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Corresponding Author	Family Name	**Grose**
	Particle	
	Given Name	**Michael R.**
	Suffix	
	Division	
	Organization	CSIRO Climate Science Centre, Oceans and Atmosphere
	Address	Hobart, TAS, Australia
	Phone	
	Fax	
	Email	Michael.Grose@csiro.au
	URL	
	ORCID	http://orcid.org/0000-0001-8012-9960
Author	Family Name	**Foster**
	Particle	
	Given Name	**Scott**
	Suffix	
	Division	
	Organization	CSIRO Data61
	Address	Hobart, TAS, Australia
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Author	Family Name	**Risbey**
	Particle	
	Given Name	**James S.**
	Suffix	
	Division	
	Organization	CSIRO Climate Science Centre, Oceans and Atmosphere
	Address	Hobart, TAS, Australia
	Phone	
	Fax	
	Email	
	URL	

	ORCID	
Author	Family Name	**Osbrough**
	Particle	
	Given Name	**Stacey**
	Suffix	
	Division	
	Organization	CSIRO Climate Science Centre, Oceans and Atmosphere
	Address	Aspendale, VIC, Australia
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Author	Family Name	**Wilson**
	Particle	
	Given Name	**Louise**
	Suffix	
	Division	
	Organization	Bureau of Meteorology
	Address	Docklands, VIC, Australia
	Phone	
	Fax	
	Email	
	URL	
	ORCID	

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Abstract

Persistent shifts in mean rainfall have wide-ranging impacts to hydrology and water availability, and a reliable set of climate projections of change to mean rainfall is a useful tool for future planning. Most climate models project a decrease in winter rainfall in southern Australia, however there is a wide model range and there is not yet a robust assessment of underlying physical processes that can inform and constrain projections. Here, a multiple linear regression model between indices of atmospheric circulation and gridded rainfall in observations and in CMIP5 climate models is developed for July, representing the peak of winter. The regression is used as an evaluation tool for models and a basis to select models. Spatial distributions of the coefficients from the regression illustrate the relative important of different circulation features for rainfall across the region, and illustrate where climate models have deficiencies. As an additional check of projections, historical years that are an analogue for the projected future mean state of the atmospheric circulation are identified and the rainfall anomaly during those years is examined. Both approaches broadly agree and support previous work in suggesting a constraint on rainfall change to a decrease only. The regression analysis also suggests that the median projection for southwest Western Australia should be revised lower than the median of all climate models. The results demonstrate value in applying statistical techniques to understand relationships of rainfall to circulation and to refine confidence in regional climate projections.

Keywords (separated by '-') Atmospheric circulation - Climate projections - Model selection

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ORIGINAL ARTICLE

Using indices of atmospheric circulation to refine southern Australian winter rainfall climate projections

Michael R. Grose[1] · Scott Foster[2] · James S. Risbey[1] · Stacey Osbrough[3] · Louise Wilson[4]

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Abstract

Persistent shifts in mean rainfall have wide-ranging impacts to hydrology and water availability, and a reliable set of climate projections of change to mean rainfall is a useful tool for future planning. Most climate models project a decrease in winter rainfall in southern Australia, however there is a wide model range and there is not yet a robust assessment of underlying physical processes that can inform and constrain projections. Here, a multiple linear regression model between indices of atmospheric circulation and gridded rainfall in observations and in CMIP5 climate models is developed for July, representing the peak of winter. The regression is used as an evaluation tool for models and a basis to select models. Spatial distributions of the coefficients from the regression illustrate the relative important of different circulation features for rainfall across the region, and illustrate where climate models have deficiencies. As an additional check of projections, historical years that are an analogue for the projected future mean state of the atmospheric circulation are identified and the rainfall anomaly during those years is examined. Both approaches broadly agree and support previous work in suggesting a constraint on rainfall change to a decrease only. The regression analysis also suggests that the median projection for southwest Western Australia should be revised lower than the median of all climate models. The results demonstrate value in applying statistical techniques to understand relationships of rainfall to circulation and to refine confidence in regional climate projections.

Keywords Atmospheric circulation · Climate projections · Model selection

1 Introduction

A warming climate holds important implications for changes to hydrology and water availability. Persistent shifts in atmospheric circulation and the associated regional rainfall are linked with major impacts to natural and human systems, and changes to circulation due to increased greenhouse gases are less certain than other effects linked to thermodynamic changes. Circulation change is a major driver of rainfall variability and change in the mid-latitudes in cool seasons, including jets and storm tracks (Hoskins and Valdes 1990; Frederiksen and Frederiksen 2007), baroclinic instability (Phillips 1951) and coherent blocking (Frederiksen and Webster 1988; O'Kane et al. 2013). For southern Australia, rainfall variability and change is primarily a response to changes to rainfall associated with fronts and cutoff lows, arising from changes in storm tracks and blocking regions (Risbey et al. 2013a, b). External anthropogenic forcing is likely to have driven a shift in circulation and rainfall in the cool season in southern Australia (e.g. Frederiksen et al. 2017), and further forcing is likely to drive further changes in circulation and rainfall (e.g. Frederiksen and Grainger 2015). Changes to convective rainfall may be important to the future rainfall change in summer (e.g. Grose et al. 2019). It would be useful to users of future climate change projections if an analysis of the circulation drivers in models could be used to quantify the confidence in the projections, and ideally to refine the projections including a narrower range of plausible projected change than is currently given.

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✉ Michael R. Grose
Michael.Grose@csiro.au

[1] CSIRO Climate Science Centre, Oceans and Atmosphere, Hobart, TAS, Australia

[2] CSIRO Data61, Hobart, TAS, Australia

[3] CSIRO Climate Science Centre, Oceans and Atmosphere, Aspendale, VIC, Australia

[4] Bureau of Meteorology, Docklands, VIC, Australia

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The national climate projections for Australia (CSIRO and Bureau of Meteorology 2015) indicate that southern Australia is projected to become drier this century with *high confidence*, based on various lines of evidence including physical processes, past trends and climate model agreement. The projected change is primarily through a decrease in the cooler season rainfall, but with a seasonal and regional signature, including greater decrease centred in winter in southwest Western Australia and a smaller decrease centred in spring in the southeast Australia (Hope et al. 2015). Drying is projected under all Representative Concentration Pathways (RCPs) of van Vuuren et al. (2011), with the greatest reduction under the highest RCP8.5. Using the Coupled Model Inter-comparison Project phase 5 (CMIP5) multi-model database (Taylor et al. 2012) as a primary input, projected change for winter (June, July and August) in the Southern region for 1986–2005 to 2081–2100 under RCP8.5 has a median of −17% and a 10–90 percentile range of −32% to −2%, but the full range of 42 CMIP5 models considered in the national climate projections are noted as possible (−37% to +1%), and the possibility of change outside this range due to deeper uncertainty is noted.

Climate models have biases and some of these biases may affect their projections of climate change (Flato et al. 2013). Previous studies propose that some models may be unsuitable or should have a low weighting for some questions or generating particular projections, and the national climate projections discourages certain models to be used as a representative 'climate futures' in applications (Whetton et al. 2012). In addition, CMIP5 is an "ensemble of opportunity", not a true statistical sample of uncertainty, so model independence needs to be accounted for in generating an ensemble. Model selection and weighting is an entire field of research [see studies such as Knutti et al. (2017) and Sanderson et al. (2017)]. There is currently no standard method of evaluating models and applying model weightings to generate climate projections of both the central estimate and range, and different regions have different relevant climate features that affect projected change. Identifying a relationship between bias and projected change in particular climate features, known as a process-based emergent constraint, is one of the most promising ways to use evaluation to inform and constrain projections (Eyring et al. 2019). A previous study (Grose et al. 2017) focussed on emergent constraints on rainfall based on atmospheric circulation indices for the southern Australian domain.

Atmospheric circulation is a crucial driver of winter rainfall change for southern Australia. Grose et al. (2017) outlined how under ongoing high greenhouse gas emissions, the maximum of baroclinic instability, the storm track and atmospheric jets in the subtropical jet region over Australia are projected to weaken and/or move further south, consistent with other work (e.g. Frederiksen and Grainger 2015). Atmospheric blocking is projected to become less frequent and for the peak of blocking in the south Pacific Ocean to possibly move further east, also consistent with previous work (e.g. Parsons et al. 2016; Woollings et al. 2018). As a whole, the study reported that the projection is for a more zonal mean flow with less split flow over eastern Australia and the Tasman Sea in winter. The study found four potential emergent constraints in circulation indices where the bias in the current climate had a relationship to the projected change. These relationships were found in the strength of the subtropical jet, the frequency of blocked days, the longitude of peak blocking frequency and the latitude of the storm track within the polar front jet branch. When outlier models in these constraint relationships were rejected, rainfall projections were constrained at the upper (less dry) end of the projected range in July (from a 10–90% ensemble range of −2 to −28% in CMIP5 to −10 to −32% in the subset).

The present study is a follow-up to Grose et al. (2017), and pursues two new methods of using atmospheric circulation indices to refine rainfall projections for southern Australia in winter. The first is the use of a statistical model of rainfall based on circulation indices as a form of model evaluation, the second is the use of circulation indices to identify years in the historical record that are analogues for the future mean (known as temporal analogues).

A statistical model of southern Australian rainfall based on atmospheric features can be used as a prediction tool (e.g. Charles et al. 2004; Timbal et al. 2009), which is a specific research field with its own pitfalls (e.g. Fu et al. 2018), and is not the focus here. Rather, we use the comparison of the statistical model generated from observations with that from climate models as a form of evaluating the climate models, then applying this evaluation as a model weighting on the raw model outputs. The temporal analogue approach is closer to statistical downscaling used as prediction models but looks only at monthly mean state rather than daily rainfalls. This approach of using circulation or flow conditions as analogues for climatic conditions was suggested as a method to generate climate scenarios in the IPCC third assessment report (Mearns et al. 2001), as used in Wilby et al. (1994). Temporal analogues have also been used in other areas, including to examine extreme heat events (e.g. Jézéquel et al. 2018), assess current mean circulation analogues for the mid-Holocene climate (e.g. Antonsson et al. 2008), to identify analogues in paleo records that are an analogue for near-term future conditions in Antarctica (Mayewski et al. 2017). Each approach is examined, the similarities and differences are compared, and the results are compared to Grose et al. (2017).

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2 Data and methods

2.1 Data

Monthly mean rainfall was taken from the 5 × 5 km Australian Water Availability Project (AWAP), described in Jones et al. (2009) and Australian Bureau of Meteorology (2019). Gridded data and area averages for the Southern region, as well as Southwest and Southeast sub-regions from the national climate projections were examined (Fig. 1). Circulation indices were calculated from the Japanese Reanalysis JRA55 reanalysis (Kobayashi et al. 2015). The indices are mainly the peak value of the zonal mean of an atmospheric variable or index such as the jet, baroclinic instability and the storm track across a box over Australia covering the subtropical jet region (90 to 180°E, 10 to 40°S), but some indices use other geographic domains (Table 1). Data were examined for 1958–2005, the start date was chosen as observations are more reliable after 1958, and the end date is chosen to allow comparison to the historical runs of climate models that end in 2005. A multiple linear regression was also fitted to the years in the periods 1958–1980 and 1981–2005, roughly aligning with a change in circulation in the southern hemisphere (Frederiksen and Frederiksen 2007).

Circulation and rainfall were examined in July as a sample of the peak of winter processes (rather than June, July

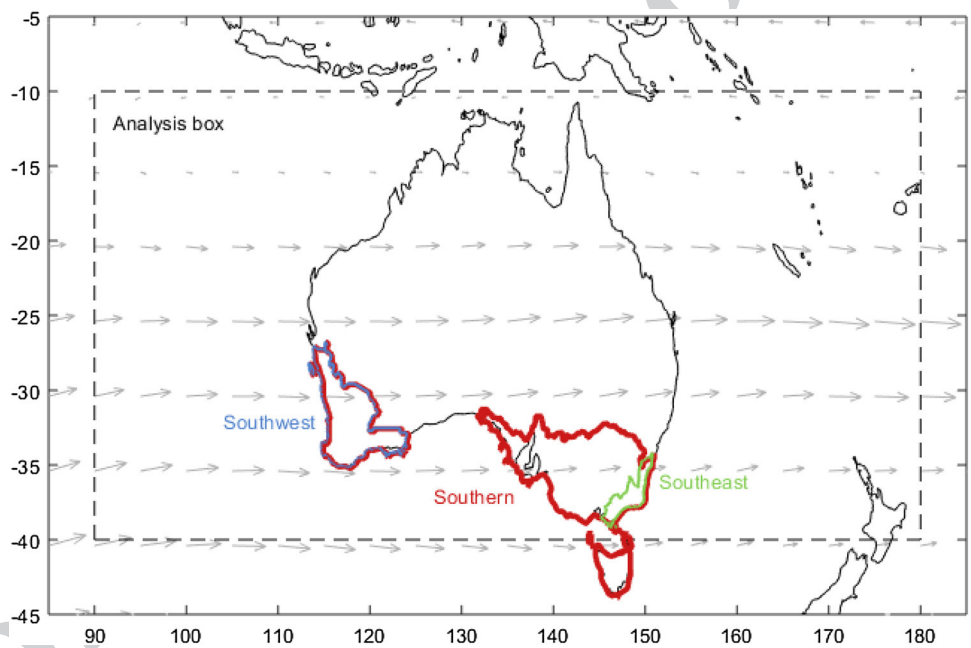

Fig. 1 Australian region showing box where zonal mean of circulation indices are calculated (dashed), the Southern rainfall region (red), the Southeast sub-region (green); and Southwest sub-region (blue). Vector arrows show the mean wind at 500 hPa in July, reflecting the westerly sub-tropical jet over this region

Table 1 Indices of atmospheric circulation relevant to southern Australian rainfall, the mean in 1958–2005 in JRA55, the model mean projected change between 1981–2005 and 2080–2099 from the 26 CMIP5 models

	Name	Description	July mean	July projected change
1	PC	Peak strength of baroclinic instability as measured by the Philips criterion	19.7	−0.3
2	PC lat.	Latitude of the peak in baroclinic instability measured by the Philips criterion	−29.1°S	−1.2°S
3	Jet	Peak strength of 300 hPa zonal winds	44.6 m s^{-1}	−8.4 ms^{-1}
4	Jet lat.	Latitude of the peak in 300 hPa zonal winds	−27.5°S	+0.9°S
5	Storm	Peak strength of the storm track (variance in the 500 hPa temperature in the 2–10 day band)	4.9	0 ms^{-1}
6	Block	Frequency of blocking days using the index of Tibaldi and Molteni (1990). For the Southern region, blocking is assessed at 150°E, for regional rainfall blocking was measured at the nearest 10° meridian of longitude	1.1 days	−0.7 days
7		Longitude of peak blocking index east of Australia	170°E	+20°E
8		Latitude of storm track peak	−29.5°S	−0.3°S
9		Peak strength of storm track on the polar front jet (using a box 90 to 180°E, 40 to 70°S)	8.8	+2.1 ms^{-1}
10		Latitude of storm track on the polar front jet	−58.4°S	+3.1°S

The first six indices are used in evaluating models, the other four are rejected

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and August). January was examined as the peak of summer in Grose et al. (2017), but is not examined here as there were no emergent constraints found in that season, and other factors than circulation such as convective rainfall change are likely to be important in this season.

2.2 Multiple linear regression to evaluate and select climate models

A multiple linear regression of inter-annual variations in July rainfall with variations in key circulation indices was performed, following the general regression formula in Eq. 1.

$$\text{Rainfall}_{i,j} = \beta_0 + \beta 1_{i,j} X_1 + \beta 2_{i,j} X_2 + \cdots + \text{Residual}_{i,j} \quad (1)$$

where rainfall in a grid cell or region (i, j) is described by an intercept β_0, and regression coefficients βk (k = 1…n) for that grid cell or region from multiple explanatory variables Xk (k = 1…n) that are in this case indices of atmospheric circulation, and the residual.

Ten circulation indices described in Grose et al. (2017) are tested here for their ability to describe rainfall within a multiple linear regression model (Table 1). These indices quantify the maximum strength (max.) and latitude (lat.) of the baroclinic instability measured using the Philips criterion (PC), the jet at 300 hPa (Jet), and the storm track (Storm), as well as the frequency and longitude of atmospheric blocking (Block). The mean of these indices in JRA55 in 1958–2005 is shown in Table 1. Each July index for 1958–2005 was detrended using a linear detrend and standardised by removing the mean and dividing by the standard deviation to make the indices, and hence their regression coefficients, commensurate regardless of their initial measurement units. Area-average and gridded rainfall was also detrended using a linear detrend.

The multiple linear regression using ten indices (Figure S1) revealed that four indices produced coefficients with rainfall with high values across much of southern and eastern Australia in AWAP/JRA55, so were included (PC, PC lat., Jet, Jet max.). In addition, two other indices showed notable regional patterns in areas of interest such as the Southeast sub-region or Australian Alps (Storm, Block), and one index produced notable coefficients in the eastern seaboard region (Storm box 2). The other indices (Block lon., Storm lat., Storm Box 2 lat.) produced coefficients of moderate values in some regions. Since we are fitting to only 48 data points (1959–2005, 48 years) there may be a risk of overfitting the regression, so to help avoid this risk the number of indices were reduced. Models using four and six indices were trialled, and the four-index version showed degraded explanatory power, so the six-index version was used. Indices of Jet and PC indices show some similarity but of opposite sign (coefficient of variation of R = 0.8, see Figure S1), but both are included as they aid explanatory power and correlated covariates is not a significant problem for estimation unless multicollinearity is notable. The rejected indices that showed notable coefficients with rainfall in some regions of eastern Australia (Block lon., Storm Box 2) are worth further investigation but are not discussed further here, as the focus is on southern Australia. The regression with six terms is used is used from here on (Eq. 2).

$$\begin{aligned}\text{Rainfall}_{i,j} = {} & \beta_0 + \beta 1_{i,j}\text{PC} + \beta 2_{i,j}\text{PC lat.} + \beta 3_{i,j}\text{Jet} \\ & + \beta 4_{i,j}\text{Jet lat.} + \beta 5_{i,j}\text{Storm} \\ & + \beta 6_{i,j}\text{Block} + \text{Residual}_{i,j}\end{aligned} \quad (2)$$

where Rainfall is the rainfall for a grid cell, region or sub-region, and βk (k = 1…n) are the coefficients for each circulation index listed in Table 1.

The six-factor multiple linear regression was fitted to JRA55 circulation indices and AWAP rainfall data, and then to the simulation of atmospheric circulation and rainfall in CMIP5 global climate models (GCMs). The 26 GCMs that had all indices available were used (Table 2). Rainfall from each GCM is interpolated to a uniform 240 × 120 global grid (approximately 1.5 × 1.5°Lat/Lon).

The coefficients from the multiple linear regression in each CMIP5 model are compared to the coefficients from JRA55/AWAP and the difference is quantified using a nearest neighbour analysis based on the Euclidean distance between the six indices (standardising the indices gives them equal weight). Differences are calculated for area-averaged rainfall and for each of the GCM grid cells compared to rainfall interpolated to the GCM grid. This Euclidean distance was then used as an evaluation of the models and basis for weighting model projections. This approach assumes that the inter-annual variations in circulation and its relation to rainfall is an appropriate analogue for multi-decadal scale changes in circulation and rainfall. Projected change in rainfall for each region was examined for the entire CMIP5 ensemble (42 models), the models tested (26 models), and sub-sets of models based on their Euclidean distance from observations.

2.3 Temporal analogue approach

The change in rainfall expected from the projected change in atmospheric circulation was explored through a temporal analogue approach. The mean of each index in 1958–2005 was calculated in JRA55, and the projected change to each index between 1981–2005 and 2080–2099 was calculated from each GCM (Table 1). The projected GCM change is then simply added to the JRA55 mean to create the analogue of the future mean of these circulation indices (Eq. 3).

$$\begin{aligned}\text{Future\_mean\_analogue} = {} & (\text{Mean JRA55 1958}-2005) \\ & + (\text{ProjectedchangeGCM 1985} \\ & -2005 \text{ to } 2080-2099, \text{RCP8.5})\end{aligned} \quad (3)$$

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Table 2 CMIP5 global climate models (GCMs) used in this study, the projection of rainfall in the Southern region between 1986–2005 and 2080–2099 under RCP8.5 (Proj), the Euclidean distance of the multiple linear regression from the GCM with JRA55/AWAP in the Southern region (Euc Sth), Southeast sub-region (Euc SE) and Southwest sub-region (Euc SW), lowest 6 values are bold, and the projected change in the six atmospheric circulation indices (see Table 1)

	Name	Proj (%)	Euc Sth	Euc SE	Euc SW	PC	PC lat.	Jet	Jet lat.	Storm	Block
1	ACCESS-1.0	−24	19.6	**24.0**	29.9	−1.6	−1.5	−7.8	0.00	−0.20	−0.52
2	ACCESS-1.3	−24	**12.3**	39.5	39.4	−0.1	−0.5	−4.0	0.50	0.25	−0.44
3	BCC-CSM1.1	−16	30.7	39.9	50.2	−1.0	−0.9	−3.7	0.25	−0.57	−0.36
4	BCC-CSM1.1-m	−18	34.9	39.1	39.4	0.1	−0.7	−3.2	−1.50	−1.32	−0.12
5	BNU-ESM	−12	**12.9**	45.1	39.4	0.2	−0.6	−0.2	2.75	−0.19	−0.32
6	CanESM2	−6	14.7	32.5	39.4	−0.6	−2.3	−8.0	−0.50	−0.73	−0.12
7	CMCC-CESM	−21	14.4	50.8	39.4	0.0	0.8	−6.8	8.75	0.37	−0.04
8	CMCC-CM	−28	21.8	**26.2**	**22.0**	−0.6	−0.5	−12.2	0.50	0.20	−0.76
9	CMCC-CMS	−21	**12.5**	**28.3**	**18.5**	−1.7	−4.2	−9.7	3.25	0.04	−0.84
10	CNRM-CM5	−24	34.5	61.5	32.0	−0.3	−0.9	−10.9	−0.60	−0.20	−1.08
11	FGOALS-g2	−4	30.3	38.6	39.4	−0.7	−0.8	−8.5	2.50	−0.15	−0.32
12	FGOALS-s2	−2	27.5	35.1	39.4	−0.2	−1.3	−0.1	0.00	0.24	0.00
13	GFDL-CM3	−32	24.1	38.1	24.2	−0.3	−1.8	−5.7	−3.25	0.33	−0.31
14	GFDL-ESM2G	−18	20.3	31.5	39.4	−0.5	−1.8	−10.2	−1.00	0.68	−1.04
15	GFDL-ESM2M	−38	23.6	34.1	39.4	−0.3	−3.5	−10.9	−0.75	0.79	−0.76
16	HadGEM2-CC	−25	30.0	39.7	39.4	−0.9	−2.7	−8.4	−1.50	−0.25	−1.56
17	IPSL-CM5A-LR	−25	**11.5**	**29.6**	**11.3**	−0.1	0.0	−9.4	3.25	1.19	−0.12
18	IPSL-CM5A-MR	−36	**7.7**	41.0	25.2	0.5	0.9	−11.4	0.50	1.58	−1.36
19	IPSL-CM5B-LR	0	19.9	31.6	27.3	0.0	−0.8	−14.6	3.50	0.15	−1.04
20	MIROC5	−5	41.8	48.6	59.1	0.5	−0.8	−16.5	−1.25	0.11	−2.32
21	MIROC-ESM	−16	24.8	48.7	23.0	−0.8	−1.4	−6.6	5.25	−0.25	−0.12
22	MIROC-ESM-CHEM	−18	15.7	40.4	**21.6**	0.3	−1.2	−6.4	5.25	−1.15	−0.28
23	MPI-ESM-LR	−7	**8.1**	**25.4**	**22.3**	−0.2	−0.6	−10.4	1.75	−0.16	−1.00
24	MPI-ESM-MR	−30	15.9	33.4	22.6	−1.1	−0.8	−12.1	1.00	0.06	−1.88
25	MRI-CGCM3	−16	19.2	**27.6**	**18.2**	0.3	−1.0	−11.6	−0.50	0.13	−1.28
26	NorESM1-M	−5	17.7	39.9	39.4	0.4	−1.4	−8.9	−3.50	−0.36	−0.60
	Multi model mean	−18	21.0	37.3	32.4						

For example, the current strength of the Jet is 44.6 ms^{-1}, the model mean projected change is −8.4 ms^{-1}, so the future analogue is 36.3 ms^{-1}. The future mean analogue is calculated for all six indices for each model and the GCM mean projection. Indices for all years are standardised by removing the mean and dividing by the standard deviation, and this same calibration is applied to the analogue future mean state. Years in the historical record with the set of six circulation indices that are most similar to the analogue future mean of those indices were identified using the Euclidean distance, then the rainfall anomaly in the composite of those years is calculated. A sub-set of 15 years was examined to maintain a relatively small sample but minimise noise. The rainfall in the 15 analogue years are then compared to the simulated change in mean rainfall simulated by the CMIP5 models, and the difference is calculated.

3 Results

3.1 Multiple linear regression in JRA55/AWAP

Maps of each coefficient from the multiple linear regression between atmospheric circulation indices in JRA55 and July rainfall for each cell in AWAP quantify the relationships with indices across Australia (Fig. 2). These maps reflect some physically meaningful spatial patterns. For example, indices associated with westerly circulation such as the strength of the baroclinic instability (PC) and strength of the subtropical jet (Jet) produce a high coefficient in areas such as southwest Western Australia and Tasmania. The sign reflects the nature of each index, where the strength of the Jet index is positively related to rainfall, whereas the strength of PC is inversely related to rainfall. Also, the latitude of maximum baroclinic instability (PC lat.) and the latitude of the maximum subtropical jet strength (Jet lat.) have a high coefficient for eastern Australia and the inland slopes

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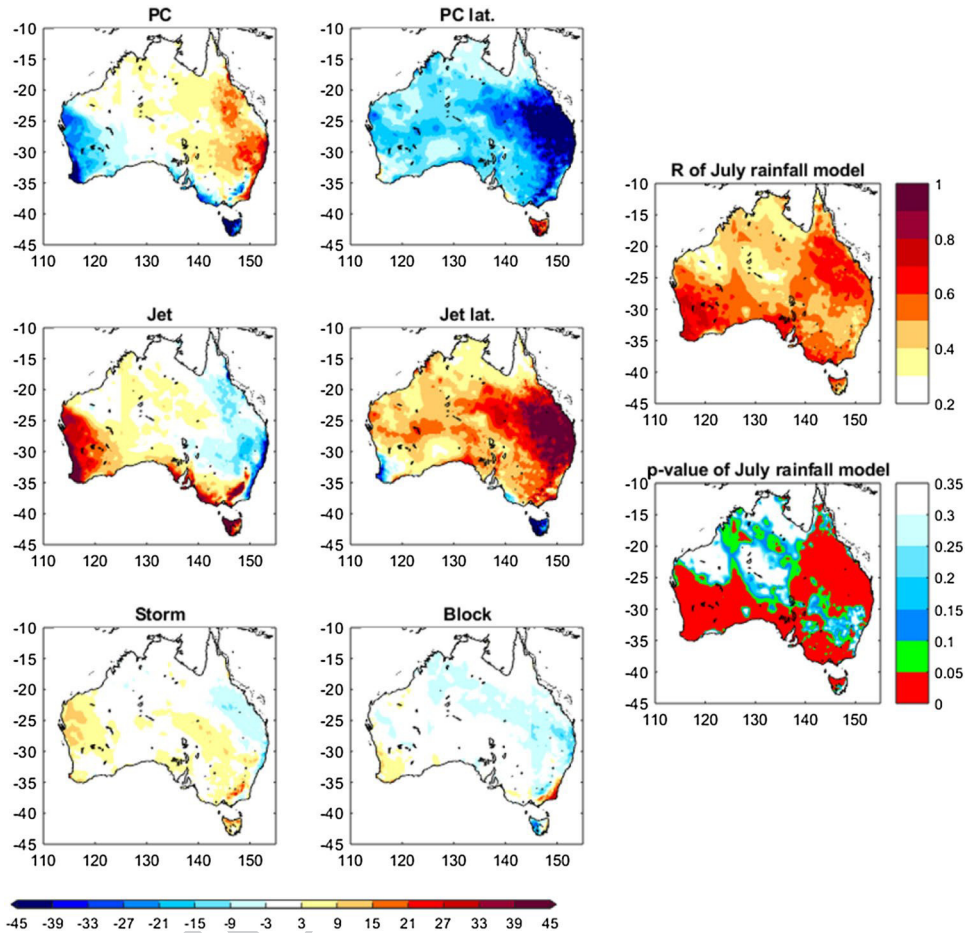

Fig. 2 Multiple linear regression of six atmospheric circulation indices from JRA55 (see Table 1) and rainfall from each cell of the AAP rainfall dataset in July 1958 to 2005, left: the coefficients of each index (note highest values go off scale), right: the correlation coefficient (R) and *p* value of the regression in each cell

of the Australian Alps, again with opposite sign. Blocking frequency (Block) has a high positive coefficient over areas on the southeast coast where it is related to the incidence of cutoff lows that are associated with higher rainfall, and a large negative coefficient in western Tasmania where it relates to lower rainfall due to a blocking of the westerly flow (Pook et al. 2013). The model has a correlation coefficient (R) over 0.7 and a significance level (*p* value) under 0.05 for regions of southwest Western Australia, South Australia and the coast of southeast Australia. For rainfall averaged over the Southern region, the fit is R = 0.71.

The spatial distribution of each coefficients is quite different in the early period 1958–1980 compared to the later period 1981–2005 (Figure S2), especially the strength of PC and Jet in eastern Australia, but other instances too. This suggests the relationship between rainfall and these circulation indices has changed over time, or that the errors in reanalyses prior to the satellite era starting in 1979 affect the results, or both. The fit of the statistical model is also different between the two periods, for the Southern region, the model has a correlation coefficient of R = 0.7 for 1958–2005, R = 0.86 in 1958–1980 and R = 0.74 in 1981–2005. The cross-sample validation fit is lower, period one model applied to period two R = 0.48, and period two model applied to period one R = 0.36. These fits also suggest there is a change in the relationship of circulation to rainfall between the two periods, or there are systematic errors in observations and reanalyses prior to 1980, or a combination of both. There is a significant difference in the mean of the storm track indices (box 1 and box 2) between the two periods (2-sample *t* test at the 95% level), but not any other index.

The multiple linear regression for rainfall averaged over the Southern region (Table 3, Fig. 3a), shows high coefficients for indices that describe the westerly circulation and movement of weather systems (PC, Jets). The difference in the regression in the early period 1958–1980 compared to the later period 1981–2005 (Fig. 3a) is clear, particularly the coefficient with PC and Jet latitude. The coefficients are different for rainfall averaged over the Southeast and Southwest sub-regions (Table 3, Fig. 3b), where the Southeast sub-region in particular shows stronger relationships with Block, Jet lat. and PC than the Southwest sub-region, and the coefficient of PC is of opposite sign. Interestingly, the recent period for the Southern region shows a stronger relationship with the Jet lat. and PC than the early period (Fig. 3a), a

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Table 3 Coefficients from a multiple linear regression for rainfall averaged over the Southern region, Southeast sub-region and Southwest sub-region with the six circulation indices, standard error is calculated using a 1000 member bootstrap with replacement

		Southern 1958–2005	Southern 1958–1980	Southern 1981–2005	SE 1958–2005	SW 1958–2005
1	PC	−11.1±4.6	−25.8±4.9	4.7±5.8	11.8±10.0	−22.4±4.9
2	PC lat.	−13.3±5.5	−3.4±6.4	−29.5±7.9	−21.8±12.4	−8.3±6.1
3	Jet	20.1±4.6	28.9±4.4	9.9±6.2	−4.9±9.8	30.9±4.8
4	Jet lat.	6.0±5.7	−6.4±6.4	23.6±7.9	18.6±13.0	−0.8±6.3
5	Storm	3.8±2.3	6.3±3.0	0.5±2.6	1.4±4.9	3.4±2.7
6	Block	−1.0±2.3	−1.2±3.4	-2.3±2.5	15.8±5.0	4.3±2.6

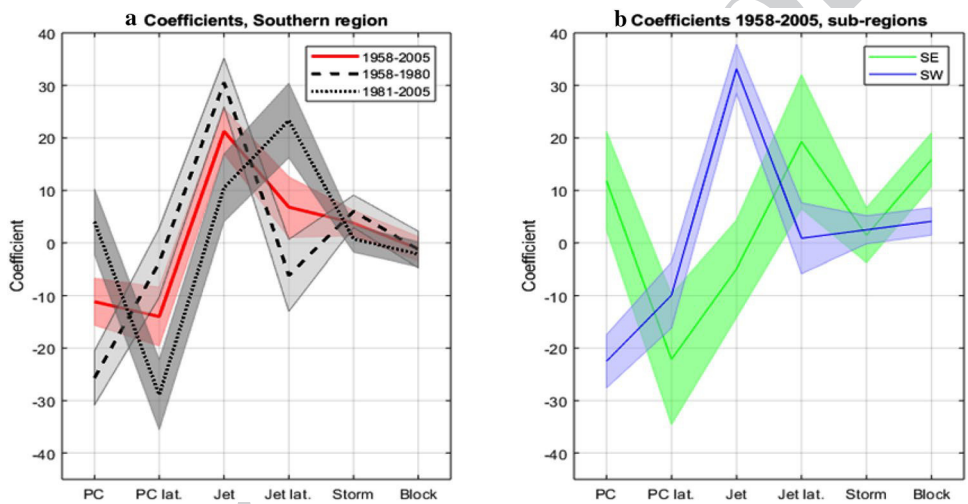

Fig. 3 Coefficients from the multiple linear regression for six atmospheric circulation indices in JRA55 (see Table 1) with AWAP for rainfall averaged over Southern region, Southwest sub-region and Southeast sub-region, and different time periods (1958–2005, 1958–1980, 1981–2005) in July. Coloured bands indicate the standard error calculated using a 1000 member bootstrap with replacement

pattern more similar to the Southeast sub-region than the Southwest sub-region (Fig. 3b).

3.2 Multiple linear regression in global climate models

The spatial distribution of the coefficients from the multiple linear regression in the mean of 26 climate models (Fig. 4) shows some broad similarity with that in JRA55/AWAP, but with lower values. The strength of the Jet and PC have relatively higher coefficients over the Southern region including the west coasts, and the coefficient with blocking is notable near the southeast coast and Tasmania, but with lower values than in JRA55/AWAP. Some differences to observations are related to the coarser resolution, where mountains, coastlines and the mean position of circulation features are poorly resolved at the regional scale. This is illustrated by the Euclidean distance from JRA55/AWAP for each cell (Fig. 4), where the largest values are found over mountain and near coastlines. Also, some features unrelated to resolution appear to be missing in the model mean, such as the relatively weaker coefficient with the latitude of PC and jet over the broad region of eastern Australia.

The magnitude of the six coefficients vary between models and some models have values more comparable to JRA55/AWAP than the model mean, reflected in the coefficients of the regression for area-averaged rainfall for Southern region and the sub-regions, and the score for the Euclidean distance scores (Fig. 5). Some persistent biases are seen in all models, including a consistently low coefficient for PC latitude in the Southern region and Southeast sub-region, meaning no model achieves a Euclidean distance from JRA55/AWAP below 5 for any region (Fig. 5). The mean of the 6 models with the lowest Euclidean distance scores for Southern region shows a closer match to JRA55/AWAP than the mean of all models, including in the coefficient with PC and Jet latitude in eastern Australia (Figure S3).

Using a significance test on the linear fit between Euclidean distance and the projected change in each circulation index (Table 2), there is no significant relationships at the 95% confidence level. There are three relationships between the 90 and 95% confidence level (p value between 0.05 and 0.1), so are noted as indicative but not significant. The first is between Euclidean distance for the Southeast region and baroclinic instability (PC) where models with lower Euclidean distance tend to have a greater decrease in PC (baroclinic instability). This result suggests that models that fit

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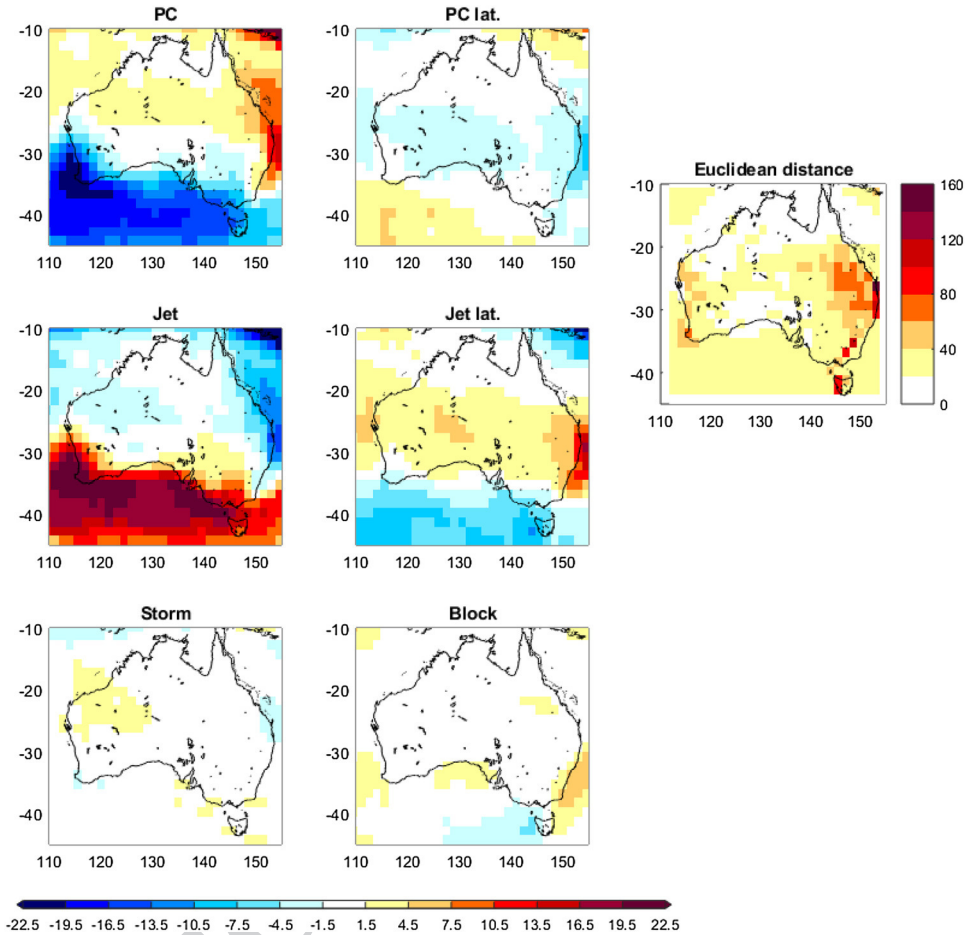

Fig. 4 Multiple linear regression of six atmospheric circulation indices (see Table 1) and simulated rainfall in July from 26 CMIP5 global climate models (GCMs) in 1958 to 2005, left: multi-model mean of the coefficients with each index (note reduced colour scale compared to Fig. 2, highest values go off scale), right: the Euclidean distance of the six coefficients from the equivalent calculated from JRA55/AWAP (smaller distance denotes a closer match)

the circulation-rainfall relationship closer to observations in the historic climate tend to have a greater sensitivity to change in baroclinic instability on the climate change scale. The second is Euclidean distance for the Southern region rainfall with Jet lat., and the third is Euclidean distance for the Southern region rainfall with strength of the storm track (Storm). In these cases, the models with the lower Euclidean distance tend to show an equatorward movement of Jet lat. and an increase in Storm track strength.

The Euclidean distance is then used as a metric to reject models for their rainfall projection. There is no significant linear correlation between any Euclidean distance and any rainfall projection, therefore there is no emergent constraint found. However, by first using all models then the subset of models below percentile values of the range in Euclidean distance, some constraint of the rainfall projection in each region appears (Fig. 6). Here, the 75% (19 models), then 50% (13 models) and then 25% (6 models) thresholds are used. For the Southern region as a whole, the rainfall projection becomes constrained at the wetter end and the median decreases somewhat, a result very similar to Grose et al. (2017). For the Southeast sub-region, the projected range becomes reduced when using only the 6 models with the lowest Euclidean distance, particularly the wetter end, but with little change in the median. For the Southwest sub-region, the median projection is considerably lower (− 10%) for all sub-groups of models compared to the whole ensemble, but with only a small change in the model spread.

3.3 Analogue years

The historical years with circulation indices most similar to the GCM mean projected climatological mean of those indices are in order: 1993, 1959, 1992, 1962, 1985, 1976, 1994, 1984, 1969, 1967, 1999, 1988, 1970, 1975 and 1961. Examining a composite of these 15 years, rainfall was below average across southern Australia but above average in eastern Australia (Fig. 7b). The results are broadly consistent across all 26 individual models (Figure S4).

This spatial distribution of the rainfall anomaly in analogue years (Fig. 7b) is similar to the mean rainfall projection from CMIP5 in southern Australia (Fig. 7c), but is quite different in eastern Australia. Area-averaged rainfall anomaly in the Southern region (− 12%) is less dry than CMIP5 (− 18%). Rainfall was below average in the Southwest sub-region in analogue years (− 18%), which is less

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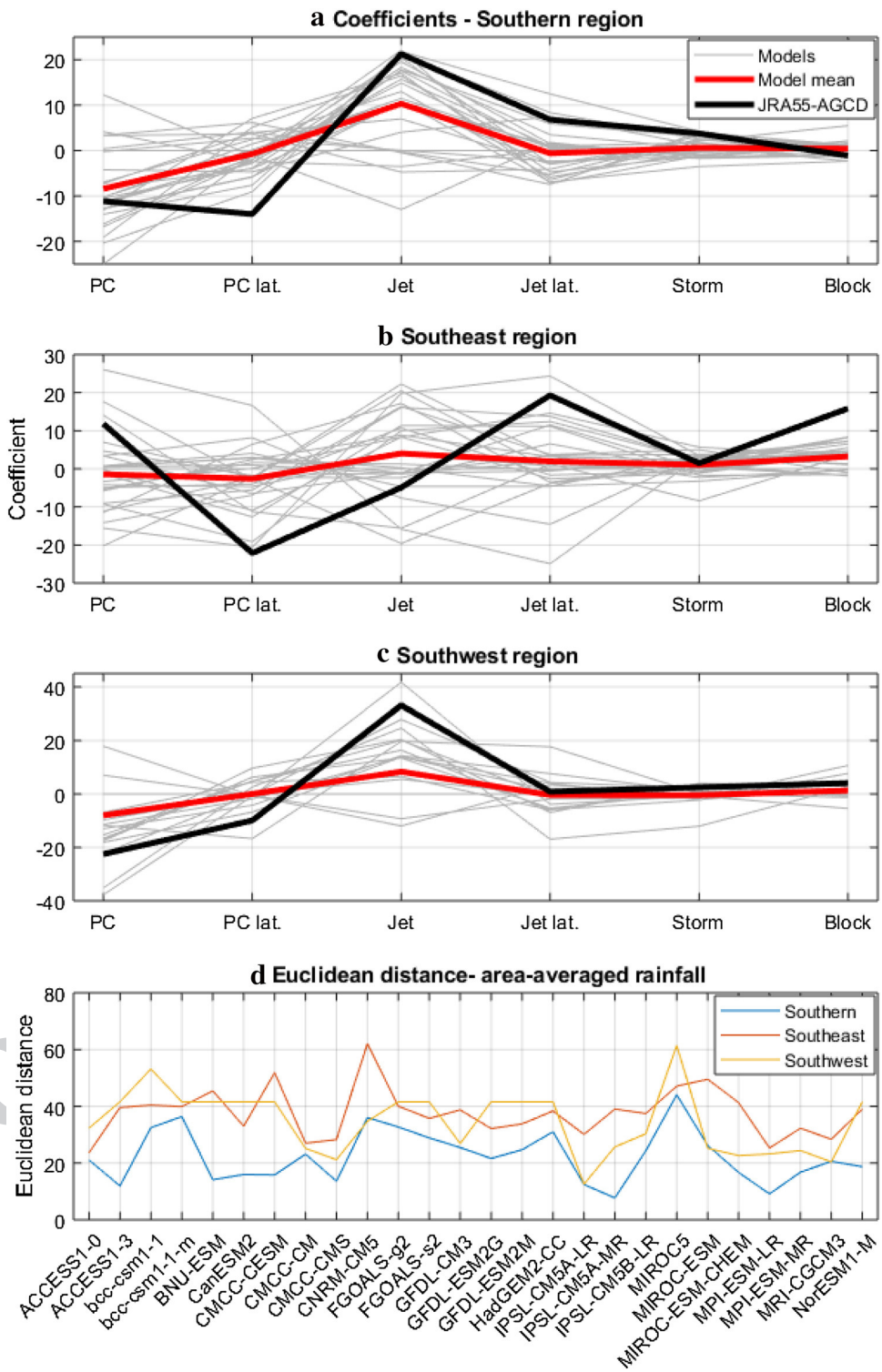

Fig. 5 Multiple linear regression of six atmospheric circulation indices (see Table 1) and rainfall in July averaged over the regions (Fig. 1) from JRA55/AWAP and 26 CMIP5 global climate models (GCMs) in 1958–2005, coefficients of model fitted to area-averaged rainfall in **a** Southern Region; **b** Southeast sub-region; and **c** Southwest sub-region, and **d** the Euclidean distance for each model for each region

dry than the CMIP5 projection (−31%) but regions to the north of the averaging region are drier than CMIP5, so the result seems to be affected by differences in the small-scale regional patterns. Rainfall was also below average across all of southeast mainland Australia. The area average for the Southeast sub-region is less dry in analogue years (−9%) than in CMIP5 (−15%), but differences in the regional-scale spatial patterns are also notable here, with the analogue years having an area of rainfall increase higher than the CMIP5 projection on the eastern seaboard and a region of drier than CMIP5 for much of southeast Australia outside the Southeast sub-region (Fig. 7d).

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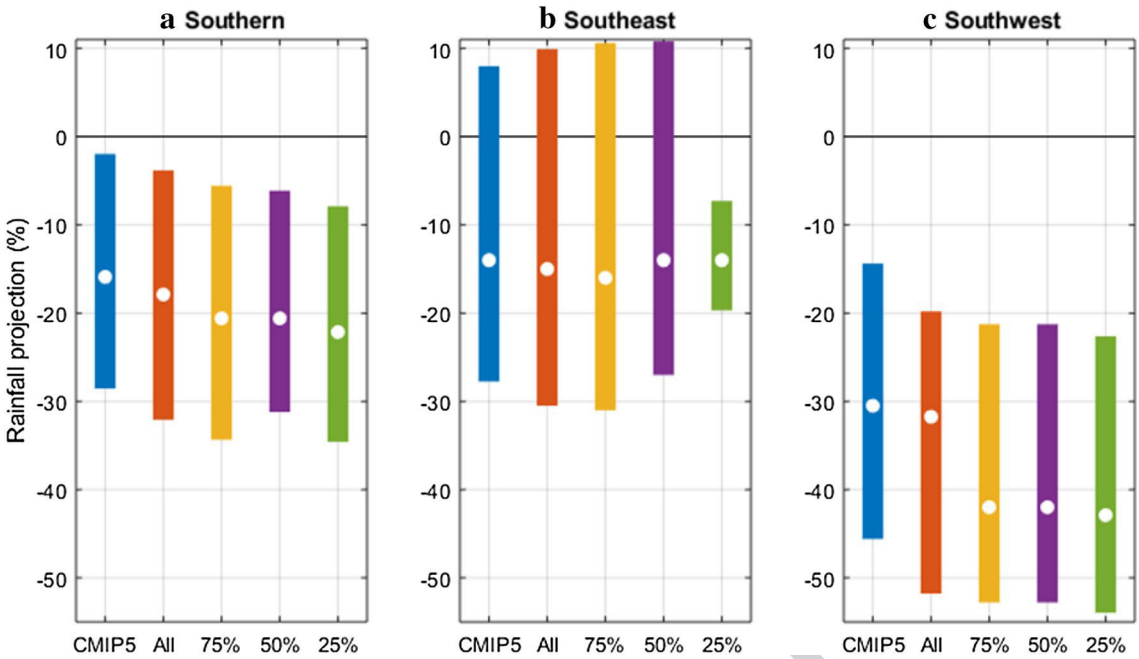

Fig. 6 Rainfall projection for July rainfall between 1986–2005 and 2080–2099 under RCP8.5, bars are the 10–90 percentile range, circle is the median for **a** Southern region, **b** Southeast sub-region, and **c** Southwest sub-region. Series are 42 CMIP5 models (CMIP5), 26 CMIP5 models tested in this study (All), and models with the lowest Euclidean distance from JRA55/AWAP for the relevant region (75%: 19 models, 50%: 13 models, and 25%: 6 models)

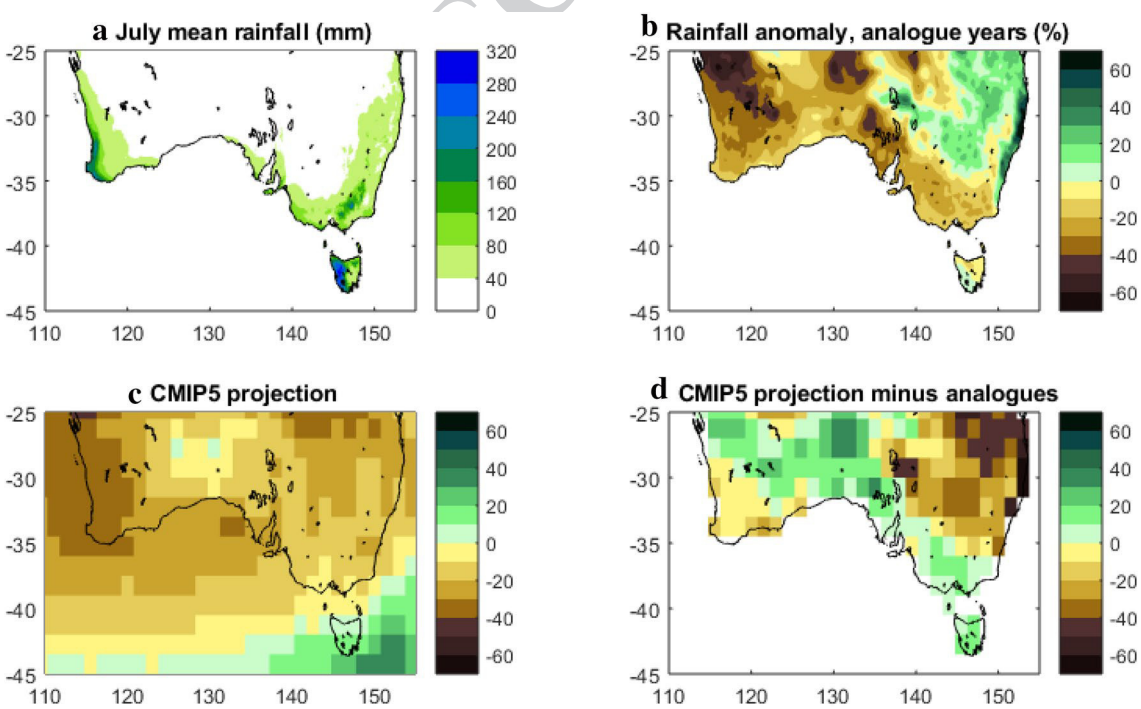

Fig. 7 July rainfall in southern Australia: **a** mean rainfall in July in AWAP in 1958–2005, **b** the anomaly of mean rainfall (%) of the 15 analogue years, **c** mean projection from 26 CMIP5 models tested in this study for 1986–2005 to 2080–2099 (%), **d** the difference between the CMIP5 projection and the 15 analogue years (%)

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Rainfall was above average in southwestern Tasmania (by up to 23%).

If we assume this composite of analogue years as an estimate of the projected change in rainfall due to changes in atmospheric circulation, and that CMIP5 gives an accurate projection of all factors driving rainfall change, then the difference between the analogue years and the total projection from CMIP5 (Fig. 7d) is an estimate of the change due to non-circulation processes such as the effect of a warmer atmosphere. This difference suggests that the non-circulation factors offset circulation-driven drying in the broad southeast Australian region and Tasmania, enhance the drying of southwest western Australia and offset a strong increase in rainfall increase on the eastern seaboard. Alternatively, the difference could suggest where CMIP5 models have deficiencies in their simulated response to circulation change, through poor resolution of topography or other factors.

4 Discussion

This paper presents the results of two different approaches to refining climate projections of southern Australian July rainfall (representing the peak of winter) using indices of the most important driver of projected rainfall change; atmospheric circulation change. The agreement between the two methods, and with previous work, provides further evidence for a constraint on the wetter end of winter rainfall projections for rainfall in the Southern region. The results from the two approaches give some different projections for the sub-regions of southern Australia.

The first analysis uses a multiple linear regression of inter-annual rainfall variability based on circulation indices as a form of model evaluation. A comparison of the regression of rainfall related to circulation indices tests the relationship between the atmospheric circulation and regional rainfall on a year-to-year basis. This represents an integrated assessment of six important indices in a single metric, so is less vulnerable to arbitrary choices of indices and their weighting. This process assumes that it is acceptable to apply an evaluation based on inter-annual variability to projections at the climate change scale, but we note that the relationship between circulation and rainfall is essential to making reliable projections, and the inter-annual relationship is at least some guide to the quality of simulated changes at the climate change scale. Further work could be done to compare the relationships at longer timescales, including decadal or multi-decadal over the historical record.

The regression produces quite different results when it is fitted to the periods 1958–1980 and 1981–2005, and this boundary is associated with a reported shift in circulation (Frederiksen and Frederiksen 2007), but also the start of the satellite era and use of remote sensing to inform reanalyses such as JRA55 (Kobayashi et al. 2015). This suggests that either there was a change in the relationship between circulation and rainfall at many locations between these two periods, or there was a notable change in the quality of reanalysis data at this time, or contributions from both. The lack of stationarity in the observed relationship between circulation indices and rainfall has implications for making climate projections, where free-running climate models should not be expected to exactly match this observed relationship over a period of a few decades, and the relationship shouldn't be expected to stay the same in the future. This lack of stationarity also suggests that analogue-based statistical downscaling methods need to use caution when selecting suitable calibration periods. Producing a multiple linear regression of rainfall based on atmospheric circulation indices represents a novel method to draw out and visualise changes in these relationships through time, regardless of their cause.

The Euclidean distance between climate models and observations is larger over areas where GCMs do not resolve important features such as mountains, which is consistent with previous findings such as that GCMs do not simulate the relationship with zonal wind over the Australian Alps (Pepler et al. 2015), and do not distinguish the regional detail of rainfall over Tasmania (Corney et al. 2013). The analysis also shows that most GCMs produce a lower regression coefficient with indices such as the jet latitude than in observations for a broad region of eastern Australia (not just the eastern seaboard east of the mountain range). This suggests that GCMs have biases in the broader scale processes in this area, providing a barrier to reliable rainfall projections not just related to the resolution of mountains. This may be a reason why there is no clear unambiguous 'added value' in the rainfall change projection through downscaling of GCMs for the eastern region (Grose et al. 2015). However, given that the relationships between PC and Jet indices changed between the two historical periods, the difference between models and observations may be due partly to natural variability rather than model bias.

To apply the evaluation to constrain projections, it would be useful if there were relationships between the Euclidean distance and projected change of either the circulation indices or rainfall. There were some indicative but not significant relationships between Euclidean distance and projection of circulation indices, but these relationships do not build a simple and consistent picture to constrain projections of circulation change. There were no significant relationships across the spread of models in Euclidean distance and rainfall projections, so there are no emergent constraints found there. However, by accepting or rejecting models based on their distances then some constraints become apparent. For the Southern region, the models with a closer match to observations are constrained at the wetter end compared to the whole CMIP5 ensemble, meaning that there is higher

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agreement on significant drying than the whole ensemble. Also, the models with a lower Euclidean distance showed a lower median projection for the Southwest sub-region than the whole ensemble by around 10%. This is physically plausible, and broadly consistent with a previous study (Grose et al. 2017) that looked at emergent constraints on the indices themselves.

The second analysis used temporal analogues to show the ensemble mean projection of circulation features and produces results broadly consistent with rainfall projections from CMIP5. Temporal analogues calculated from each model and the model mean were broadly consistent. This supports circulation changes as the dominant driver of rainfall change in southern Australia in general, and that CMIP5 models simulate the relationship between change in circulation and rainfall in a similar pattern as observations. There is a difference between the temporal analogues and the CMIP5 projection, where CMIP5 is less dry in the Southeast sub-region and drier in the Southwest sub-region than the analogue years. This suggests that either CMIP5 has a bias in the rainfall projection associated with this circulation change, including an underestimate of the drying in the southeast, or that projected changes unrelated to these circulation indices are offsetting the effect. These other factors may include thermodynamic changes or other forcings such as the lifting of the anthropogenic aerosol burden. Alternatively, some or all of the differences may be due to errors in the CMIP5 models, or else noise in the sample of 15 years to generate the analogues. Large differences between the temporal analogue and CMIP5 in the eastern seaboard region are worth further investigation.

As well as examining the multiple linear regression as an evaluation over longer timeframes such as decadal variability, further work could include applying the model to other seasons, other places, and comparing the results to statistical downscaling. The multiple linear regression could include changes to temperature and humidity to model the change in rainfall incorporating thermodynamic as well as dynamic aspects of rainfall change in an integrated way. Similarly, the simple circulation analogue approach could also be compared to the results from other sophisticated statistical models of daily rainfall that use circulation and other atmospheric analogues as input.

5 Conclusions

The results presented here support constraining the wet end of rainfall projections for the Southern region from CMIP5, giving higher agreement and confidence in a drying climate in southern Australia due to climate change than CMIP5 suggests. This means that a projection of little change or a slight increase in rainfall in the Southern region, suggested by some CMIP5 members, should be given less confidence than projections in the rest of the model range. The methods demonstrate a further physical basis for informing the projected change in rainfall for regions where circulation indices are important, further to Grose et al. (2017).

The results from the two approaches differ regarding the projection for sub-regions of southern Australia. The model rejection analysis suggests a 10% drier median rainfall projection for the Southwest sub-region than the entire CMIP5 ensemble for the end of the century under a high emissions scenario. The temporal analogue analysis suggests a slightly wetter median projection for the southwest but a drier projection for the broad southeast Australian region than CMIP5 projects.

The results suggest that the use of a statistical model of rainfall based on atmospheric circulation indices has utility beyond prediction, through use as an evaluation method and tool to examine physical relationships between rainfall and circulation.

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