Bias in downscaled rainfall characteristics

Notes on revision for referees and editor

We once again thank the referees and editor for their very helpful reviews and suggestions. We have addressed the major issues in the previous authors' comments uploaded to the Interactive Discussion. In response to these major comments, we have

5 adjusted the manuscript where appropriate (introduction, discussion as well as relevant places throughout). Here we directly address the remaining referee comments

Anonymous Referee #1

p.1, l.21: '... any quantile mapping bias correction method is ...'

done

10 p.1, l.26: '... Of most interest are possible changes...'

done

p.1, l.28: '... the spatial resolution of these models is too coarse...'

done

p.2, l.9: '...Teutschbein and Seibert...'

15 | done |
| --- |

p.5, l.14: (Addor and Seibert, 2014) in brackets

done

p.5, l.18ff: Make sure to introduce all variables properly (Pr, P, p, upper/lower case D/d/W/w).

20 | This section has been revised and reworded so that it should be clear that D_n and W_n refer to the nth day being dry or wet respectively. |
| --- |

p.5, l. 26/l.29: Figure 1 and Figure 2. Later on you are often using the abbreviation Fig. only. Maybe you want to decide for one format consistently. Same inconsistency for Section/Sect.

25 | We have double checked figure and section references and they are consistent with the HESS style guide (i.e. abbreviated to Fig./Sect. except when starting a sentence). |
| --- |

p.7, l.7: 'Sect. 3.3.1'. Maybe 1 should be deleted here.

done

p.8, l.22: Close the bracket.

done

30 Maybe Sect. 3.1 could be moved closer to Sect. 3.4 or they could even be combined? p.10, l.5: Charles et al., submitted meanwhile.

We prefer section 3.1 and 3.4, but acknowledge that the section title is not representative. Section 3.1 is intended to show regional, spatial information, whereas section 3.4 is spatially averaged. We rename section 3.1 to "Assessment of Regional Performance of Modelled Rainfall".   The Charles et al. paper has been submitted to HESS and the reference updated.

35

p.10, l.29: 'seasonal changes are more like half of the bias in seasonal averages'. To me, using 'like' here, sounds a bit unclear and colloquial, please rephrase.

40 | "more like" replaced with "closer to" |
| --- |

Some of the graphs and their placements are still in a quite raw condition. I assume this is going to be revised in the final version (e.g. labels and units of colour bars, legends, cut off axis labels, maybe adapting the range of x-axis (Fig. 14-16, 6-8?), full stops at the end of each caption). Generally, I think 16 figures is a lot. Do you really need all of them to convey the message of the paper? Maybe Fig. 2 could be skipped, as it is part of Fig. 13? Or Fig. 5 could be moved to the appendix as it

45 is supportive to another point? Or Fig. 14-16 and Fig. 6-8 respectively could be combined in one figure? Fig. 9: Is it necessary to add the smaller steps at the higher percentiles on the x-axis? I found it less intuitive at first glance.

The figures have been reworked in in some cases combined as suggested.

Fig. 10/11: You could consider adjusting the colour bars, as no blue colour appears.

Anonymous Referee #2

- The authors may consider to revise the title of the paper to account for the runoff aspect.

> We prefer to leave the title as is, as the companion paper (Charles et al., 2019) deals directly with runoff

- Also, consider to reduce the number of figures and correct the figure legends (be clear that WRF simulations are referred to, not the GCMs). Also add more explanations to the figure captions (abbreviations, before/after BC, add data set used to construct the figure, e.g. Fig.7 and similar). I further suggest to enlarge the axis annotations.

> As above, all figures have been redrawn to be clearer encompassing the referee #2's suggestions

- P3, L12 and L18: Better refer to parametric and non-parametric distributions, because also empirical distributions are 'distributions'.

> We have adjusted this but note that non-parametric distributions are not necessarily empirical so retain 'empirical' in parentheses.

- P3, L16ff: Does this statement refer to corrections on the calibration data, or when applied to data outside the calibration period? Overly flexible methods might introduce artifacts at the tails outside the calibration period. Inappropriate (too stiff) parametric methods may introduce unrealistically high values, when much higher values than observed appear in a future scenario (Volosciuk et al., 2017) because of the extrapolation.

> This was presented in a split-sample experiment by Teng et al. (2015) and a citation has been provided.

- P3, L23: How was this evaluated? Again, only on the calibration data or also on data outside the calibration period? For the calibration data, an almost perfect correction results by design by all methods.

> This was presented in a split-sample experiment by Teng et al. (2015) and a citation has been provided.

- P4, L16ff: Evans et al. (2014) is not the correct reference for how WRF reads in lateral/lower boundary data from a GCM. Put this reference to the next sentence: "The NARCLiM projections (Evans et al., 2014)..."

> Done

- P5, L26 and L29: correct 'Figure' to 'Figure 2.' (you might want to drop this figure, as the information is already in Fig. 13).

> Updated. Note figure 2 has been dropped and is included in figure 10 as suggestd.

- P6, L.16f: Only if it is assumed that the bias is time-independent, otherwise it was demonstrated that the chosen timescale for constructing the transfer functions impacts for instance the annual mean (Haerter et al, 2011; Reiter et al., 2018).

> Correct, and we refer here to historical bias correction. The quantiles themselves are designed to be corrected exactly but we are highlighting here that P99 is not corrected exactly due to interpolation.

- P6, L27: remove "after bias correction".

> Done

- P6, L31: effect of overfitting? Would this also occur if a monthly BC is used instead of a seasonal?

> Added "this could be reduced to zero using monthly correction factors, although at the potential cost of overfitting".

- P7, L6: maybe better use "considerably" (or similar), "significantly" has a connotation related to statistical testing.

> Significantly replaced with considerably

- P7, L8: Be more precise: Instead of "This results .." write e.g. "Due to good performance in correcting dry-dry transition probabilities, the bias in mean and maximum dry spells is well corrected, ...".

> Replaced "this results" with "Since dry spells are directly related to dry-dry transition probabilities,"

- P7, L10 and Fig.9: Does Figure 9 show the 3-day rainfall bias of the WRF simulations (text) or of the GCMs (legend)? And then, before or after the bias correction?

> Figure 9 is calculated on bias-corrected downscaled GCM time series, legend and caption updated accordingly.

- P7, L18: Explain what PET means; if it is a data set, then describe it in section 2.

> PET is spelt out (potential evapotranspiration). This part of the paper is taken from Charles et al. (2019), so rather than include details here we have provided an extra citation.

- P7, L27: Give more than one reference for "a number of studies..".

Additional references have been provided here

- P8, L3: Be precise which models are used where. Sometimes reanalysis and GCM results are wrongly used, when WRF models forced by either NCEP or a GCM are meant. There are other places in the manuscript as well (e.g. legend of Fig. 9, or titles of Fig. 11 and 12).

We have updated these throughout the manuscript, as well as changing WRF in some instances to NARCliM when appropriate.

- P8, L8: Add "… wet-wet transition probabilities are largest over the high-runoff producing region (Fig. 12),…".

included

- P8, L32: replace "northeast" with "to the right".

Done

- P9, L18: Replace "Fig.16" by "Figure 16".

"Fig. 16" remains as it is consistent with HESS style

- P10, L4f: Replace "Charles et al. (2019, submitted). (Or insert reference if already published).

Reference updated

Anonymous Referee #3

- Figure 3: It could be helpful for the reader to place Victoria geographically. Maybe you want to have a subplot in Figure 3 outlining Victoria in Australia.

Figure 3 (now Fig. 2) has been updated with an inset subplot showing Victoria in relation to Australia.

- Page 4, line 18: It seems that a combination of both CMIP3 and CMIP5 data have been used. Why use CMIP3 at all? CMIP5 has been around for quite some time now. This paper is not trying to show the improvement, or lack thereof, in model performance between CMIP3 and CMIP5.

The available NARCliM data is downscaled from CMIP3 data only; CMIP5 models are currently being downscaled by NARCliM modellers. As mentioned in our previous response to reviewers (and included in the discussion section of the revised manuscript), using dynamically downscaled data for hydrological projections is largely opportunistic, relying on currently available data. Ideally, we would use CMIP5 downscaled data but this is not currently available. We intend for the findings of this paper to be applicable to bias correction for CMIP5 and CMIP6 dynamically downscaled model data. We have included a citation to the future NARCliM work in the relevant place.

- Page 5, line 26: Figure 2 instead of "Figure"

Done

The revised manuscript follows:

Bias in downscaled rainfall characteristics

Nicholas J. Potter[1], Francis H.S. Chiew[1], Stephen P. Charles[2], Guobin Fu[2], Hongxing Zheng[1], Lu Zhang[1]

[1]CSIRO Land and Water, Canberra ACT, 2601, Australia
[2]CSIRO Land and Water, Floreat WA, 6148, Australia

5 *Correspondence to*: Nicholas J. Potter (Nick.Potter@csiro.au)

Abstract. Dynamical downscaling of future projections of global climate model outputs can ~~potentially~~ provide useful information about plausible and possible changes to water resource availability, for which there is increasing demand for regional water resource planning processes. By explicitly modelling climate processes within and across global climate model gridcells for a region, dynamical downscaling can provide higher resolution hydroclimate projections, as well as independent
10 (from historical timeseries) and physically plausible future rainfall timeseries for hydrological modelling applications. However, since rainfall is not typically constrained to observations by these methods, there is often a need for bias correction before use in hydrological modelling. Many bias correction methods (such as scaling, empirical and distributional mapping) have been proposed in the literature, but methods that treat daily amounts only (and not sequencing) can result in residual biases in certain rainfall characteristics, which flow through to biases and problems with subsequently modelled runoff. We
15 apply quantile-quantile mapping to rainfall dynamically downscaled by NARCliM in the State of Victoria, Australia and examine the effect of this on: (i) biases both before and after bias correction in different rainfall metrics; (ii) change signals in metrics in comparison to the bias; and (iii) the effect of bias correction on wet-wet and dry-dry transition probabilities. After bias correction, persistence of wet states is under-correlated (i.e. more random than observations), and this results in a significant bias (underestimation) of runoff using hydrological models calibrated on historical data. A novel representation of
20 quantile-quantile mapping is developed based on lag-one transition probabilities of dry and wet states, and we use this to explain residual biases in transition probabilities. This demonstrates that any quantile mapping bias correction method~~s are~~ is unable to correct the underestimation of autocorrelation of rainfall sequencing, which suggests that new methods are needed to properly bias correct dynamical downscaling rainfall outputs.

1 Introduction

25 There is a growing and on-going need for information about plausible and possible changes to water resource availability in the future due to climate change. End users of hydroclimate projections need more spatially detailed information as well as information on water metrics for low- and high-flow events, as well as interdecadal metrics (Potter et al., 2018). Dynamical downscaling (such as provided by the NARCliM project for south-eastern Australia, see Sect. 2.1) has potential to provide this type of information, however there remain challenges associated with this data. In this paper, we examine the suitability of
30 NARCliM projections for providing hydroclimate projections for south-eastern Australia. Specifically, we look at the extent of biases in rainfall, which necessitate daily bias correction, and the effect of quantile-quantile mapping (QQM) bias correction on rainfall sequencing metrics that are important for runoff generation. Subsequent research in a related paper (Charles et al., 2019) focuses attention on the effect of these biases on runoff.

Of particular~~most~~ interest ~~is~~ are possible changes to rainfall characteristics~~, particularly those~~ that could affect runoff and
35 streamflow. Information on future changes to rainfall are typically derived from ensembles of global climate models (GCMs), however the spatial resolution of these models ~~are~~ is too coarse to provide information at the scale needed for hydrological impact modelling (i.e. catchments or gauges). Downscaling is the process by which finer scale spatial detail is extracted from the larger scale GCM change information (Maraun et al., 2010). Many water resource studies use 'empirical scaling', where historical rainfall observations are scaled (perhaps annually or seasonally) for direct use. These methods are relatively simple
40 to use, and results from empirical scaling typically lie in the middle of the range of results from other downscaling methods

(Chiew et al., 2010; Potter et al., 2018). However, as empirical scaling methods rely on the historical record of rainfall, future changes in rainfall sequencing (e.g. changes to multi-day accumulations and wet/dry transitions) and consequent effects on runoff cannot be properly modelled. Dynamical downscaling, in which a regional climate model (RCM) of finer spatial resolution than the host GCM generates rainfall sequences by simulating physical climatic processes, does generate rainfall

5 sequences independent from historical observations. However, challenges remain with using dynamical downscaling output since rainfall (and other climate variables) are not explicitly constrained by observations (see, e.g., Piani et al., 2010; Chen et al., 2011; Teutschbein and SiebertSeibert, 2012). As such, dynamical downscaling outputs typically need to be bias corrected for direct use in hydrological models. In particular, a common feature of dynamical downscaling is the tendency to underpredict the occurrence of zero- and low-rainfall days, which is sometimes known as the drizzle effect (e.g. Maraun, 2013). RCM

10 output has been bias corrected for applications in Tasmania (Bennett et al., 2014) and central coast of New South Wales (Lockart et al., 20146) but both these studies found residual biases in multi-day rainfall events, dry spell durations, and autocorrelation of rainfall occurrences. Themeßl et al. (2012) bias corrected RCM output over Europe and found residual biases in rainfall extremes and a modification of the climate change signal.

Water resources in Victoria are shared by urban users, irrigators, industry and the environment. Long-term water strategies

15 and shorter term sustainable water strategies are required for Victoria's water regions by the Victorian Water Act. A key aspect of these water planning processes is accounting for scenarios of climate change as determined by the available science. Cool-season rainfall in Victoria since 2000 has averaged 15% less than the long-term average during the 20th century (Hope et al., 2017). This has been linked to the observed expansion of Hadley Cell circulation (Post et al., 2014). The median scenario of climate change for Victoria typically has reduced rainfall and runoff later in the century, with slightly larger percentage declines

20 in the western parts of the State (Post et al., 2012; Potter et al., 2016). Providing better information to improve water planning processes includes developing finer spatial resolution projections as well as different metrics of daily rainfall amounts and occurrences. The dynamically downscaled NARCliM climate projections (NSW/ACT Regional Climate Modelling, Evans et al., 2014), described in Sect. 2.1 allows the opportunity to provide these improvements, but require bias correction in order to produce sufficiently correct daily rainfall distributions.

25 The underlying assumption of bias correction is that the RCM output faithfully represents the climate processes responsible for rainfall, although the amounts themselves may not be accurate. Water resource projection modelling is concerned with future changes, and so an argument could be made that although the rainfall amounts are biased for hindcast (historical) simulations, they will presumably be equally biased for future simulations, so that changes can be inferred from comparing biased historical and future rainfall and runoff. However, the sensitivity of runoff to rainfall means that biased rainfall can

30 have large effects on the change signal of runoff (Teng et al., 2015). Furthermore, hydrological models are calibrated to historical rainfall and runoff sequences, and since the distribution of runoff is usually highly skewed, using biased rainfall sequences can distort the distribution of runoff, thus creating large biases in high and low runoff amounts. This makes inferences on the changes to runoff characteristics highly uncertain when biased rainfall inputs are used.

Bias correction identifies a relationship or mapping between observed historical rainfall and hindcast RCM rainfall. This

35 mapping when applied to hindcast RCM rainfall results in a distribution of rainfall identical (or very similar, depending on the methods) to the historical observations. This mapping can then be applied to future RCM rainfall, resulting in unbiased future rainfall sequences. Of course, applying the relationship into the future assumes the bias in RCM rainfall does not change into the future or for different (wetter or drier) climate periods. Bias-correction methods (see Schmidli et al., 2006; Boée et al., 2007; Lenderink et al., 2007; Christensen et al., 2008; Piani et al., 2010; Themeßl et al., 2011; Teng et al., 2015;) fall into three

40 main categories:

- Scaling or change-factor methods;
- Non-parametric (eEmpirical) quantile-quantile mapping (QQM); and
- Parametirc (Ddistributional) QQM.

Scaling methods simply consider the change in mean, and apply a constant factor to correct bias in RCM rainfall. Quantile-quantile mapping matches each quantile (or a selection of quantiles) of the two distributions. This can be done using the empirical cumulative density or fitting a distribution to both observed and hindcast RCM daily rainfall amounts.

Teng et al. (2015) demonstrated that representing daily rainfall distributions with double-gamma distributions was largely
5   identical to empirical QQM, implying that distributional and empirical approaches give similar results so long as the distribution is sufficiently flexible. Arguably, the choice between non-parametric (empirical) or parametric (distributional) mapping is a representation of the bias-variance tradeoff problem. Empirical mapping will reduce bias to zero, but at the cost of increasing the variance of predictions, since the mapping will be very sensitive to individual amounts. Distributional mapping fits the data across the entire rainfall distribution, but can result in the hindcast RCM rainfall not being mapped
10   exactly to the historical distribution. For this study we apply empirical quantile-quantile mapping for each season across integral percentiles as described below. Overall there is a small but relatively unimportant difference between different methods for QQM (Teng et al., 2015).

Whereas quantile-quantile mapping can effectively reduce historical error in daily rainfall amounts to zero, albeit with some of the caveats already mentioned, the bias corrected rainfall timeseries could still harbour biases and unrealistic characteristics
15   that will result in runoff biases after being routed through a rainfall-runoff model. Specifically, QQM bias correction cannot remove biases in rainfall sequencing and multi-day accumulations that might not be readily apparent when considering only the daily distribution of rainfall amounts (Addor and Seibert, 2014). Unfortunately it is not easy to tell exactly which characteristics of rainfall drive runoff generation, and in general the sensitivity will depend on catchment physical characteristics, storm type and intensity, as well as antecedent moisture and groundwater stores (Goodrich and Woolhiser,
20   1991; Bell and Moore, 2000; Beven, 2001). Spectral and multifractal approaches (e.g. Milly and Wetherald, 2002; Matsoukas et al., 2000; Tessier et al., 1996) show that rainfall variability at shorter timescales is by and large incorporated into soil moisture buffers thus dampening runoff variability at these timescales. However, over timescales of several days and greater, variability in runoff matches variability in rainfall more and more closely. As such, it is evident that large, intense rainfall events (measured perhaps by the upper tail of the rainfall distribution), more seasonal rainfall regimes (Wolock and McCabe,
25   1999), relatively larger variability of rainfall (Potter and Chiew, 2011), and large multi-day accumulations of rainfall are most important for runoff generation (Addor and Seibert, 2014), particularly for high flow events (Jaun et al., 2008), and we focus on these kinds of rainfall metrics in this study.

The main aim of the paper is to investigate the effect of bias correction on rainfall characteristics relevant to runoff generation. Specifically, we investigate whether key rainfall metrics contain biases in dynamically downscaled GCM hindcasts relative to
30   observations. We examine if bias correction acts to either enhance or moderate any such biases, and whether bias correction affects change signals (i.e. GCM future relative to GCM historical). Section 2 describes the data and methods used in this study, Sect. 3 presents results, and Sect. 4 and 5 contain discussion and conclusions.

2 Data and Methods

2.1 The NARCliM Project

35   The NSW and ACT Regional Climate Modelling Project (NARCliM; https://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/About-NARCliM; Evans et al., 2014) is a regional climate change project to deliver high resolution dynamically downscaled climate change projections. As noted previously, GCMs run at a spatial resolution that is unable to provide meaningful information for decision makers at catchment and basin scale. To resolve subgrid processes, the NARCliM project uses the 'Weather Research and Forecasting' (WRF) regional climate model, which is a mesoscale atmospheric model
40   with many applications both in numerical weather prediction and climate projections (Skamarock and Klemp, 2008), forced by atmospheric variables output from GCMs. WRF reads in output from a GCM along its lateral and lower boundaries and

simulates the climate on a finer resolution within those boundaries (Skamarock et al., 2008). Out of the 23 CMIP3 (Meehl et al., 2007) GCMs available at the time the project started, four were eventually chosen for downscaling: MIROC3.2 (medres), ECHAM5, CCCM3.1 and CSIRO-Mk3.0 (Evans et al., 2013). Initially, GCMs that did not adequately represent climate dynamics of the region were eliminated. Based on a meta-analysis, GCMs were then ranked, and independence of model error,

5   as well as future changes, was assessed to represent the range of model ensemble (Evans and Ji, 2012a). A similar procedure was applied to select the configurations of WRF used to downscale each host GCM (Evans and Ji, 2012b). The three WRF configurations are labelled R1, R2 and R3, further information is provided elsewhere (Evans et al., 2012; Ekström, 2016; Gilmore et al., 2016). We discuss the physical credibility of the NARCliM ensemble in greater detail in Sect. 4 below. Current work (NARCliM1.5) is continuing to develop the modelling framework at a higher spatial resolution (5km × 5km), using

10   CMIP5 models and improved RCM configuration (Downes et al., 2019).

2.~~1~~2 Daily Data

Daily accumulated precipitation from NARCliM is produced at approximately 10km × 10km grids, which was bilinearly interpolated to a regular grid using Climate Data Operators (CDO; https://code.mpimet.mpg.de/projects/cdo). ~~The historical~~

15   ~~(baseline) period for WRF is 1990–2009, and we relate WRF historical rainfall features to observations and NCEP/NCAR~~ ~~reanalysis over the same period.~~ NARCliM provides bias corrected data (Evans and Argüeso, 2014), which applies a parametric gamma distribution quantile-quantile mapping procedure, which is similar in many respects to the non-parametric procedure we apply to the raw NARCliM data in this paper.
~~Observed rainfall data is obtained from the Australian Water Availability Project (AWAP; Jones et al., 2009). This is a~~

20   ~~0.05°×0.05° gridded dataset interpolating observations from point rainfall records from the Australian Bureau of Meteorology.~~ The historical (baseline) period for NARCliM projections is 1990–2009, and we relate NARCliM historical rainfall features to observations and NCEP/NCAR reanalysis over the same period in this paper. ~~We use rainfall projections output from the~~ ~~Weather Research and Forecasting (WRF) model, which is a mesoscale atmospheric model with many applications both in~~ ~~numerical weather prediction and climate projections (Skamarock and Klemp, 2008). WRF reads in output from a GCM along~~

25   ~~its lateral and lower boundaries and simulates the climate on a finer resolution within those boundaries (Evans et al., 2014).~~ ~~The NARCliM projections use three different configurations of WRF in combination with four CMIP3 (Meehl et al., 2007)~~ ~~GCMs (MIROC, ECHAM, CCCMA and CSIRO Mk3.0) that were selected to represent GCM uncertainty based on their skill~~ ~~and independence (Evans et al., 2013). (Note that a newer runs of NARCliM, currently being processed, use the CMIP5 model~~ ~~ensemble, and preparations are in place to take advantage of the upcoming CMIP6 ensemble.) The historical (baseline) period~~

30   ~~for WRF is 1990–2009, and we relate WRF historical rainfall features to observations and NCEP/NCAR reanalysis over the~~ ~~same period.~~ Realisations of future rainfall follow the A2 Scenario of the Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000) at 2060–2079. Change signals presented later are thus averages over 2060–2079 compared to 1990–2009. Observed rainfall data is obtained from the Australian Water Availability Project (AWAP; Jones et al., 2009). This is a 0.05°×0.05° gridded dataset interpolating observations from point rainfall records from the Australian Bureau of Meteorology.

35   The AWAP rainfall observations are projected over a regular latitude-longitude grid, hence the need for interpolation of NARCliM data ~~and~~ to be aligned with this~~commensurate with this, the WRF outputs are bilinearly interpolated to a 0.1°×0.1°~~ ~~grid aligned with the AWAP grid~~. The AWAP rainfall data is then regridded by using weighted averages of AWAP gridcells overlapping the 0.1°×0.1° AWAP grid.

2.~~2~~3 Quantile-~~Q~~quantile Mapping ~~B~~bias ~~C~~correction

40   Quantile-quantile mapping bias correction works by estimating the cumulative density function for observed and modelled historical daily rainfall amounts: F_o and F_m. These are then combined to produce a mapping function:

$$P_o = F_o^{-1} \circ F_m\,(P_m)$$

(Fig. 1). The map $F_o^{-1} \circ F_m$ thus returns the observed daily distribution (or approximately so, depending on the method) when applied to the modelled historical timeseries, and a bias corrected future timeseries when applied to the modelled future timeseries. We use the R package 'qmap' (Gudmundsson et al., 2012), to estimate the cumulative density functions for the mapping function. This estimates quantiles for both observed and modelled non-zero rainfall at integral percentiles including 0 (minimum) and 100 (maximum). The quantile for a particular daily rainfall amount is then estimated using linear interpolation between percentiles, and linear extrapolation in case of future modelled rainfall lying outside the historical distribution. Compared to using the empirical distributions directly, differences between the bias-corrected modelled rainfall distribution and the distribution of observations can occur (of the order of 2–3%) because the interpolation between large rainfall percentiles (particularly 99 to 100) will not match observed percentiles exactly. As noted by Teng et al. (2012), sufficiently flexible approaches to bias correction give very similar results. QQM bias correction in this way was applied separately to each three-month season (i.e. DJF, MAM, JJA and SON) in each grid cell independently.

2.34 Defining Transition Probabilites

Whereas QQM bias correction can correct the daily distribution exactly, daily bias correction is not set up to correct sequences and accumulations (Addor and Seibert, 2014). To this end, we consider not only how bias correction affects daily metrics of rainfall, but also the sequencing of wet days that produce runoff. One way of measuring this is through transition probabilities of wet and dry sequences. To this end, we consider a simple two-state Markov Chain rainfall occurrence model. Here, the probability of a wet or dry day depends on whether the previous day was wet or dry. A "dry" day can be defined as either zero rainfall or rainfall below a given threshold (such as 1 mm). Define the wet-to-wet and dry-to-dry transition probabilityies (i.e. the probability of a wet day following a wet day) as $w = \Pr(W_n|W_{n-1})$ $w = \Pr(W|W)$ and the corresponding dry-to-dry transition probability as $d = \Pr(D_n D|D_{n-1} D)$. These determine the Markov Chain since $\Pr(D_n D|W_{n-1} W) = 1 - w$ and $\Pr(W_n W|D_{n-1} D) = 1 - d$. Further, tThe probability of the occurrence of a dry day occurrences, p, is fully determined by the w and d parameters, as given by Cox and Miller (1965):

$$p = \frac{1 - w}{2 - d - w}$$

Equivalently,

$$w = 1 - p\,\frac{1 - d}{1 - p}$$

This relationship can be plotted for a range of probabilities p (dotted lines in Fig. 10). Note that ifIf a series of occurrences of dry and wet days has zero autocorrelation (i.e. the state probability is independent of the rainfall state in the previous day), then it follows that $\Pr(D_n D|D_{n-1} D) = \Pr(D_n D|W_{n-1} W) = \Pr(D_n)\Pr = p$. As such, the diagonal line where $p = d$ (dashed line in Fig. 102Fig. 2) corresponds to an independently (i.e. zero autocorrelation) series of occurrences. The area above and to the right of the dashed diagonal line corresponds to a series of occurrences with positive autocorrelation (i.e. $\Pr(D_n D|D_{n-1} D) > p$ and so that dry sequences are more likely to persist), whereas the area below and to the left of the dashed line corresponds to series with negative autocorrelation. The framework developed here Figure 2 is used in Sect. 3.3 as a novel way to represent the relationships between state-transition probabilities and rainfall quantiles to investigate the effect of bias correction on transition probabilities.

3 Results

3.1 ~~Change Signal versus Bias~~Assessment of Regional Performance of Modelled Rainfall

Figure ~~3~~2 shows mean annual rainfall across Victoria from (a) observations, (b) downscaled (NCEP/NCAR) reanalysis ~~(2nd column)~~ and GCM-downscaled ~~(3rd column~~(c), historical and~~;~~ ~~4th column~~(d), future~~)~~. ECHAM5-R1 was chosen as a representative GCM ensemble member here as it had the median historical regional rainfall across Victoria from the NARCliM~~WRF~~ model ensemble. The spatial rainfall fields downscaled from both the reanalysis and GCM both show reasonable agreement with the spatial pattern of the observed mean annual rainfall, with relatively larger rainfall across the mountain ranges to the east of the State and across the southern coast. There is less rainfall to the more arid north-west region as well. However, both rainfall fields are evidently positively biased with around 100–200 mm of excess rainfall consistently across most of the State (Fig. 2f, g), relatively more for the far Eastern part of Victoria for the reanalysis data and across the mountain ranges for the GCM data, interspersed with small patches of negative bias (observations larger than downscaled data). Averaged across Victoria, the mean absolute bias is approximately 26% for the reanalysis~~ ~~ and 43% for the GCM data. In comparison, the absolute change signal averages 3%, rising to around 10% in the Eastern part of Victoria (Fig. 2h).

3.2 Bias Correction of NARCliM~~WRF~~

Consistent with Fig. ~~3~~2, the raw NARCliM~~WRF~~ rainfall is mostly wetter (positive bias) across Victoria (Fig. 3a~~4~~), except for a tendency towards underprediction in the south-east coast for some models. The quantile-quantile bias correction method is formulated to correct historical quantiles of rainfall exactly so that bias-corrected mean annual rainfall, as well as any quantiles, are approximately equal. However, the method used here does not correct high rainfall quantiles (e.g. P99 and above) exactly, due to the interpolation between quantiles as described in Sect. 2.3~~2~~ (Fig. 4b~~5~~). This residual bias appears to be randomly distributed spatially and results in bias-corrected mean annual rainfall not being exactly corrected. However, this effect is generally less than 5% of the mean annual rainfall. This effect can be removed entirely by using empirical density functions rather than interpolated values, but with the effect of increasing prediction uncertainty. This residual bias in QQM bias corrected rainfall is more pronounced at P99 (Fig. 4a~~5~~) where interpolation between P99 and P100 (maximum) can have a larger effect.

Figure~~s~~ ~~6 to 8~~ show~~s~~ the distribution of bias for different rainfall metrics before bias correction and the residual bias after QQM bias correction. The bias in raw NARCliM~~WRF~~ ranges from 5% to 50% for all percentiles (Fig. 6~~5~~a), increasing as the percentile increases (i.e. more relative bias for higher rainfall amounts). ~~After bias correction, a~~As with Fig. 3~~4~~, bias at all percentiles is effectively reduced to zero after bias correction, although the residual bias is relatively larger at larger percentiles (higher rainfall), similarly to Fig. 5~~4~~b. NARCliM~~WRF~~ rainfall is overestimated at all seasons and months before bias correction (Fig. 5b~~7~~), although winter rainfall is relatively less biased than summer rainfall. Bias correction reduces bias to zero annually and seasonally, since QQM is applied to each season separately. Since the intra-seasonal relative monthly rainfall amounts are not exactly equal to the observed amounts, seasonal bias correction occasionally overcorrects bias, particularly in February, April, May and June, with the bias corrected rainfall in these months being less than observed whereas they were overpredicted before bias correction; this could be reduced to zero using monthly correction factors, although at the potential cost of overfitting. Overall though, the absolute relative bias is reduced and closer to zero in all months compared to the raw RCM monthly amounts.

Figure~~ure~~ 8~~5~~c shows relative bias in rainfall sequencing related metrics. Autocorrelation of rainfall amounts is underpredicted before bias correction, and the magnitude of this bias actually increases after bias correction. Whereas QQM reduces bias in dry-dry transition probabilities (i.e. the probability of dry sequences persisting), bias in wet-wet transition probabilities increases after bias correction so that, similarly to autocorrelation, the probability of wet spells persisting is ~~significantly~~ considerably underpredicted after bias correction. We examine this in more detail in Sect. 3.3~~.1~~ using the transition probability

framework developed in Sect. 2.4~~3~~. Since dry spells are directly related to dry-dry transition probabilities, ~~This results in~~ the bias in mean and maximum dry spells is ~~being~~ well corrected, whereas maximum 3-day rainfall accumulation and wet-spell occurrences all have negative bias after QQM bias correction. Different percentiles of 3-day rainfall accumulation (calculated as percentiles of a 3-day moving sum of rainfall timeseries) have different residual bias (Fig. 6~~9~~). Three~~3~~-day accumulation
5   percentiles below the 80th are all slightly overestimated after bias correction, but above the 80th percentile, a large residual underestimation is present. This reduces at around the 99th percentile but is moderated somewhat for the 3-day maximum (i.e. 100th percentile). As noted by Olson et al. (2016), WRF models were selected according to their skill in reproducing selected 2-week periods of heavy rainfall. This provides a potential explanation for the smaller bias in 3-day maxima relative to 3-day 99% rainfall.

10   It is likely that underpredicting wet spell occurrences and persistence (Fig. 5c~~8~~ and Fig. 6~~9~~) will result in runoff from the bias corrected rainfall being underpredicted too. To explore this, runoff was modelled from bias corrected rainfall and observed ~~PET~~ potential evaporanspiration data (see Charles et al., 2019) using GR4J calibrated on observed rainfall and potential evapotranspiration ~~PET~~ data using 90 catchments in and around Victoria. Ungauged areas use parameters donated from the nearest neighbour calibration catchment. Further details are provided by Charles et al. (2019~~, submitted~~). Figure 7~~10~~ plots the
15   percentage difference in ensemble-median mean annual runoff for each 0.1°×0.1° cell compared to mean annual runoff modelled using AWAP observed rainfall. The ensemble median of runoff across Victoria is underpredicted by between 10–20% across almost all of Victoria suggesting that the residual bias in wet spell occurrences and persistence is problematic for runoff modelling. Whereas the smallest percentage biases appear to be over the high-runoff producing region, this region has the highest absolute biases with bias in runoff of more than −20 mm. Characteristics and biases of runoff from bias corrected
20   NARCliM~~WRF~~ rainfall is explored in more detail by Charles et al. (2019~~, submitted~~).

3.3 Residual Bias in Rainfall State Transition Probabilities

A number of studies have highlighted the residual bias in rainfall sequencing after QQM bias correction (e.g. Addor and Seibert, 2014; Li et al., 2016; Ines and Hansen, 2006), whereas Terink et al. (2010) and ~~)~~Rajczak (2016) contend that bias correction produces reasonable transition probabilities and spell durations. The results in this study ~~above~~ demonstrate that
25   dry-dry transition probabilities for NARCliM have low residual bias (possibly due to the emphasis in QQM on preserving zero-rain occurrences), but that wet-wet transition probabilities have more bias after QQM bias correction. This results in the persistence of wet spells being underestimated even though the volumetric amount of rainfall is, by design of QQM bias correction, equal to observed rainfall at any gridpoint.

After bias correction, dry-dry transition probabilities for a 1 mm threshold are reduced, but still have a small negative bias
30   (Fig. 5c~~8~~). Figure 8~~11~~ shows the dry-dry transition probabilities calculated from observed rainfall (top left), bias corrected reanalysis (middle column), bias corrected historical GCM (right column). Both the bias-corrected reanalysis and bias-corrected GCM results show a spatial pattern very similar to observations with higher dry-dry transition probabilities to the northwest of the State, and at similar places along the southern coastline. However, the reanalysis and more so the GCM result has a lower dry-dry transition probability across almost all of the region. As such, dry spells from the bias-corrected model
35   output are likely to be shorter in duration and less common than that from the observed rainfall (although bias correction does reduce the bias in dry spells somewhat compared to the bias in the raw data as seen in Fig. 8~~5~~c).

Whereas the dry-dry transition probabilities were largest in the north-west, drier, part of Victoria, the wet-wet transition probabilities are largest over the high-runoff producing region (Fig. 9), which corresponds to the high-relief, high-altitude part of the State. As with the dry-dry transition probabilities, both bias-corrected reanalysis and bias-corrected GCMs reproduce
40   the spatial pattern of wet-wet transition probabilities, but there is considerable residual bias in these probabilities across the entire region. The residual bias in GCM transition probabilities is over 10% over almost all of Victoria. This results in underestimation of wet spell occurrences and durations and multiday accumulations of rainfall (Fig. 8~~5~~c). The bias in wet-wet

transition probabilities is more problematic for modelling runoff than the bias in dry-dry transition probabilities, not only because it is of larger magnitude, but because:

- runoff is sensitive to multiday wet spells
- the larger wet-wet probabilities occur in high runoff producing areas, which we would like to model correctly for regional water availability projections
- QQM bias correction reduces the bias in dry-dry transition probabilities, but increases the magnitude of the bias in wet-wet transition probabilities (Fig. ~~8~~5c).

Figure 10~~13~~ shows the observed (green), raw (blue) and bias-corrected (red) historical GCM rainfall amounts for a sample grid cell overlaid on the transition-probability space developed in Sect. 2.~~4~~3 (i.e. Fig. 2). Other grid cells and GCMs show very similar responses (as can be seen in the low spread of results for *d* and *w* in Fig. ~~8~~5c). Quantile-quantile mapping bias correction equates the quantiles ~~q~~ for each rainfall amount such that equal rainfall amounts for observations and bias-corrected rainfall occur on the same probability contours (dotted ~~orange~~ lines in Fig. 10~~13~~), with raw values translated along the rainfall amount curve. That is, values on the blue line in Fig. 10~~13~~ map to corresponding values on the red line; the slight variation between the lines is due to different bias corrections in each season. As such, wet-wet and dry-dry transition probabilities for a given rainfall threshold (e.g. 1 mm) for bias-corrected rainfall are equal to the transition probabilities for the corresponding amount in the raw data. For example, in Fig. 10~~13~~, the exceedance probability for 1 mm in the observed data (black line) is 0.774. The corresponding quantile in the raw data is 2.675 mm. This amount is mapped to 1 mm in the bias-corrected data, and the corresponding wet-wet and dry-dry transition probabilities for 2.675 mm are identical to the transition probabilities for 1 mm in the bias-corrected data. Recall from Sect. 2.~~4~~3 that the slope −1 line in Fig. 10~~13~~ where $p = d$~~p=d~~ corresponds to an independent sequence of events and to the right ~~northeast~~ of this line in the transition-probability space represents more (positive) serial correlation. This implies that the observed rainfall timeseries contains more correlation structure in the sequence of wet and dry spell occurrences than the modelled rainfall sequence, and that QQM bias correction cannot rectify this since daily QQM retains the autocorrelation structure of the raw time series since daily amounts are simply rescaled. We surmise that a bias correction method that adjusts occurrences is needed to properly correct biases for hydrological modelling.

3.4 Change signals

Here we examine change signals in rainfall metrics (i.e. percentage difference in RCM future relative to RCM historical averages) specifically looking at whether bias correction alters the change signals. Figure 11a~~14~~ shows the change signals in different rainfall percentiles. For the raw data, there is a small decrease in low to moderate rainfall amounts less than the non-zero 40th percentile and a future increase in non-zero percentiles above 50%. The nature of QQM bias correction means that raw and bias corrected equal percentiles cannot be compared directly. Nevertheless a similar pattern is found with the bias corrected data, namely that larger rainfall amounts have larger relative changes than smaller rainfall amounts.

Figure 11b~~15~~ shows change signals in mean annual, seasonal and monthly average rainfall. The magnitude of the median change signal in mean annual rainfall is around −5%, and seasonal changes are comparable to the annual change except for SON rain which has a decrease projected by the NARCliM~~WRF~~ ensemble of around 20%. Compared to the raw bias in mean and seasonal rainfall (Fig. 7~~5~~b) of between 25%–50%, these change signals are between one-half and one-tenth of the bias. After bias correction, there is little difference in the magnitude and direction of change in seasonal and monthly averages. However, the mean annual rainfall change is moderated somewhat, and this is somewhat problematic since mean annual changes are most often considered in regional projection applications. Charles et al. (2019~~, submitted~~) discuss this effect in more detail.

Although the residual bias in rainfall sequencing metrics is not eliminated, and in some cases (e.g. wet-wet transition probabilities) is actually increased after bias correction, Fig. 11c~~16~~ shows that the change signals in rainfall sequencing metrics is largely unaffected by bias correction. With the exception of maximum 3-day rainfall accumulation, the distributions of

sequencing change signals are largely identical before and after bias correction. The difference in change signal for maximum 3-day rainfall accumulation is presumably related to the relatively larger increase in large rainfall events (e.g. P99 in Fig. 11a~~14~~).

4 Discussion

We demonstrate in Sect. 3.4 that change signals (future mean relative to historical) in rainfall metrics can be considerably smaller than the bias (modelled historical relative to observed historical). On the one hand, this seems problematic since biases in processes can be considered so large that the changes are insignificant. On the other hand, there is no particular legitimacy for this viewpoint, certainly not from a statistical sense. The magnitude of bias does not provide any sort of confidence level in changes to rainfall metrics. However, given such relatively large biases, it is reasonable to assume that there are some errors in the way particular climate processes are modelled, either through the host GCM or the RCM. It would be desirable to understand the reasons and climatic process responsible for biases and assess whether these processes are unrealistic, as well as whether these biases render the changes physically implausible. ~~Such an assessment is beyond the scope of this paper however.~~

We acknowledge that the underlying performance of GCMs in accurately simulating climate dynamics of the region under consideration is extremely important. In the context of the study area in the current manuscript, South-Eastern Australia, the selection of GCMs representing important climate processes has been an on-going research strand both for the CMIP3 climate model ensemble (Smith and Chandler, 2009; Kirono and Kent, 2011; Kent et al., 2013; CSIRO, 2012; Evans and Ji, 2012a; McMahon et al., 2015), which is used for the current NARCliM dataset, as well as the CMIP5 ensemble (see CSIRO and Bureau of Meteorology, 2015; Hope et al., 2016). The RCM component of NARCliM, WRF, has been tested extensively (Evans et al., 2012; Andrys et al., 2016; Ekström, 2016; Olson et al., 2016; Ji et al., 2016; Gilmore et al., 2016).

The use of models that produce plausible climate dynamics is of course desirable, however in practice it is not necessarily always possible. Apart from the fact that the 'best' models identified by the above references differ according to the criteria used, using a dynamical downscaling ensemble for hydrological applications is an opportunistic endeavour, relying largely on existing data products, which have been prepared with many applications in mind, not just hydrological applications. As such, it is not always practical to choose the GCMs and RCMs that best represent climate dynamics important for hydrological applications; many studies have also contended that accuracy in representing historical conditions is no guarantee that future changes are correctly modelled (e.g. Knutti et al., 2010; Racherla et al, 2012).

Overall, there is reasonable confidence in NARCliM projections generally, for both rainfall and temperatures (Evans et al., 2012; Olson et al., 2016; Ji et al., 2016), particularly at daily scale for rainfall (Gilmore et al., 2016), although NARCliM has a quantitative cold and wet bias generally (Ji et al., 2016). Evans and McCabe (2010) examined the RCM component (WRF) of NARCliM, concluding that the El Niño-Southern Oscillation, the chief climate process modulating interannual variability of rainfall (Power et al., 1999), was well modelled over south-eastern Australia. Evans and McCabe (2010) also concluded that the severity and duration of recent prolonged droughts over south-eastern Australia were also captured, although the spatial pattern was not characterised exactly. The sub-tropical ridge, which determines the seasonal positioning of storm tracks over southern Australia, was less well represented by WRF (Andrys et al., 2016). For hydrological applications, a specific combination of land and atmospheric circulation schemes (R2) is recommended for hydrological applications (Olson et al., 2016). Although we consider the entire modelling ensemble in this paper, in a related paper (Charles et al., 2019) we use only that specific RCM physics scheme for modelling runoff. Based on the results cited here, we have confidence in the modelling setup of NARCliM to represent atmospheric circulation for southern Australia reasonably well, although we acknowledge that bias correction of NARCliM for end-user applications should consider model skill in atmospheric circulation.

In general, bias correction does not tend to alter the change signals in rainfall metrics (with the exception of 3-day accumulation and low rainfall percentiles). Nevertheless, small differences in rainfall metrics can result in large differences in runoff metrics and other water availability measures (e.g. low flows and high flows). High runoff and even average runoff amounts can be very sensitive to 3-day rainfall accumulation, which we saw can be altered through daily bias correction. It is recommended that the effects of bias correction are included in any uncertainty analysis undertaken.

Section 3.4 of the manuscript shows that bias correction can affect change signals (future relative to historical) of different hydroclimatic metrics (see also Hagemann et al., 2011; Gutjahr and Heinemann, 2013; Dosio, 2016). Under the assumption that bias is time invariant, Gobiet et al. (2015) argue that bias correction improves the accuracy of climate change signals. Cannon et al. (2015), however, argue that trend-preserving methods should be used (see also Li et al., 2010; Wang and Chen, 2014). Maraun (2016) and Maraun et al. (2017) summarise the debate surrounding the use of trend-preservation methods and conclude that the decision should be informed by the credibility or otherwise of the GCMs in representing the processes driving the changes. This further highlights the need for informed selection and screening of GCMs at the start of the modelling process. However, we argue that there is value in reporting both pre- and post-bias correction future changes in light of the difficulties involved in model selection and assessment, particularly in the case of pre-existing and computationally expensive projections such as dynamically downscaled ensemble such as NARCliM.

The simple QQM method used here does not consider spatial correlation between rainfall gauges or gridcells at all. Maintaining spatial correlations is clearly important for runoff generation, and neglecting this can lead to 'inflation'. Inflation refers to a phenomenon in bias correction (Maruan, 2013) or statistical downscaling (von Storch, 1999) where an unmeasured predictand variable is estimated using the predicted values from a statistical model. Since models contain error, the variance of a timeseries of predicted values is expected to be less than the variance of the true time series of the variable. In the present context of bias correcting rainfall from RCMs, Maraun (2013) demonstrates that bias correction reduces subgrid spatial heterogeneity compared to actual precipitation, and that this is particularly problematic when GCM or RCM resolution is much greater than that of observations. In this case, the spatial correlation between gauges is increased. As a result, large rainfall amounts become overestimated and low amounts underestimated. Preserving the correct spatial correlation between gauges or gridpoints is an important issue, and the issue of unintended spatial effects of (temporal) bias correction is compounded by applying bias correction independently to each gridcell, as we have done here – although this tends to reduce subgrid spatial correlation (see Bardossy and Pegram, 2012; Hnilica et al., 2017). Maraun (2013) recommends aggregating catchment rainfall prior to bias correction to reduce the issue of inflation, and Charles et al. (2019) examine this in more detail in relation to catchment runoff production. Variance inflation due to differing grid cell sizes (Maruan, 2013) is less an issue for the current study, as NARCliM grid cell size is comparable to that of the gridded rainfall observations, and the next generation of dynamically downscaled climate projections (Downes et al., 2019) is to be provided at 0.05°×0.05° resolution, identical with the gridded rainfall products used in Australia. However, the issue of using a bias correction methodology that corrects daily amounts (and more generally temporal structure) while preserving spatial structure across catchments and basins remains a challenge and is a direction for further research.

Although in this study, rainfall alone is bias corrected; for runoff applications, temperature or a suitable representation of potential evapotranspiration is needed. Methods exist for correcting rainfall and temperature simultaneously (e.g. Hoffmann and Rath, 2012; Piani and Haerter, 2012; Mehrotra et al., 2018). However, potential evapotranspiration has a second-order effect on runoff compared to rainfall (Chiew, 2006; Potter et al., 2011), and bias correction was shown to not significantly affect the inherited relationships between rainfall and temperature (Wilcke et al., 2013). Certainly, the host GCM and RCM should correctly represent relationships between atmospheric variables in the study region, further highlighting the need for climate model assessment in construction of the model ensemble.

We demonstrate in Sect. 3.4 that change signals (future mean relative to historical) in rainfall metrics can be considerably smaller than the bias (modelled historical relative to observed historical). On the one hand, this seems problematic since biases

Another important consideration is the relevant metrics to be considered by end users. Bias correction by season, for example, can alter change signals annually, and care must be taken as to which metrics are of interest, and which are the most appropriate bias correction methods to apply in order to properly account for the metrics of interest. Certainly, caution must be applied when considering rainfall and runoff metrics that were not considered when applying bias correction to projections. Low flow metrics are particularly problematic (Potter et al., 2018), where different downscaling and bias correction methods can give very different answers.

Although daily bias correction methods as outlined in this paper tend to result in residual bias in multi-day metrics, generally change signals in transition probabilities are very similar before and after bias correction. This information could thus potentially be extracted from RCMs to drive local weather generation or stochastic methods to provide future rainfall projections that can be suitable for local hydrological projections. Maintaining interannual and muti-decadal correlations, as well as spatial correlations between rainfall gauges, remains a challenge for stochastic methods, however.

5 Conclusions

Projections of future changes to rainfall and runoff from dynamically downscaled climate models often necessitates a form of bias correction to rainfall fields to obtain sufficiently realistic rainfall inputs for hydrological models. Dynamical downscaling offers potential benefits to regional hydroclimate projections, such as the ability to better model daily rainfall metrics, low flow metrics (after modelling runoff with a hydrological model), and finer spatial scale information, but comes with challenges related to bias. Whereas bias in rainfall amounts can be corrected using quantile-quantile mapping (QQM) methods, biases in rainfall occurrences (such as rainfall autocorrelation, dry-dry and wet-wet transition probabilities) are not properly corrected with QQM.

The relative magnitude of change signals (future RCM to historical RCM) of the different rainfall metrics examined here is typically less than the magnitude of the bias. Mean annual rainfall change is an order of magnitude smaller than the bias in mean annual rainfall but seasonal changes are more like closer to half of the bias in seasonal averages. Although this might call into question the validity of the change signal, one approach is to assume that the magnitudes of the changes are responsive to changing greenhouse gas emissions, insofar as the changing atmospheric processes are realistically modelled by the dynamical downscaling process. Indeed this is the basic premise behind empirical scaling, i.e. that the change is the authentic signature of the climate modelling especially since the RCMs are not explicitly tuned to observed rainfall.

Individual percentiles and seasonal totals are, by design, effectively reduced to zero using QQM. Some interpolation and extrapolation occurs in the approach used here, so there is some random residual bias in higher percentiles (i.e. high rainfall amounts). This can be eliminated altogether by using the exact empirical density functions, but at the cost of increased predictive uncertainty. Using empirical densities also raises problems with extrapolation past historical amounts. Monthly totals retain some residual bias because of compensating biases within each season due to small errors in rainfall seasonality by the RCMs. Metrics associated with rainfall sequencing (e.g. serial correlation, wet-wet and dry-dry state transition probabilities and quantiles of 3-day accumulation) all have significant residual bias, particularly so for wet-wet state transition probabilities in which the magnitude of bias in raw RCM historical runs is amplified after bias correction. This leads to a considerable underestimation of mean annual runoff after rainfall is routed through a hydrological model because runoff is very sensitive to multiday accumulations of rainfall and sequencing of wet spells in particular.

An analysis of the lag-one transition probabilities (i.e. wet state to wet state and dry state to dry state) showed that NARCliMWRF rainfall had transitions to different states that are more random (i.e. more independent) compared to observed rainfall. QQM bias correction is unable to correct these transition probabilities as QQM retains the transition probabilities for any particular quantile. Since persistence of wet spells is critical for runoff generation, a different approach to bias correction is needed to successfully use NARCliMWRF for runoff projections that can correct rainfall sequencing to better represent the observed correlation structure in wet and dry occurrences.

Change signals in annual, seasonal and monthly average rainfall as well as rainfall sequencing metrics are largely preserved after bias correction, with the exception of maximum 3-day rainfall accumulation. However there is a slight tendency for DJF and MAM rainfall change signals to increase after bias correction and this leads to a tangible reduction in the magnitude of the projected decrease in mean annual rainfall. This is problematic for applications since mean annual change is the most commonly used metric for hydroclimate projections. One possible solution is to rescale the bias corrected rainfall according to raw changes signals but this depends on whether we believe the raw or the bias corrected change signal is correct. However, the fact that rainfall sequencing metrics (such as state transition probabilities and daily rainfall autocorrelation) are largely unchanged by bias correction suggests the possibility of using this information to drive either weather-generation models or stochastic/resampling-based bias correction methods to produce hydrologically realistic rainfall sequences for hydroclimate projection applications.

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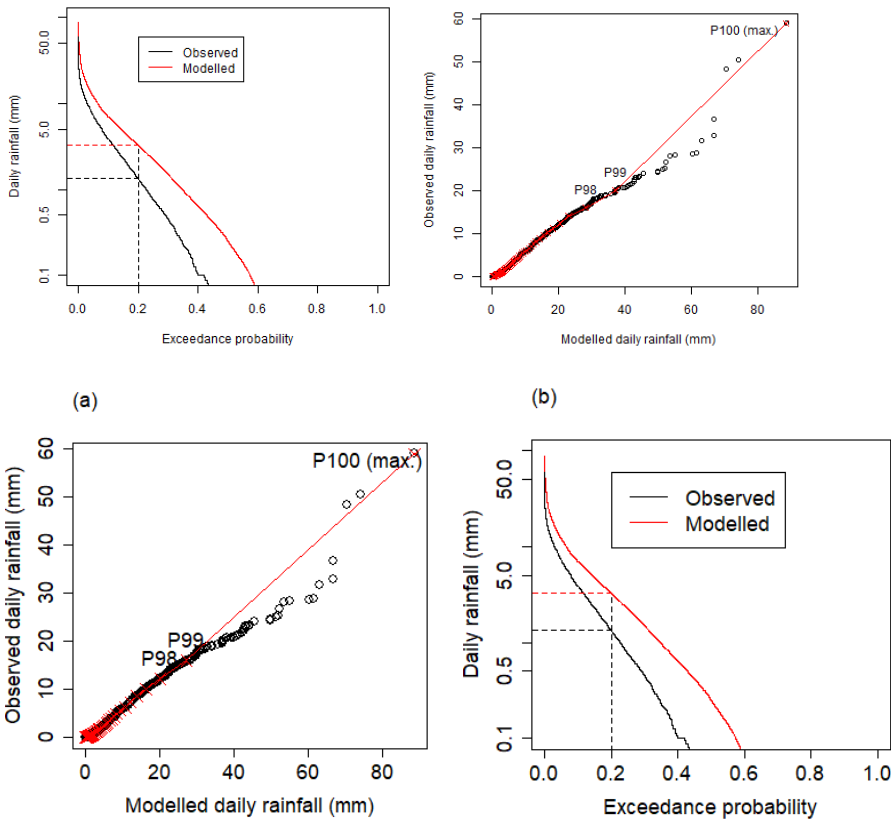
Figure 1: Schematic of QQM bias correction. ~~The left panel shows the e~~(a) Empirical cumulative density functions for both observed and modelled rainfall in a given gridcell. Percentiles are estimated from both distributions, which are equated in bias correction to generate a mapping function (~~bright panel~~). Values lying between percentiles or outside the modelled maximum value are interpolated or extrapolated linearly.
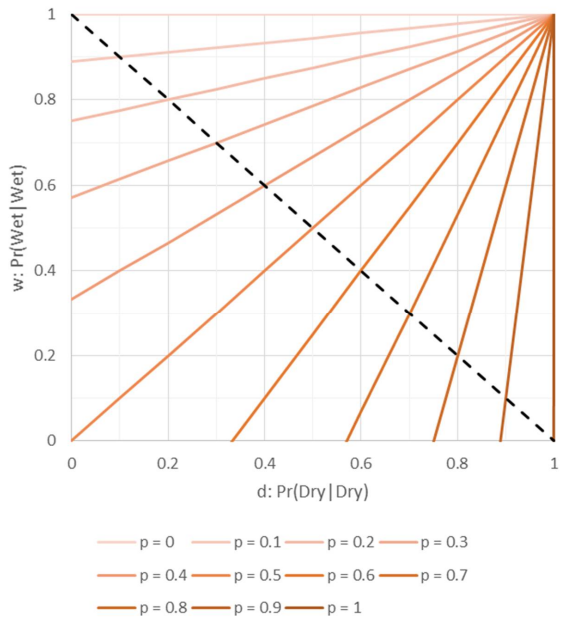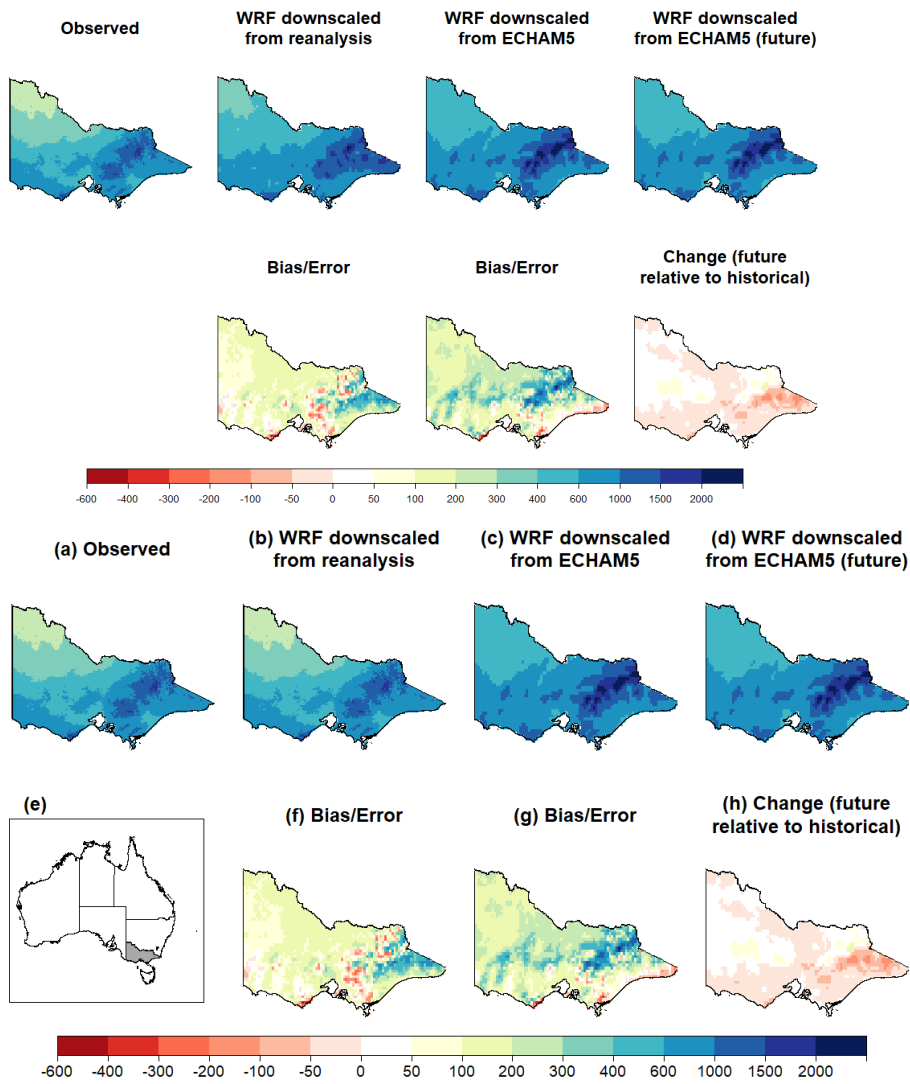
Figure ~~32~~: ~~Magnitude of change signal of m~~Regional mean annual rainfall (mm yr^{-1})~~compared to bias~~. Inset map (e) shows the location of the State of Victoria in Australia. Other panels show: (a) observed (AWAP) rainfall; (b) rainfall downscaled from reanalysis (NCEP/NCAR); (c) historical rainfall downscaled from median GCM (ECHAM5/R1); (d) future rainfall downscaled from GCM; (f) bias in reanalysis downscaling (compared to observed); (g) bias in GCM downscaling; (h) change factor of GCM downscaled rainfall.
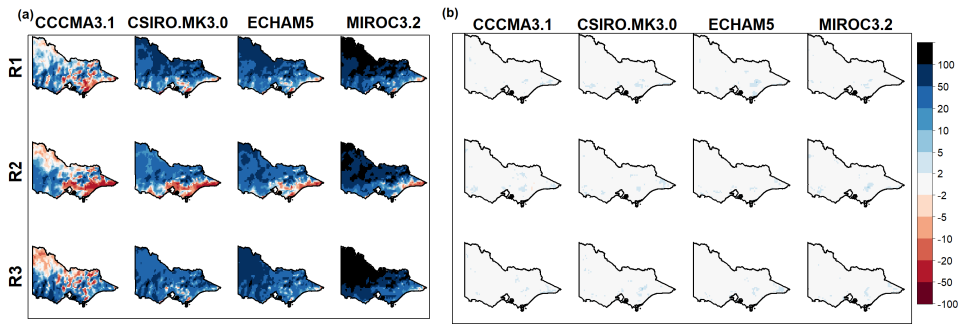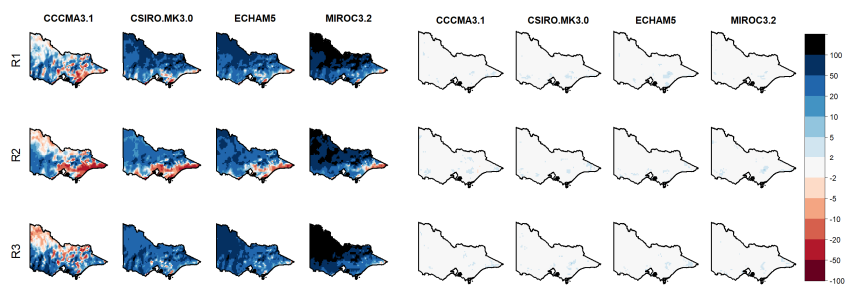
Figure 34: Percentage bias in mean annual rainfall: (a) (raw data, left panels; (b) residual bias (after bias correction), right panels).
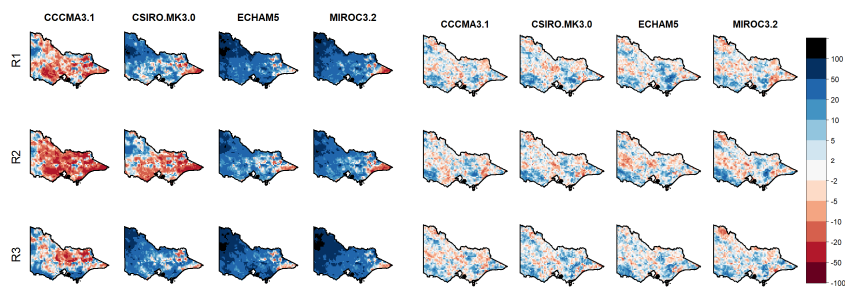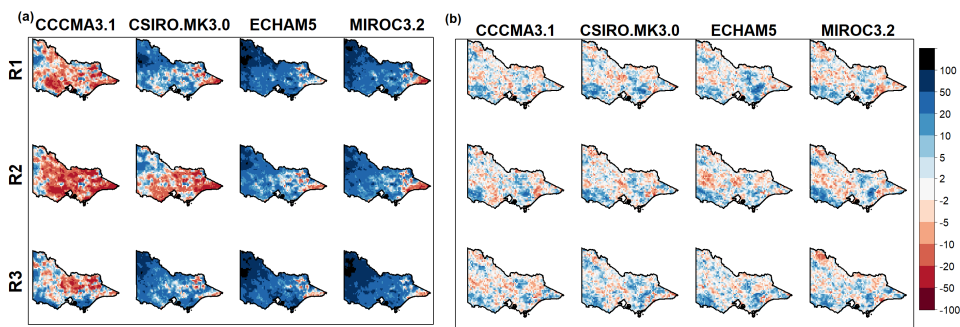
Figure 54: Percentage bias in P99: 99th percentile of rainfall (P99): (a) raw data; (b) residual bias (after bias correction). (raw data, left panels; residual bias, right panels).
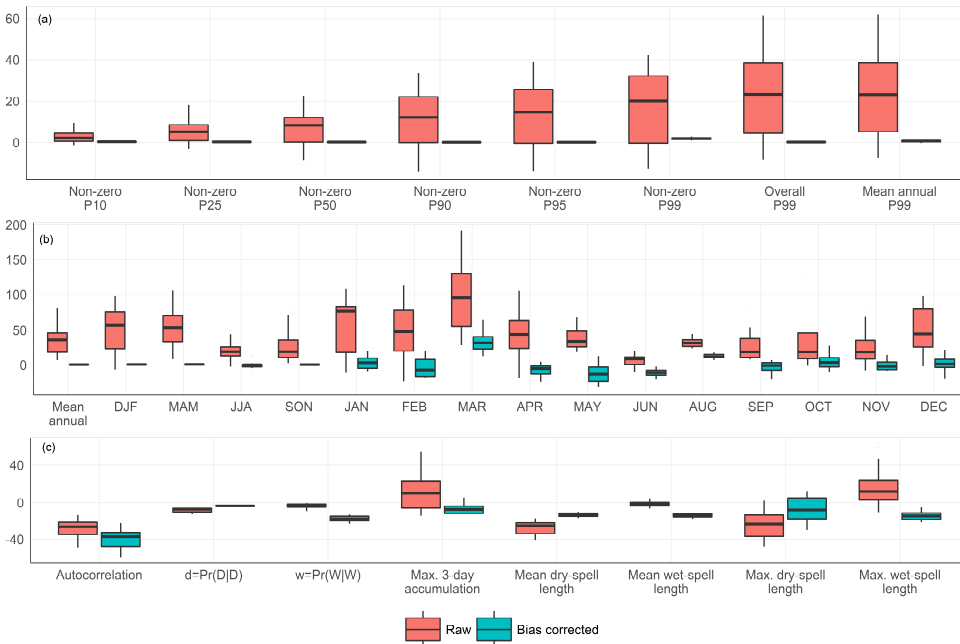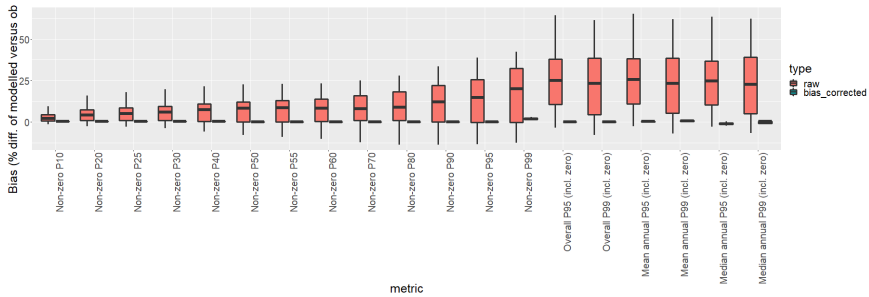
Figure 65: Relative bias (modelled compared to AWAP) of: (a) rainfall percentiles before and after; (b) mean annual, seasonal and monthly rainfall; (c) rainfall-sequencing metrics both before and after bias correction. The range of results represents the spread of GCM hindcast spatial averages over Victoria from the NARCliM WRF 12-model ensemble
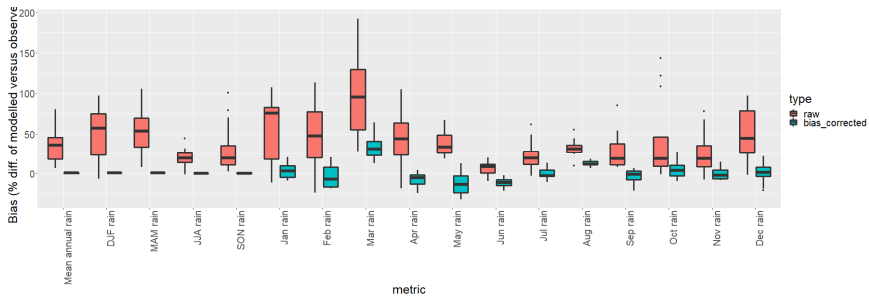
Figure 7: Relative bias in annual, seasonal and monthly averages
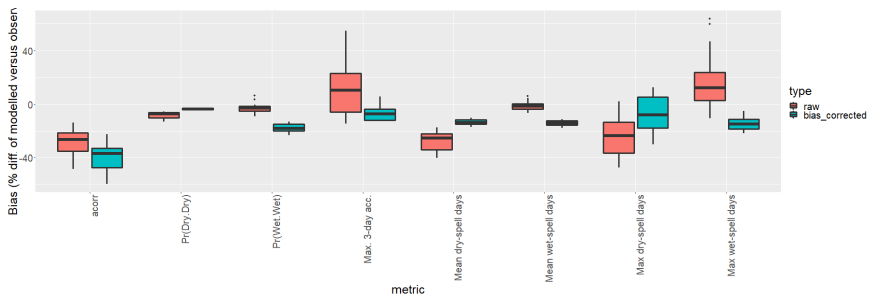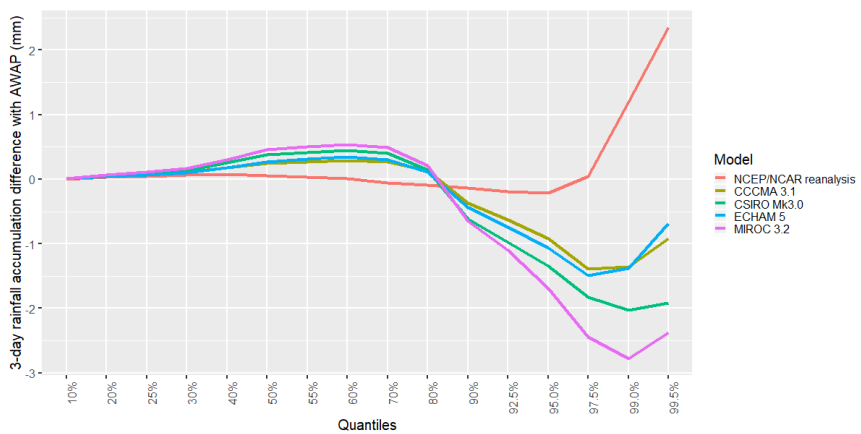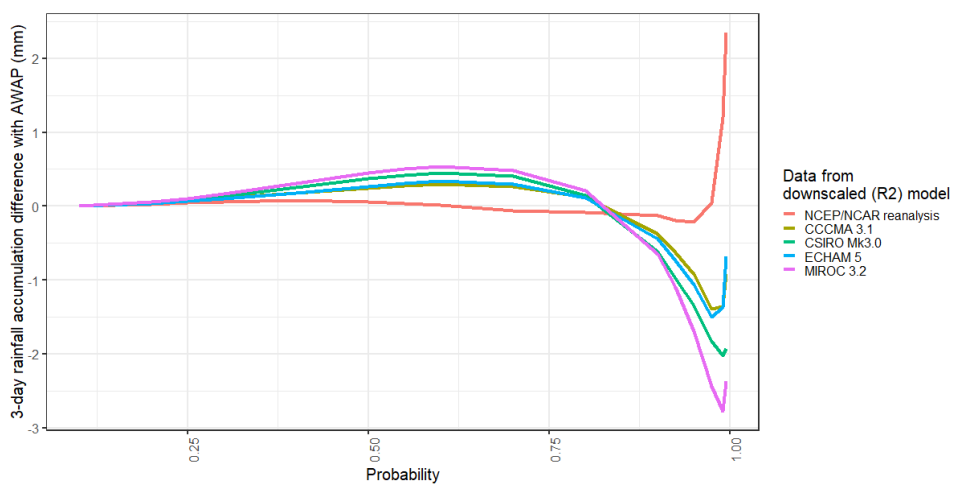
5   **Figure 96: Biases in spatial average 3-day rainfall accumulation percentiles. Here a 3-day moving average filter was applied to each hindcast timeseries and equivalent quantiles taken at increasing probability values (x-axis).**

(a) **Runoff from AWAP (mm)**   (b) **Bias in median runoff (mm)**   (c) **Bias in median runoff (%)**
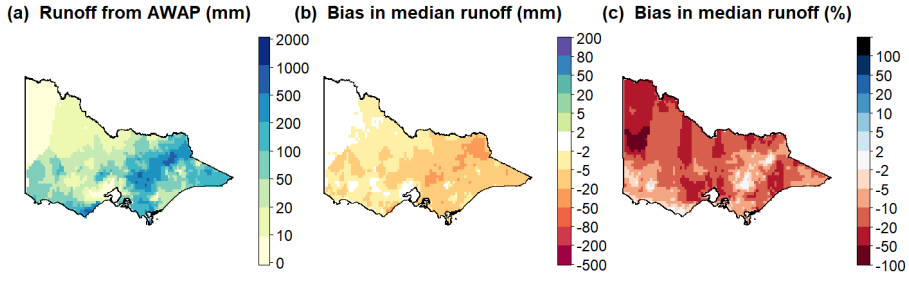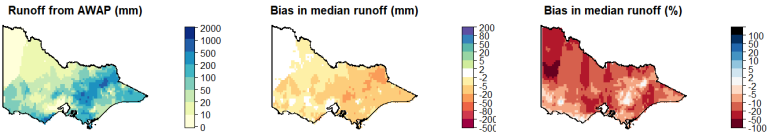
Figure 7̶1̶0̶: Ensemble median modelled runoff over Victoria: (a) from AWAP historical observations; (b) absolute bias (mm); (c) percentage bias (%).A̶b̶s̶o̶l̶u̶t̶e̶ ̶(̶m̶m̶)̶ ̶a̶n̶d̶ ̶p̶e̶r̶c̶e̶n̶t̶a̶g̶e̶ ̶b̶i̶a̶s̶ ̶i̶n̶ ̶m̶e̶d̶i̶a̶n̶ ̶r̶u̶n̶o̶f̶f̶ ̶c̶o̶m̶p̶a̶r̶e̶d̶ ̶t̶o̶ ̶m̶o̶d̶e̶l̶l̶e̶d̶ ̶r̶u̶n̶o̶f̶f̶ ̶f̶r̶o̶m̶ ̶A̶W̶A̶P̶ ̶r̶a̶i̶n̶f̶a̶l̶l̶.
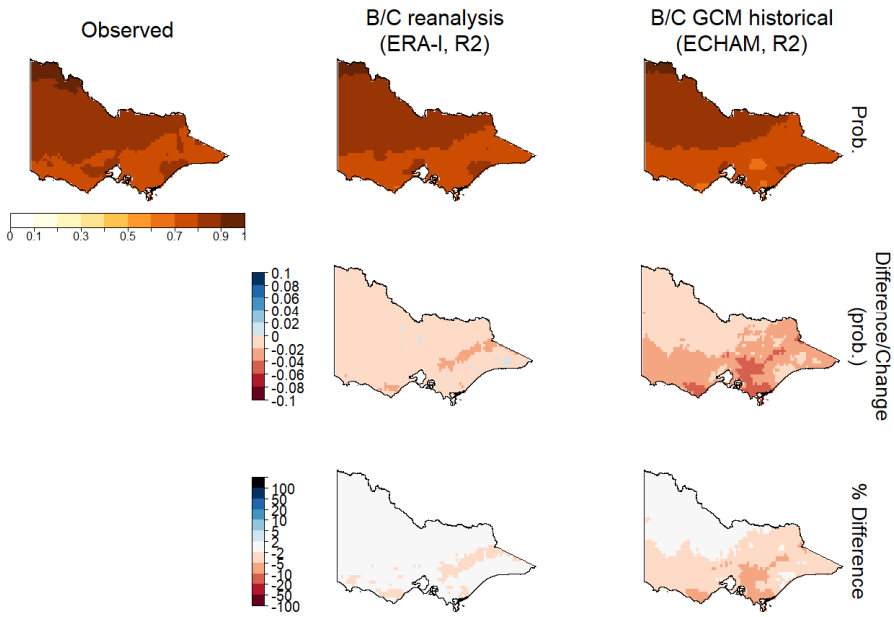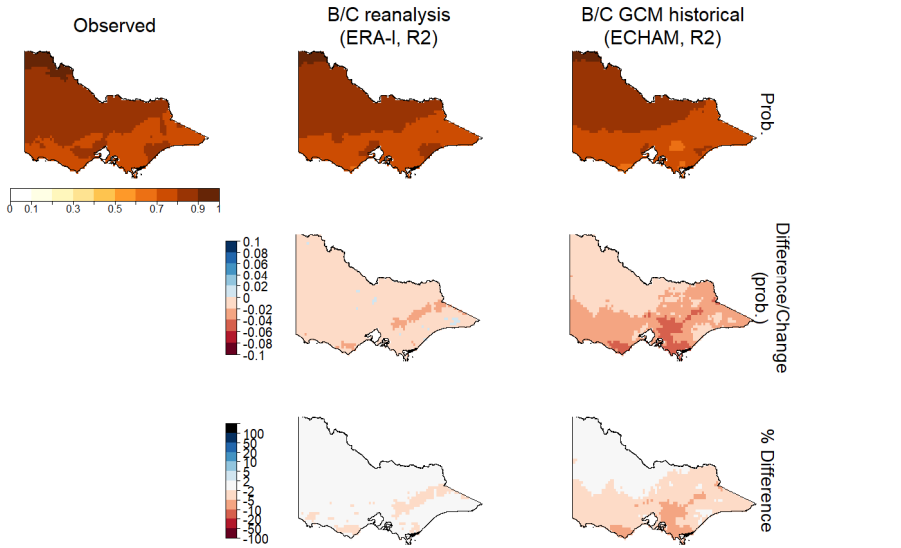
Figure 811: Dry-dry transition probabilities (1mm threshold)
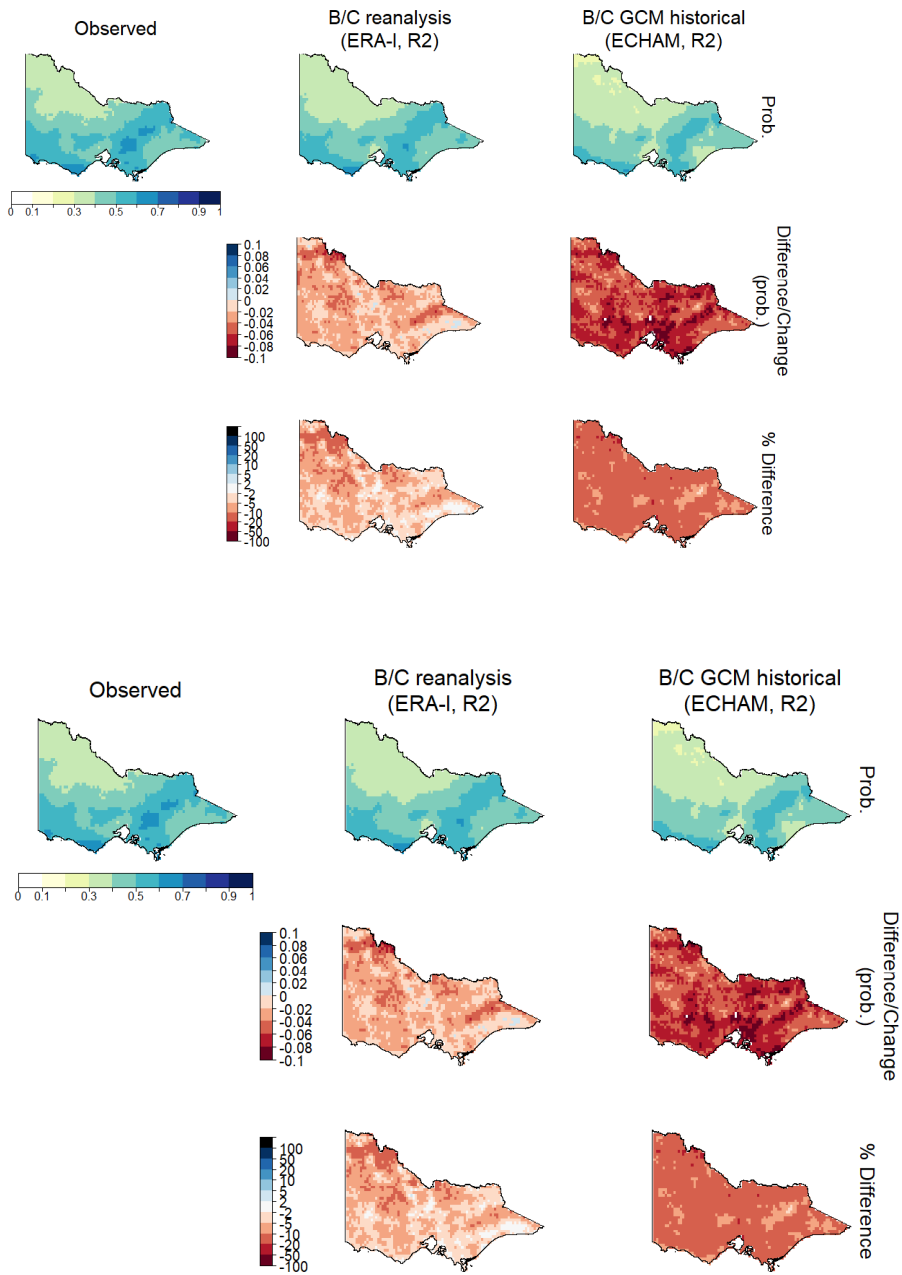
Figure 9~~12~~: Wet-wet transition probabilities (1mm threshold)
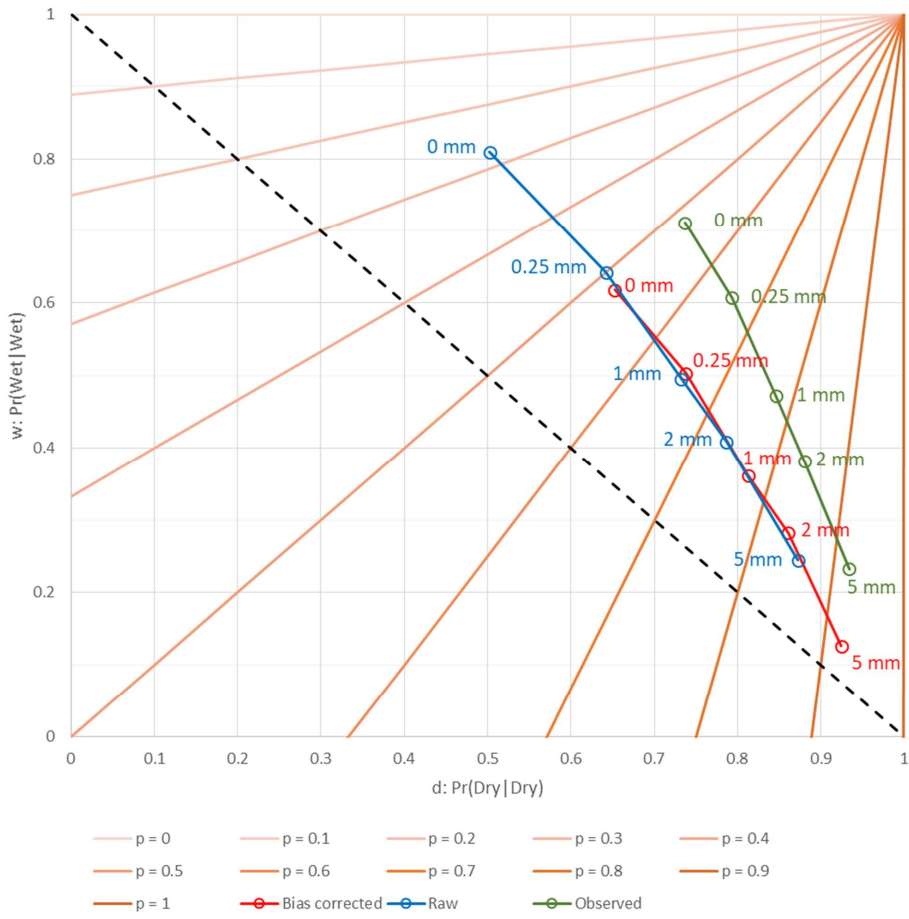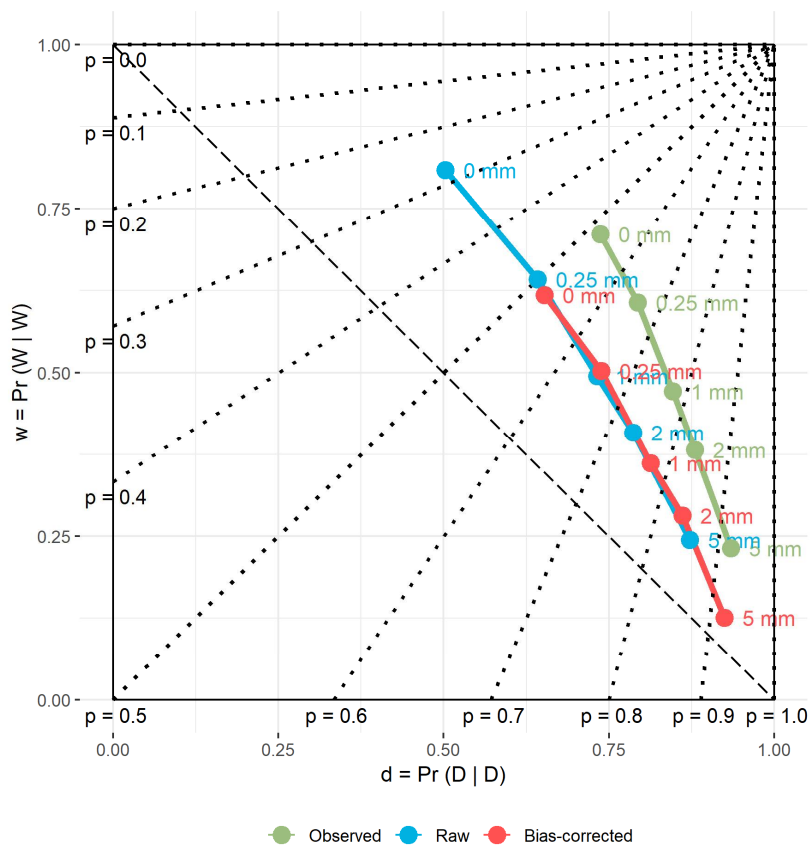
Figure 10~~13~~: An alternative perspective on quantile-quantile mapping: daily rainfall amounts and associated probabilities plotted in *d-w* space ~~(cf. Fig.ure 2)~~. Quantile-quantile mapping <ins>bias correction (red) works by</ins> map~~pings~~ <ins>daily rainfall</ins> amounts from the raw data (blue ~~curve~~) <ins>to</ins> ~~to~~ the probability contours (~~dashed~~<ins>dotted</ins> lines) corresponding to the <ins>appropriate</ins> observed <ins>daily</ins> amount <ins>(green)</ins>.
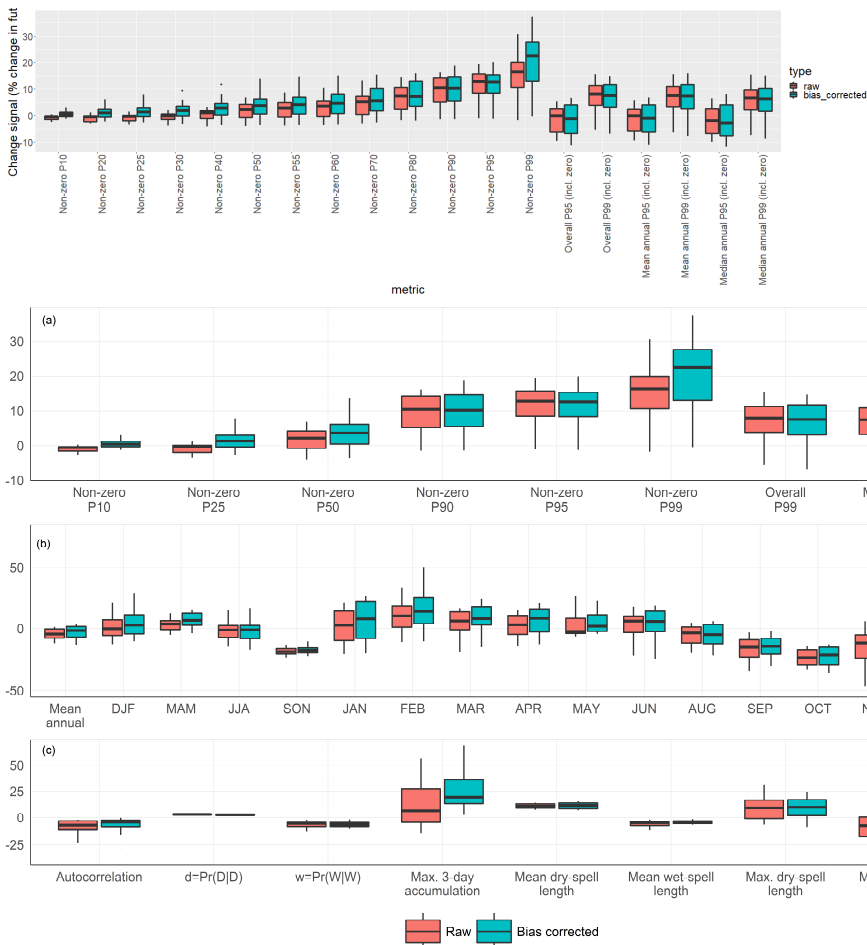
(a)

(b)

(c)

Raw   Bias corrected

Figure 1114: Change signal (percentage difference of RCM future relative to RCM historical) in (a) rainfall percentiles before and after bias correction.; (b) mean annual, seasonal and monthly rainfall; (c) rainfall-sequencing metrics both before and after bias correction.
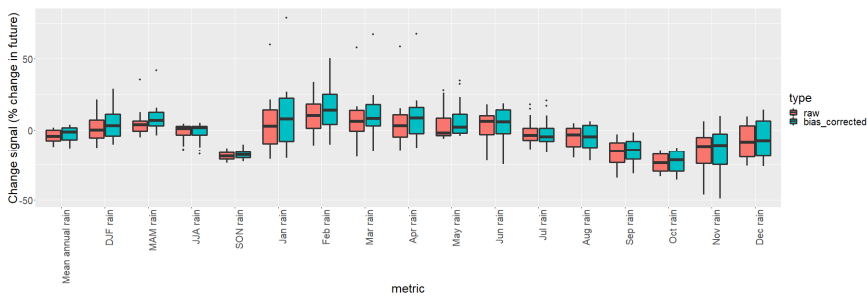

Figure 15: Change signal in mean annual, seasonal and monthly averages before and after bias correction
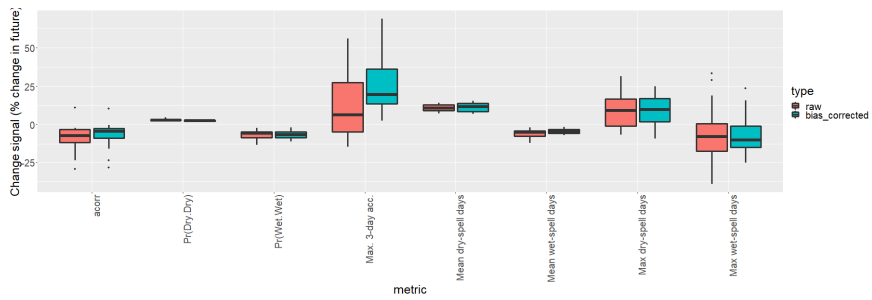
Figure 16: Change signal in rainfall sequencing metrics before and after bias correction