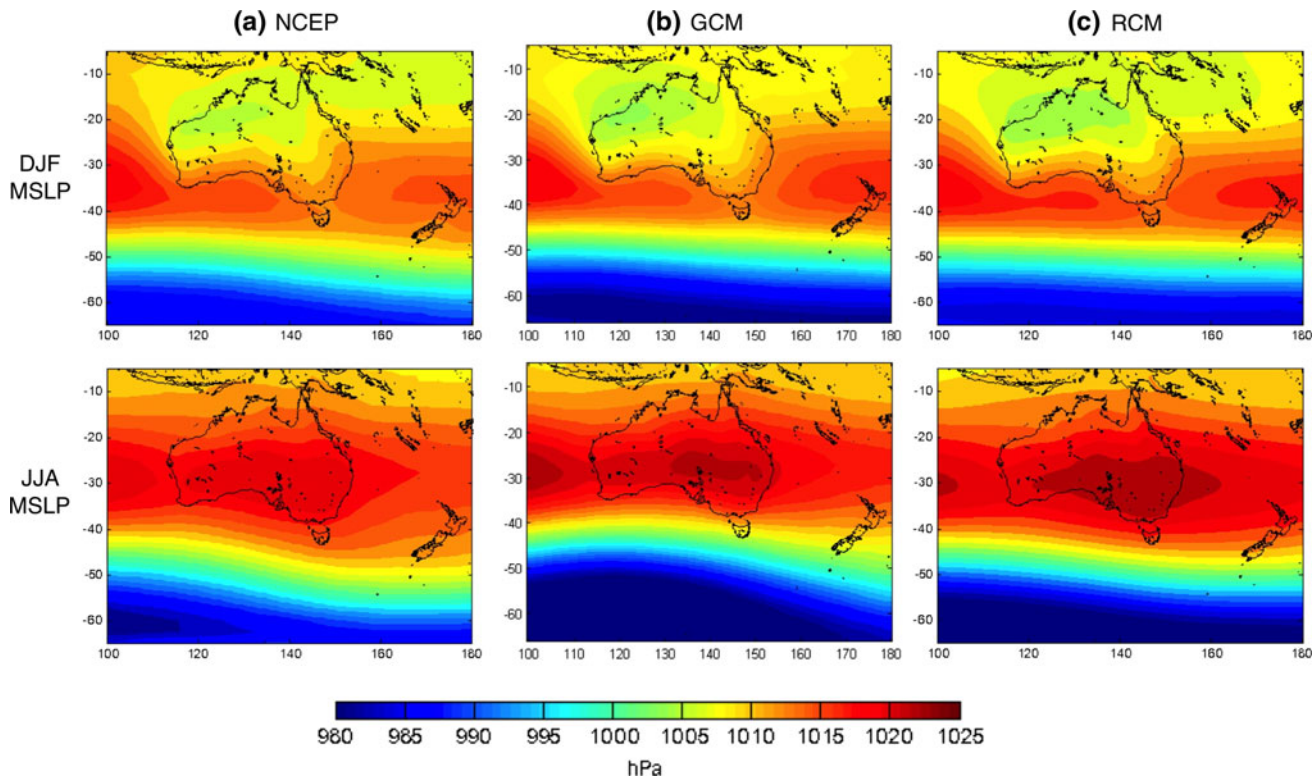

Fig. 2 Mean sea level pressure (MSLP) in the period 1980–1999 in the seasons indicated (DJF and JJA): **a** NCEP Reanalysis 1 in DJF, **b** example GCM CSIRO-Mk3 in DJF, **c** model-mean of CCAM RCM simulations
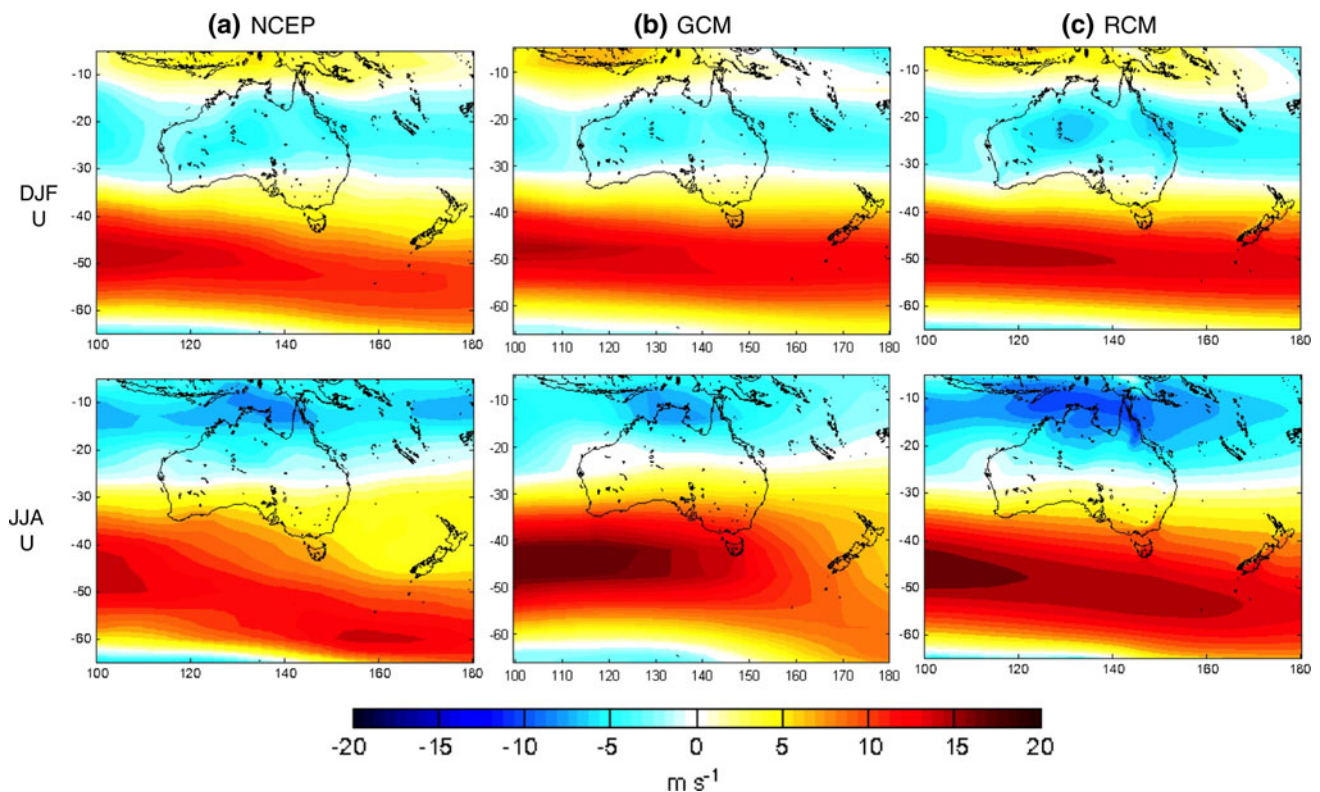
Fig. 3 Mean 850 hPa zonal wind speed in the period 1980–1999 in the seasons indicated (DJF and JJA): **a** NCEP Reanalysis 1 in DJF, **b** example GCM CSIRO-Mk3 in DJF, **c** model-mean of CCAM RCM simulation

structure in winter (Fig. 4b), including a very weak polar jet south of New Zealand. The mean wind speeds and broad structure in the RCM simulations (Fig. 4c) are much more similar to the NCEP Reanalysis 1 and reflect the greater skill of this RCM simulation relative to the example GCM. However, the RCM polar front jet is located further north and is stronger than in NCEP Reanalysis 1, and there are also some key differences in the spatial pattern. Importantly, in winter there is a narrower and differently shaped split over eastern Australia in the RCM, and the origin of the split is also further west in the RCM than in NCEP Reanalysis 1 (illustrated by the shape of the 15 m s^{-1} contour). These differences from NCEP Reanalysis 1 are even more pronounced when looking at June in isolation (bottom row).
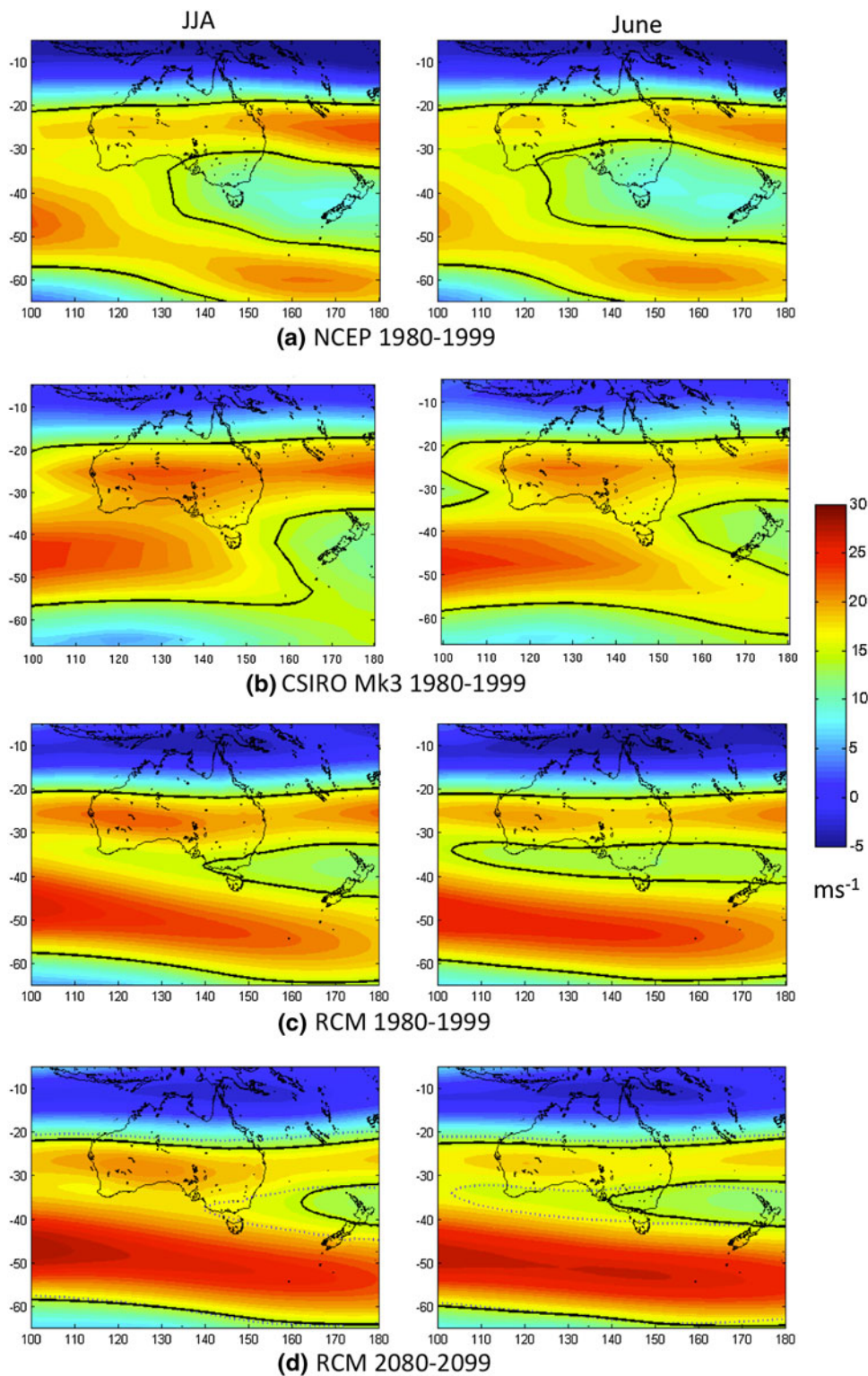
The change over the projection with climate warming is shown by the difference between the end of the twentieth Century (Fig. 4c) and the end of the twenty-first Century (Fig. 4d). The strength of the polar front jet increases in winter over the century (Fig. 4c, d), and also in spring, summer and autumn (not shown), consistent with previous model results (e.g. Kushner et al. 2001). In winter, the width of the split diminishes and the origin of the split moves further east. Again, these features are even more evident in June only. These results are consistent with

previous findings of Katzfey and McInnes (1996), who found a strengthening of the jet and a reduction in the split jet structure in a 2× CO$_2$ simulation compared to 1× CO$_2$. This suggests that a strengthening of the jet and a closing of the split are plausible responses to rising greenhouse gas concentrations in the atmosphere, despite limitations in the simulation of the jet in the RCM.

3.3 Blocking

The Blocking Index was calculated at 5° intervals across the range 100–180°E from NCEP Reanalysis 1 and the mean of the RCM simulations (Fig. 5). The longitudinal pattern and the annual cycle of blocking index are broadly similar between NCEP Reanalysis 1 and the RCM, but there is a consistent low bias in the RCM (Fig. 5b) compared to NCEP Reanalysis 1 (Fig. 5a) in all months and at all meridians of approximately 5 m s^{-1}. This is evident in the seasonal cycle at 140°E (Fig. 5c), a meridian adjacent to Tasmania. This under-estimation of the blocking index is similar to models at GCM resolution such as CSIRO-Mk3 (not shown). This result is consistent with the finding of Scaife et al. (2010) who found that the low bias in blocking in climate models is related to mean climatological biases and not just to horizontal resolution.

Over the century, the Blocking Index in the RCM shows a shift in seasonality, with increases in blocking in December to May, and decreased blocking in June to November (Fig. 5b, d). The change at 140°E is for a maximum reduction in July to September of −7.9 m s^{-1}, and a maximum increase in February of +5.2 m s^{-1} (Fig. 5e). The results suggest that this seasonal shift in blocking is a response to climate warming, and this may be a valid trend despite the bias in blocking in the RCM.
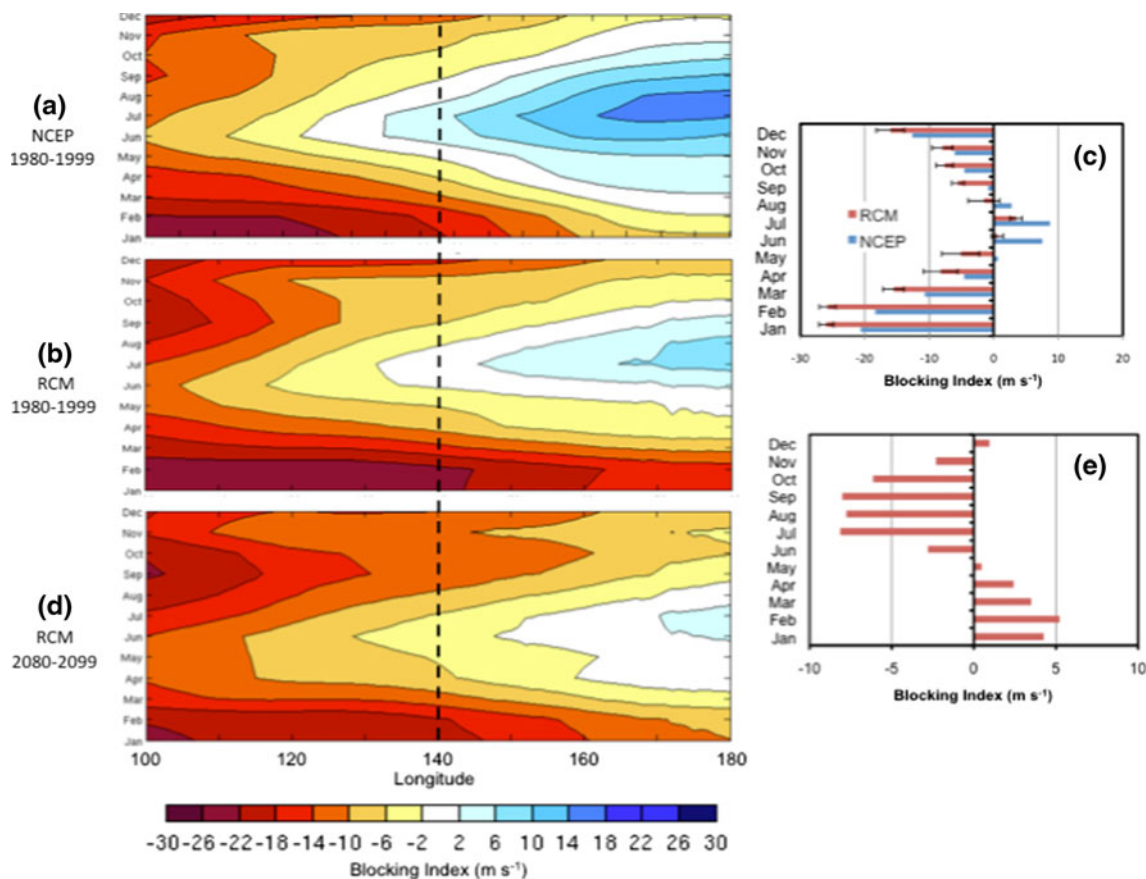
Fig. 5 Blocking Index in the Australian region (100–180°E) for each month of the year, **a** mean in NCEP Reanalysis 1 in 1980–1999, **b** the RCM mean in 1980–1999, **c** the seasonal cycle of Blocking Index at 140°E in NCEP Reanalysis 1 and the RCM (mean of six simulations, *error bars* show standard deviation between the six simulations) in 1980–1999, **d** the RCM mean in 2080–2099, **e** the mean change in the seasonal cycle in the RCM mean between 1980–1999 and 2080–2099 (*dashed line* in **a**, **b**, and **d** indicates the longitude of the 140°E meridian)

3.4 Cutoffs

Using the large analysis window, the RCM shows an underestimate of the number of cutoff days compared to NCEP Reanalysis 1 and ERA40 Reanalysis in the baseline period (Fig. 6). The under-prediction is 30 % on an annual basis, which is less than in the CSIRO-Mk3 GCM simulation (47 %). Previous studies have also found an under-prediction of cutoff number by ~45 % in other GCMs (Katzfey and McInnes 1996; McIntosh et al. 2008; Pook et al. 2010), so this improvement may be attributable at least partly to increased horizontal resolution. The under-estimate is greatest in February (50 %), which is similar to the example GCM, and least in October (17 %), which is significantly less than in the example GCM (58 %).

Just as notable as the bias in the number of cutoff days is the bias in latitude. There is distortion of the latitude position and the north–south vertical profile of cutoffs in the RCM compared to reanalyses (Fig. 7). There is a large bias in mean surface latitude of cutoffs in the simulations

that is smallest in January (1.7°) and greatest in August (9.0°) (Fig. 7a). The bias at the 500 hPa level shows a different profile (Fig. 7b). This creates a different vertical profile in the RCM compared to Reanalyses, where in the model the surface low develops north of the upper level cutoff, whereas it is the opposite in Reanalyses (Fig. 7c). In August, the mean position of surface cutoffs is in the middle of the subtropical zone in the RCM with a mean latitude of ~29°S, whereas in the reanalyses they lie at the southern margin of the subtropics at ~38°S.

In contrast to latitude, there is a small bias in cutoff longitude at the surface (mean bias 1.0°) that is comparable to the bias in the example GCM (Fig. 8a). The RCM generally underestimates the persistence and areal extent and depth of cutoffs, but shows no strong bias in cutoff depth (Fig. 8). The mean lifetime of detected cutoffs at the surface in NCEP Reanalysis 1 in the baseline period (1980–1999) is 3.6 days, whereas the RCM lifetime is 2.5 days (model range 2.4–2.6 days). There is no significant bias in cutoff depth at the surface, with some
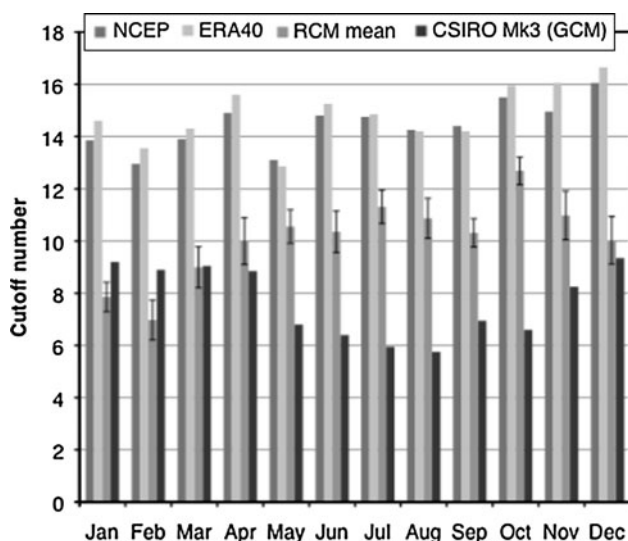
Fig. 6 Mean monthly cutoff number in 1980–1999 estimated using the Synview software package in the large detection window (20–45°S, 135–170°E, Fig. 1) in NCEP Reanalysis 1 and ERA40 reanalysis, RCM simulations (mean of six simulations, *error bars* show standard deviation between the six simulations) and an example GCM (CSIRO-Mk3)

improvement over the example GCM indicated in July and August (Fig. 8b). There is a low bias in cutoff areal extent at the surface [annual mean 30 %, highest in June (46 %) and lowest in January (10 %)], which is comparable to the example GCM (Fig. 8c).

Within the large analysis window, the number of cutoff days is projected to reduce dramatically through the twenty-first Century (Fig. 9; Table 1). The decrease in cutoff days occurs in every season, but is most marked in spring and summer. The multi-model mean reduction in the number of cutoff days between 1980–1999 and 2080–2099 is 67 % annually, and is 85 % in summer. The reduction in the number of cutoffs is consistent with Katzfey and McInnes (1996) and supports their hypothesis of a reduction in cutoff number in response to a general reduction in baroclinicity with climate warming. The doubling of CO_2 in their study is similar to the greenhouse forcing in this study, since the A2 emissions scenario represents an approximate doubling of CO_2 concentrations between the end of the twentieth Century and the end of the twenty-first Century. Cutoff number is correlated with atmospheric blocking in the growing season (April to October), so the decrease in cutoff number in in winter and spring is consistent with a decrease in atmospheric blocking in these seasons (Fig. 5). The correlation between cutoff number and blocking in the warmer months has not been reported, but it is notable that the decrease in cutoff number in summer and autumn is in contrast to the projected increase in atmospheric blocking in these seasons.

The decrease in the number of cutoff days in the simulations is consistent with the trend seen in NCEP Reanalysis 1 and the RCM in the period 1970–2009. The period only since 1970 was examined in NCEP Reanalysis 1, since it has systematic biases before 1970 in high latitudes and the Southern Ocean adjacent to Tasmania (Hines et al. 2000). The number of cutoff days in NCEP Reanalysis 1 declines over the period 1970–2009 at a linear trend of -0.57 days year^{-1}, and the decline in cutoff days over the same period in the RCMs is comparable at -0.39 days year^{-1} (model range -0.67 to -0.12 days year^{-1}). As a proportion, these rates are identical at -0.32 % year^{-1} (model range -0.56 to -0.09 % year^{-1}). Reductions in cutoff days in occur in all seasons except MAM, and the NCEP Reanalysis 1 agrees reasonably well with the RCM in each season. For example, the trend in winter is -0.04 days year^{-1} in NCEP Reanalysis 1 and -0.06 ± 0.06 days year^{-1} in the RCM.

There are also some notable projected changes in the mean depth, areal extent and latitude of cutoffs, but little change in mean longitude of cutoffs (Table 1). Cutoff depth is projected to significantly increase annually (Table 1), and increases in depth are projected in all seasons. The strongest projected increase is in summer (multi-model mean change is 1.6 hPa or 45 % of baseline mean). The projection under the A2 scenario features a surface temperature change of 2–3 °C. McInnes et al. (1992) found that increased SST of 2–3 °C led to an increase in cutoff depth of 1–2 hPa in a model experiment. Therefore, these projections support the finding of a general increase in cutoff depth by McInnes et al. (1992), but indicate that this increase is stronger in spring and summer. The CCAM simulations also indicate that the areal extent is projected to decrease in winter but increase in summer, and that the mean cutoff latitude is projected to move north in summer (Table 1). There are only small projected changes in mean longitude. The reduction in cutoff days in spring and summer to very low incidences leads to a much noisier timeseries in the last half of the projection for these parameters. This reduces the clarity and confidence in the trends in depth, areal extent and latitude seen in these seasons. It also means that many projected changes in summer are large but not statistically significant (Table 1) because of the small number of lows in the future period in summer.

3.5 Tasmanian rainfall from cutoffs

There is a large under-prediction of the number of cutoffs within the Tasmanian analysis window, especially in winter (Fig. 10), and this leads to an underestimation of rainfall from cutoffs (Fig. 11). The proportion of April to October rainfall that comes from cutoffs in the recent

Fig. 7 Mean latitude of cutoff lows in 1980–1999 estimated using the Synview software package in the large detection window (20–45°S, 135–170°E, Fig. 1) in NCEP Reanalysis 1, ERA40 reanalysis, the RCM simulations for 1980–1999 (mean of six simulations, *error bars* show standard deviation between the six simulations), **a** latitude of cutoffs at the surface, also shown is an example GCM (CSIRO-Mk3), **b** mean latitude of cutoffs at the 500 hPa level, **c** mean latitude of cutoffs at the surface and at 500 hPa level (only model mean and NCEP Reanalysis 1 shown for clarity)
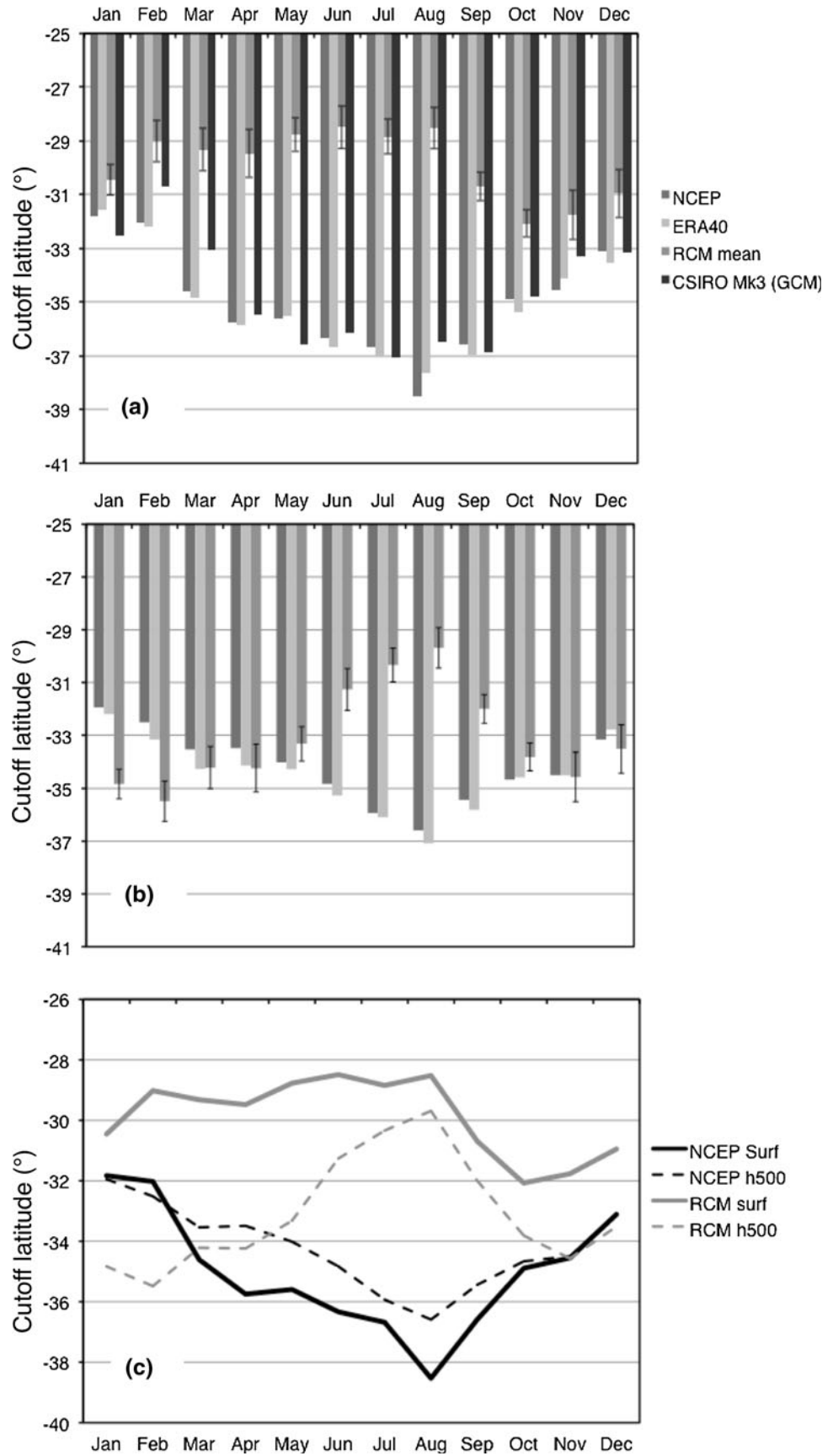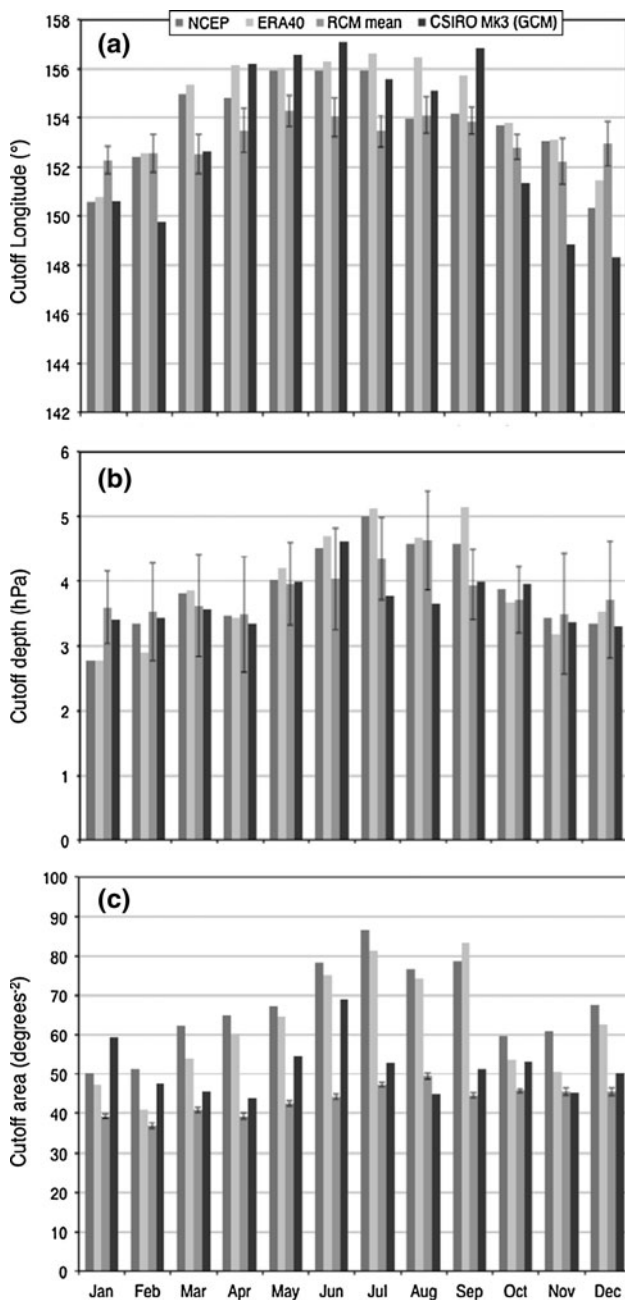
Fig. 8 Mean characteristics of cutoff lows in 1980–1999 estimated using the Synview software package in the large detection window (20–45°S, 135–170°E, Fig. 1) in NCEP Reanalysis 1 and ERA40 reanalysis, the RCM simulations (mean of six simulations, *error bars* show standard deviation between the six simulations) and an example GCM (CSIRO-Mk3), **a** central longitude at the surface, **b** central depth at the surface (central pressure compared to outside) and **c** areal extent at the surface

period calculated using manual analysis of weather charts (Pook et al. 2010) and the AWAP gridded rainfall dataset (Jones et al. 2009) and the Tasmanian analysis window shows that the proportion is up to 55 % near the east coast

(Fig. 11a). A similar proportion of rainfall from cutoffs is present in the RCM simulations when using the wider Australian window (Fig. 11b). However, this window is too wide for looking strictly at Tasmanian rainfall from cutoffs. When the window designed specifically in Tasmania is used, a much smaller proportion of rainfall is indicated, less than 10 % (Fig. 11c). This proportion reduces to less than 3 % in the RCM during the end of century period 2080–2009 (Fig. 11d).

The under-prediction of cool-season cutoff rainfall in the RCM is mainly a result of the large latitude distortion of cutoffs in the RCM. During the cooler season, cutoffs in the RCM are further north than seen in reanalysis (Fig. 7), and are therefore not detected using the Tasmanian analysis window. The RCM does not generate enough cutoff lows relevant to Tasmania that conform to the rules established from observations in the cooler months where they have the most impact.

Despite the large underestimation, the spatial pattern of rainfall brought by cutoffs shows some basic similarity to the manual analysis where the proportion is highest over the east coast, followed by Flinders Island. Also, the decline in the proportion of rainfall brought by cutoffs (Fig. 11c, d) is consistent with the reduction in incidence of cutoffs (Fig. 9).

4 Discussion and conclusions

There are several biases and deficiencies in the simulation of the split jet, atmospheric blocking and cutoff lows by GCMs in the Australian region. Most of these biases are improved but not fully removed in these RCM simulations compared to typical GCMs. Some additional biases are present in the RCM that were weaker or not present in the GCMs. The different magnitude and character of the biases in the RCM used in this study (CCAM) compared to GCMs are a function of the specific features of the model, including dynamics and parameterisations within the model, but also finer spatial resolution. The downscaling shows the effect of moving from 2°–3° to 0.5° grid resolution. The presence of biases, including additional biases compared to GCMs, shows that horizontal resolution is not the only issue in the reliable simulation of these characteristics of the atmospheric circulation in the Australian region in climate models.

The split jet shows an improved but still distorted shape in the RCM simulations compared to an example GCM. Atmospheric blocking as measured by the Blocking Index showed a consistent low bias in the RCM simulation, similar to GCMs. There is a smaller under-prediction of the number of cutoff days in the entire region in the RCM than

Fig. 9 Timeseries of the
number of cutoffs in the
Australian region estimated
using Synview software in the
large detection window
(20–45°S, 135–170°E, Fig. 1)
for NCEP Reanalysis 1 (*blue*),
ECMWF ERA40 Reanalysis
(*black*), each of the six RCM
simulations (*red*) and an
example GCM simulation
(CSIRO-Mk3, *green*) calculated
for: **a** annual, **b** autumn,
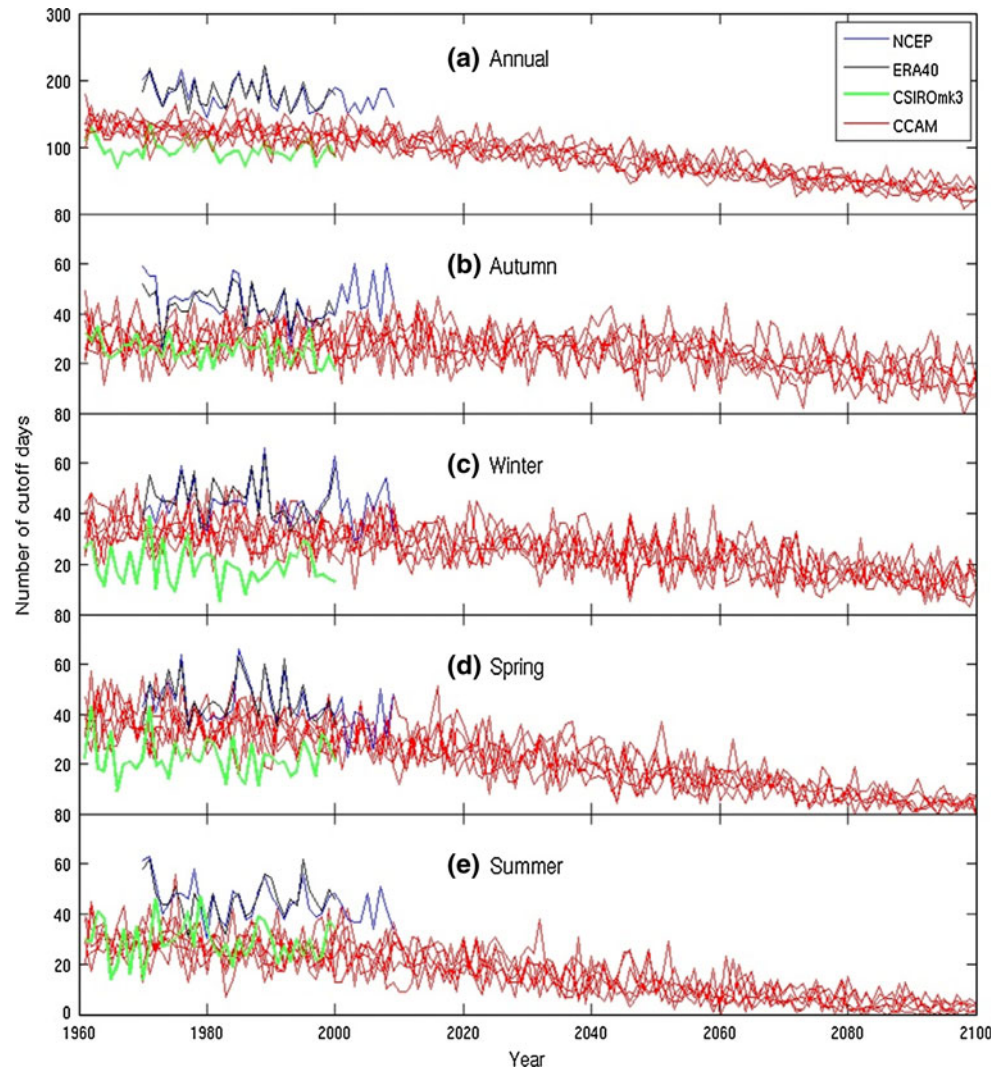**c** winter, **d** spring, **e** summer

Table 1 Projected change in cutoffs over the twenty-first century (1980–1999 to 2080–2099) under the A2 scenario in six CCAM simulations

	Annual	Winter	Summer
Cutoff number	**−67 % (−75, −60)**	**−54 % (−63, −47)**	**−85 % (−93, −80)**
Cutoff depth	**0.6 hPa (0.3, 1.0)**	0.4 hPa (0.1, 0.6)	1.6 hPa (0.4, 2.9)
Cutoff area	−5 % (−15, 3)	**−20 % (−27, −3)**	40 % (16, 55)
Cutoff latitude	**1.9° (1.3, 3.1)**	0.2° (−0.9, 1.0)	**5.1° (4.1, 6.6)**
Cutoff longitude	−0.1° (−0.6, 1)	−1.3° (−2.5, 0.4)	1.7° (0.7, 2.3)

Multi-model mean value is given with highest and lowest model listed in brackets. Results are bold where at least half of the six simulations show
a change that is significant to the 95 % confidence level

in typical GCMs. There are several other noteworthy biases
in the RCM such as a low bias in the lifetime and areal
extent of cutoffs. A large latitude bias and north–south
distortion of cutoffs is present in the RCM that was not
present in GCMs.

The biases in the simulation of cutoffs at this location
(approximately 30–40°S, 150–156°E), particularly the

north–south distortion and the underestimation of cutoff
number and areal extent, can be linked to biases in the
wider circulation. The mean pressure bias indicates that the
subtropical ridge extends too far into the Tasman Sea, and
this is consistent with an under-prediction in cutoffs. The
~5° northward bias in the position of the polar front jet,
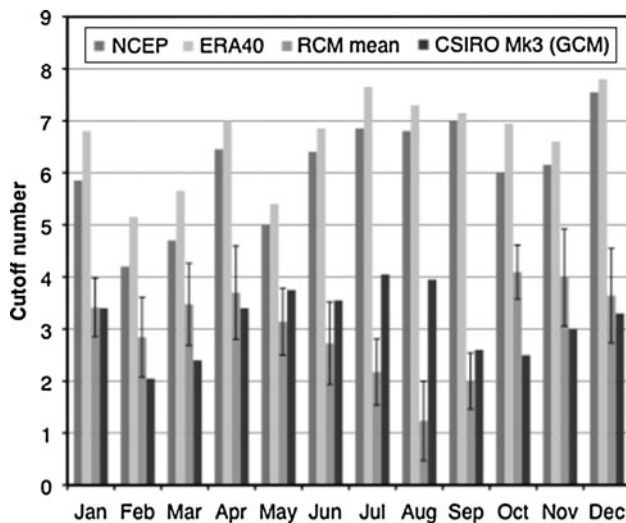the weak and northerly biased split jet and the low bias of

Fig. 10 Number of cutoff lows in 1980–1999 estimated using Synview software for the Tasmanian analysis window (35–50°S, 135–155°E, Fig. 1) from NCEP Reanalysis 1, ERA40 reanalysis, the RCM simulations (mean of six simulations, *error bars* show standard deviation between the six simulations), and an example GCM (CSIRO-Mk3)

>5 m s^{-1} in the blocking index are also consistent with this result. Katzfey and McInnes (1996) noted that the northern bias in the polar front jet is related to a deficiency in GCM parameterisations particularly in modelling high latitude processes around Antarctica. Deficiencies such as this are likely to be a cause of bias in these simulations through mean circulation, the split jet structure, atmospheric blocking and the simulation of cutoff lows.

These results indicate that insufficient or inaccurate representation of the physics in the model, unrelated to horizontal resolution, are a major impediment to the reliable simulation of cutoffs. It also highlights the need for models to simulate the mean climate reliably in order for them to accurately simulate the character of individual systems. A general conclusion from this result is that incomplete or inaccurate representation of the mean state of the circulation is a source of model bias for these features, and this is not just related to horizontal resolution.

There is a marked under-prediction of Tasmanian rainfall from cutoffs in the RCM simulations, but a consistent spatial pattern compared to observations with a higher proportion in the eastern region. This under-prediction of cutoff rainfall raises an important question of which systems are bringing the rainfall in the simulation. The rainfall totals in the RCM compare very favourably to observations (Corney et al. 2010), but if this rainfall is not brought by the correct mechanisms, including the large contribution

from cutoffs, then it reduces the confidence in the projection of rainfall trend. This is especially pertinent on the east coast of Tasmania where a large fraction of rainfall is brought by cutoffs.

Changes under the A2 scenario by the end of the century in these projections include a strengthening of the westerly circulation, a change in the seasonality of blocking, a reduction in the number of cutoff days but an increase in the central intensity of cutoff lows. In winter there is a projected reduction or closure of the split jet. Some of these changes are at least partly interrelated: for example, the reduction in the number of cutoffs in winter is consistent with a strengthening of the mean circulation, a decrease in the split jet structure and a reduction in blocking in this season. These results support the findings of previous modelling studies, including the increased westerly circulation (e.g. Kushner et al. 2001) and the closing of the split jet structure (Katzfey and McInnes 1996). The reduction in the number of cutoffs over eastern Australia is consistent with the results from Katzfey and McInnes (1996) in $2\times$ CO_2 GCM simulations compared to control simulations, and supports their hypothesis that the reduction is influenced by the reduced baroclinicity from greater warming of the polar regions compared to the mid-latitudes and smaller split jet (Katzfey and McInnes 1996). An increase in the intensity of cutoff lows, especially in spring and summer, supports previous findings of McInnes et al. (1992) and their hypothesis that an increase is linked to increased surface temperatures and also to increased moisture in the boundary layer. Given the similarity to previous studies, and the changes are consistent with increases to surface temperature, baroclinicity and water vapour, these projected changes represent a plausible response to climate warming notwithstanding the biases described above.

This preliminary analysis could be extended in several ways. A set of model experiments using the same model with various grid configurations could be used to isolate and attribute the influence of horizontal resolution on the simulation of the features described in this paper. The effect of various grid scales, as well as various parameterisation schemes and different dynamical cores could then be tested using a set of model experiments. Also, the effect of using a model with variable resolution rather than a regular grid is unknown, so comparisons between different model configurations may also be useful. A set of long control simulations would also help to characterise the internal variability and performance of model simulation of these features over a multi-decadal time frame. Further model simulations using models with low biases would be further evidence that the projected changes in this study are attributable to climate warming.

Fig. 11 Proportion of total
rainfall in April to October
brought by cutoff lows in
Tasmania, Australia, **a** mean
proportion of total rainfall using
manual analysis of weather
charts (Pook et al. 2010) and
AWAP rainfall dataset (Jones
et al. 2009), **b** mean proportion
of total rainfall in the RCM
ensemble for 1981–2009 using
the Australian analysis window,
c mean proportion of total
rainfall in the RCM ensemble
for 1981–2009 using the
appropriate Tasmanian analysis
window, **d** as for **c** but for
2080–2099 (note *different
colour* scales)
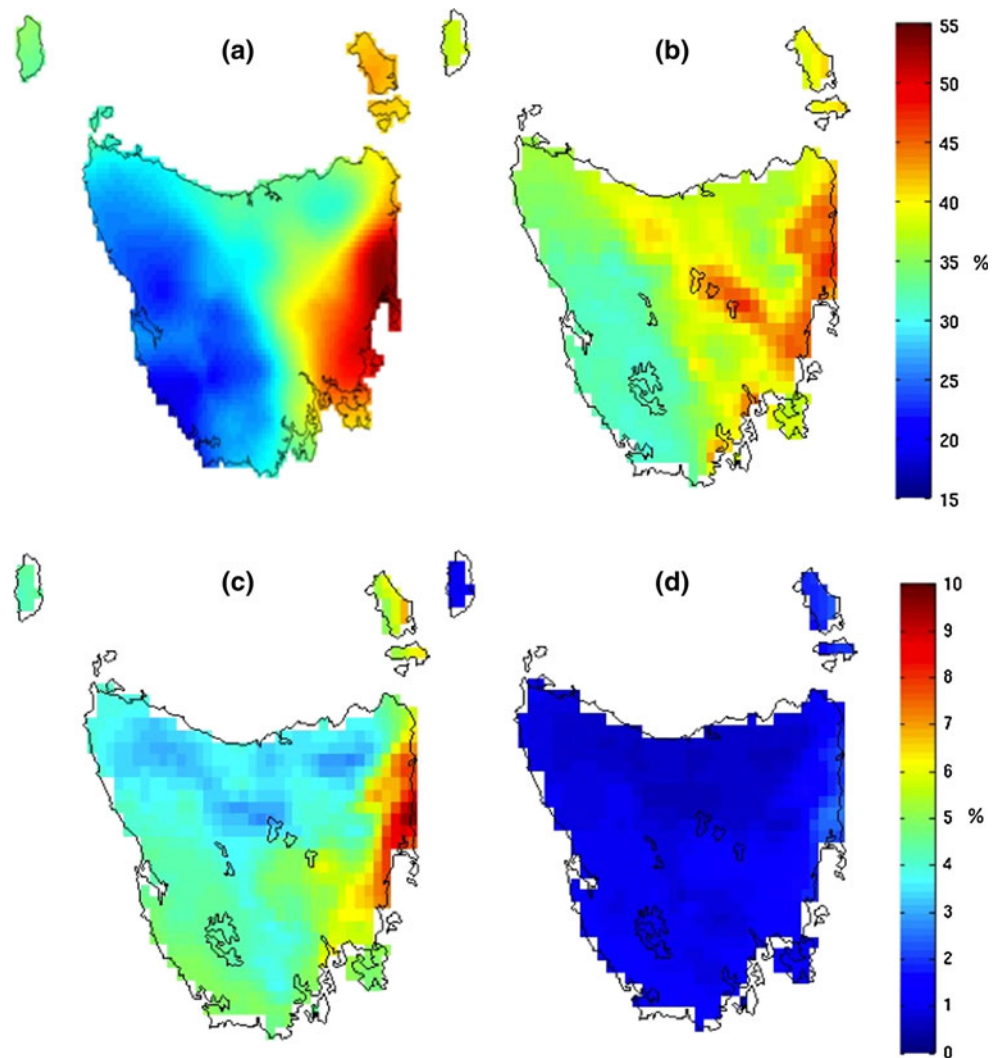
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