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NARCliM Extreme Precipitation Indices Report

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Executive Summary

This report presents extreme precipitation indices, their biases, and projected future changes for the state of New South Wales (NSW), and Australian Capital Territory (ACT). These results are based on simulations performed as part of the NARCliM (New South Wales / Australian Capital Territory Regional Climate Modelling) project [12, 26].

In general the extreme precipitation indices are projected to increase in the future, however in most cases these increases will not be larger than current inter-annual variability.

Summary answers to the six project objectives are given here

1. How have rainfall extremes varied across NSW and the ACT through the instrumental climate record?

   Most indices have large areas showing significant increases over the last century, and almost no areas with significant decreases. This indicates a consistent intensification of precipitation extremes over this time frame.

2. What changes in rainfall extremes have occurred across NSW and the ACT over the recent past?

   In the last 30 years (since 1984) the trends are more varied spatially with very few locations having significant trends. Perhaps the only exception to this is the maximum consecutive wet day spell which shows significant decreases across parts of southern NSW and Victoria.

3. How do projections of rainfall extremes based on the NARCliM climate projections for the base case epoch (1990-2009) compare to rainfall extremes based on observations for this period?

   The NARCliM ensemble generally has little bias compared to precipitation extreme indices derived from AWAP. That is the observations generally fall within the NARCliM ensemble spread and in most cases the bias is not significant compared to inter-annual variability.

4. How are rainfall extremes projected to change in the near and far futures based on the NSW and ACT Regional Climate Modelling project (NARCliM) climate projections?

   Rainfall extremes are projected to increase in the near and far future based on NARCliM projections. In the near future all increases are within the inter-annual variaiblity and therefore are not statistically significant. In the far future this remains true for most indices and regions, however several indices and regions do now show statistically significant increases.

5. What geographical areas within NSW are at greatest risk due to projected changes in rainfall extremes?

The state planning regions that display the most frequent significant increases in extreme preciptiation indices are: Far West; Murray Murrumbidgee; and New England and North West. Some significant increases were also found in the Hunter and South East and Tablelands regions.

6. What further research should be carried out in regard to rainfall extremes to address critical stakeholder knowledge needs?

   Given the complex nature of phenomena that produce extreme precipitation, and that relatively little region specific work on future changes in these phenomena has been done, a wide array of research questions and potential avenues for further research remain. These are detailed in section 7.1.

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Chapter 1

Introduction

This report presents seasonal and annual extreme precipitation indices, their biases, and projected future changes for the state of New South Wales (NSW), and Australian Capital Territory (ACT). These results are based on simulations performed as part of the NARCliM (New South Wales / Australian Capital Territory Regional Climate Modelling) project [12, 26]. We include results from simulations performed using Regional Climate Models (RCMs) and an observational gridded dataset (AWAP). The report is organized as follows: chapter 1 introduces the report and the NARCliM project, chapter 2 presents definitions of the precipitation indices used in this report, chapter 3 presents climatologies and trends from observations, chapter 4 compares the NARCliM modelled present with the AWAP observed present (1990–2009) and chapters 5 and 6 contain the changes from the present to the near (2020-2039) and far (2060-2079) future periods respectively. This report uses the bias-corrected RCM output (*i.e.* corrected for model biases compared to observations) throughout.

1.1 NARCliM Project Description

The NARCliM project is designed to create regional scale climate projections for use in climate change impacts and adaptation studies, and ultimately to inform climate change policy [12, and others]. Details on NARCliM can be found on the UNSW website `http://www.ccrc.unsw.edu.au/NARCliM/` and the AdaptNSW website `http://www.climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/About-NARCliM/`. NARCliM is a unique project because its design has used a bottom-up approach, heavily involving end user input. This was intended to facilitate useability of model outputs by the end users (*e.g.* adaptation community). Other benefits of early end-user involvement are an improved understanding by the end users of the climate modelling process and its limitations.

The project is limited to a 12-member RCM ensemble. This has been created by choosing four global climate models (GCMs) and downscaling each of these with three different RCMs (three versions of WRF using different parameterizations of sub-grid atmospheric physics). All RCM simulations were performed at 10 km resolution over NSW/ACT. The NARCliM domain is shown in Figure 1.1.

Like previous regional climate projection projects, NARCliM has two main phases. In phase one, three RCMs are used to downscale the NCEP/NCAR reanalysis [22] from 1950 to 2009.

The reanalysis is a numerical "reproduction" of global climate and weather patterns over years 1950-2009, and is constructed by combining weather observations, and climate models. This particular reanalysis was chosen due to its relatively long-term coverage allowing to perform a 60-year long historical simulation. Southeast Australia has experienced strong decadal variability in precipitation over the second half of the 20th century with particularly wet decades in the 1950s and 1970s. These reanalysis-driven simulations provide a strong test of the RCM's ability to simulate both these very wet periods and the recent dry period known as the Millennium Drought [29]. This phase provides an estimate of the RCM quality including any systematic RCM biases.

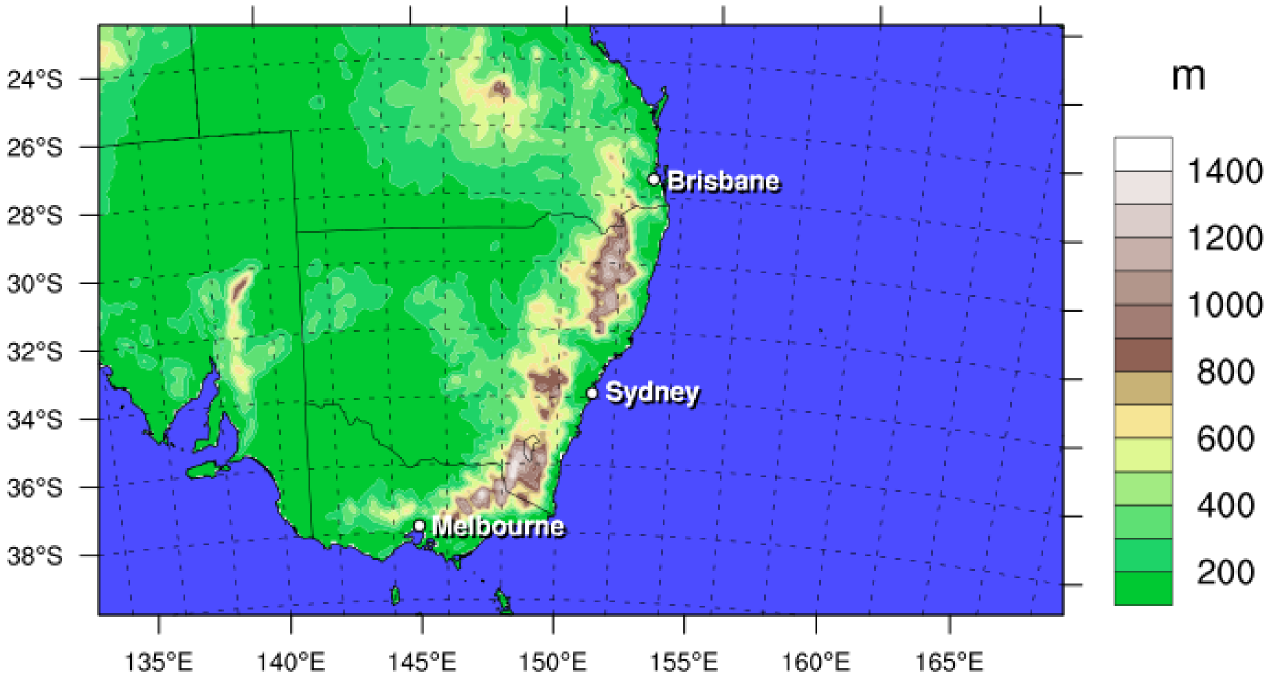

Figure 1.1: Map of NARCliM domain

In phase two, the three RCMs are used to downscale four GCMs in three 20-year time slices (1990-2009, "present"; 2020-2039, "near future"; 2060-2079, "far future"). For future projections the SRES A2 emission scenario [14] is used. This scenario assumes an overall relatively high growth rate of atmospheric greenhouse gas emissions. A careful choice of both RCMs and GCMs is required for this small ensemble to adequately sample the model uncertainty. The methodology used to make these decisions is described in the reports [11, 10]. The GCMs chosen are the MIROC3.2, ECHAM5, CCCMA3.1 and CSIRO-MK3.0. The chosen RCMs, and the parametrizations used therein are given in Table 1.1 below. These are versions of the WRF model for different parametrizations of planetary boundary layer, surface layer, cumulus physics, and radiation.

NARCliM Ensemble Member	Planetary Boundary Layer Physics / Surface Layer Physics	Cumulus Physics	Microphysics	Shortwave and Longwave Radiation Physics
R1	MYJ / Eta similarity	KF	WDM 5 class	Dudhia / RRTM
R2	MYJ / Eta similarity	BMJ	WDM 5 class	Dudhia / RRTM
R3	YSU / MM5 similarity	KF	WDM 5 class	CAM / CAM

Table 1.1: The three RCMs selected from a 30 model ensemble. MYJ / Eta similarity: Mellor-Yamada-Janjic Planetary Boundary Layer (PBL) scheme [16] with Eta similarity surface layer; YSU / MM5 similarity: Yonsei University PBL scheme [13] with the MM5 similarity theory surface layer [28, 7, 32]; KF: Kain-Fritsch cumulus scheme [20, 21, 19]; BMJ: Betts-Miller-Janjic cumulus scheme [2, 1, 16, 17]; WDM5: WRF Double Moment 5-class microphysics scheme [24]; Dudhia: Dudhia shortwave radiation scheme [6], RRTM: Rapid Radiative Transfer Model longwave radiation scheme [25]; CAM: NCAR Community Atmosphere Model version 3.0 shortwave and longwave radiation schemes [3].

This report uses the bias-corrected RCM output (*i. e.,* RCM output corrected for biases between the models and observations). During the bias-correction procedure, we first compare distributions of daily model output and observations for all seasons. Then, we apply the correction factors (independent of season) to RCM output to make the distributions of daily RCM output match daily observations. For present, near-future, and far-future periods, we use Australian Water Availability Project (AWAP) observations [18] for period 1990-2009 to calculate corrections. For reanalysis runs, we use AWAP data for climatological period 1961-1990 to calculate the corrections. The in-depth description of the bias-correction methodology, and the guidance on when to use the bias-corrected vs. the original output is given in report [9] while plots of the bias corrected climatology can be found in [27].

Some averaged results are presented for state planning regions in NSW and the ACT shown in Figure 1.2. These results are presented as box-and-whisker plots and show the ensemble spread for each of the indices.

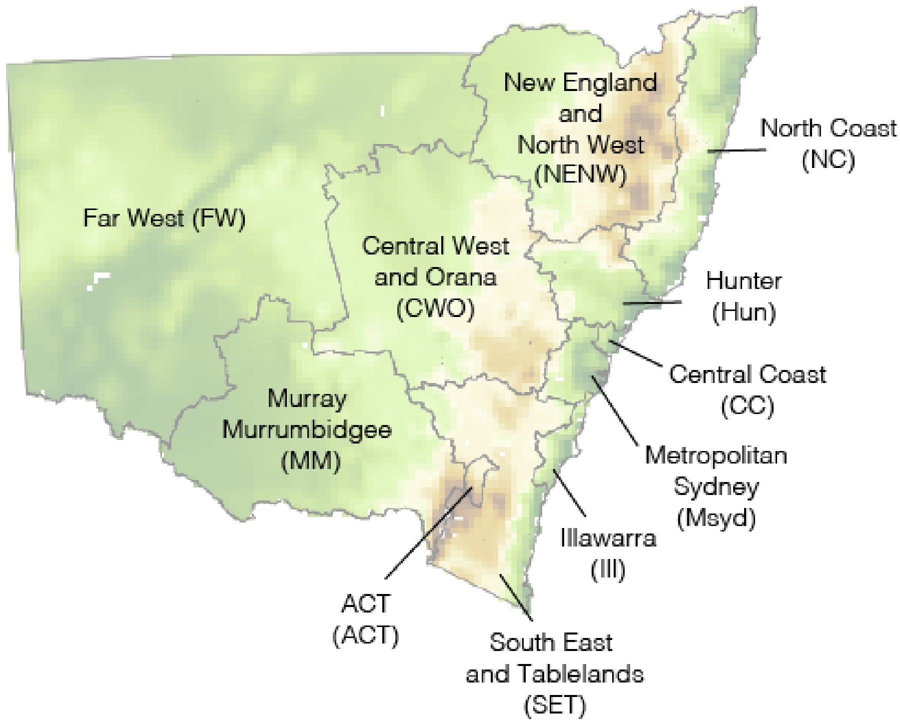

Figure 1.2: Names of state planning regions and abbreviations in NSW and ACT

Chapter 2

Extreme Precipitation Indices Definition

In order to establish a baseline set of indices that characterise moderate extremes of temperature and precipitation the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (http://etccdi.pacificclimate.org) has compiled a set of 27 indices, 11 of which pertain to precipitation. In addition, a set of 34 core indices has been defined by the World Meteorological Organization (WMO) Commission for Climatology (CCl) Expert Team on Climate Risk and Sector-specific Climate Indices (ET-CRSCI). Many of the ET-CRSCI indices are copies or generic versions of the ETCCDI indices.

Table 2.1 contains the full set of indices examined in this report. The official definitions are used for all indices except R95p, R99p, R95pTOT and R99pTOT which rely on percentiles calculated on a base period. The official base period is 1961-1990, here we use 1990-2009 as our base period. An examination of the impact of this change in base period is given in Chapter 3.

Note that Rx1day and Rx5day are defined on a monthly basis, while all the other indices are defined on an annual basis.

Indicator ID	**Name**	**Definition**	**Units**
Rx1day	Monthly maximum 1-day precipitation	Let RR_{ij} be the daily precipitation amount on day i in period j. The maximum 1-day value for period j are: $Rx1day_j = max(RR_{ij})$	mm
Rx5day	Monthly maximum 5-day precipitation	Let RR_{kj} be the precipitation amount for the 5-day interval ending on day k, in period j. The maximum 5-day values for period j are: $Rx5day_j = max(RR_{kj})$	mm
SDII	Simple Daily Intensity Index	Let RR_{wj} be the daily precipitation amount on wet days, w (RR $\geq$ 1mm) in period j. If W represents number of wet days in j, then: $SDII = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$	mm/day
R10mm	Number of heavy precipitation days	Let RR_{ij} be the daily precipitation amount on day i in period j. Count the number of days where: $RR_{ij} \geq 10mm$	days
R20mm	Number of very heavy precipitation days	Let RR_{ij} be the daily precipitation amount on day i in period j. Count the number of days where: $RR_{ij} \geq 20mm$	days
CDD	Consecutive dry days	Maximum number of consecutive days with RR$<$1mm	days
CWD	Consecutive wet days	Maximum number of consecutive days with RR$\geq$1mm	days
R95p	Contribution from very wet days	Let RR_{wj} be the daily precipitation amount on a wet day w (RR $\geq$ 1.0mm) in period i and let $RR_{wn}95$ be the 95th percentile of precipitation on wet days in the 1990-2009 period. If W represents the number of wet days in the period, then: $R95P_j = \sum_{w=1}^{W} RR_{wj}$ where $RR_{wj} > RR_{wn}95$	mm
R99p	Contribution from extremely wet days	Let RR_{wj} be the daily precipitation amount on a wet day w (RR $\geq$ 1.0mm) in period i and let $RR_{wn}99$ be the 99th percentile of precipitation on wet days in the 1990-2009 period. If W represents the number of wet days in the period, then: $R99P_j = \sum_{w=1}^{W} RR_{wj}$ where $RR_{wj} > RR_{wn}99$	mm
R95pTOT	Contribution from very wet days as a percentage of the total wet day precipitation	$R95pTOT = \frac{100*R95p}{PRCPTOT}$	% of PRCPTOT
R99pTOT	Contribution from extremely wet days as a percentage of the total wet day precipitation	$R99pTOT = \frac{100*R99p}{PRCPTOT}$	% of PRCPTOT
PRCP-TOT	Annual total wet day precipitation	Precipitation from wet days (RR$\geq$1mm)	mm

Table 2.1: Definitions of precipitation related indices from the ETCCDI and ET-CRSCI sets.

Chapter 3

AWAP Observed Climatologies

Here we present observed precipitation indices calculated from the AWAP project, produced by the Bureau of Meteorology [18]. This dataset is directly compared to RCM output in later chapters. AWAP is a daily dataset at 5 km by 5 km spatial resolution. The dataset is generated by interpolating surface station measurements of precipitation, maximum and minimum temperature and vapour pressure. AWAP data starts in 1900 for precipitation, 1910 for temperature, 1970 for vapour pressure, and extends up to the present - it is constantly updated with the most recent observations. During most of the period of NARCliM reanalysis runs (1950-2009), AWAP gridded dataset includes information from $\sim$ 6000 to 7000 rainfall stations and $\sim$ 300 to 800 temperature stations. A substantially smaller number of temperature stations ($\sim$ 100) were used for earlier years (1910-1956).

The gridding of the *in-situ* daily observations was generated using an anomaly-based approach to take advantage of their smoother spatial distribution and they were then converted to absolute values by adding (or multiplying in the case of precipitation) a climatological analysis. More details on the analysis method used to interpolate station data onto the AWAP grid can be found in Jones et al. (2009) [18].

Observational gridded datasets are the most appropriate kind of data to compare to regional climate models. Such gridded data generally constitute area-averaged estimations, making them directly comparable to model output. Before plotting, we interpolate the AWAP observations onto the NARCliM domain 2 grid using a simple inverse distance weighting method.

We present the climatology of Indices based on AWAP data using the NARCliM reference period (1990-2009), and compare this to the official reference period (1961-1990). We then present trends in these indices over the AWAP historical record calculated using a trend model that explicitely accounts for first-order autocorrelation in the residuals.

3.1 Present-Day (1990-2009) AWAP Observations

This subsection contains present-day (1990-2009) seasonal and annual climatologies for the ETC-CDI and ET-CRSCI precipitation indices based on AWAP observations. Seasons are defined as summer=DJF, autumn=MAM, winter = JJA, spring=SON. These observations are directly comparable to the output from present-day runs presented in Chapter 4.

Most extreme precipitation indices have maxima along the NSW coast, particularly in the north. Secondary maxima are frequently found over the Snowy Mountains in the south and the New England and North West region in the north.

The Rx1day and Rx5day indices (Figures 3.1 and 3.2) show that the highest values for northern NSW occur in summer, while southern NSW has a much less pronounced seasonal cycle in precipitation extremes.

Some indices, such as SDII (Figure 3.3) show relatively high values extending westward across the northern tier of NSW, while others, such as R10mm, R20mm, PRCPTOT and R99p (Figures 3.4, 3.5, 3.6 and 3.8) restrict the highest values to be relatively close to the coast.

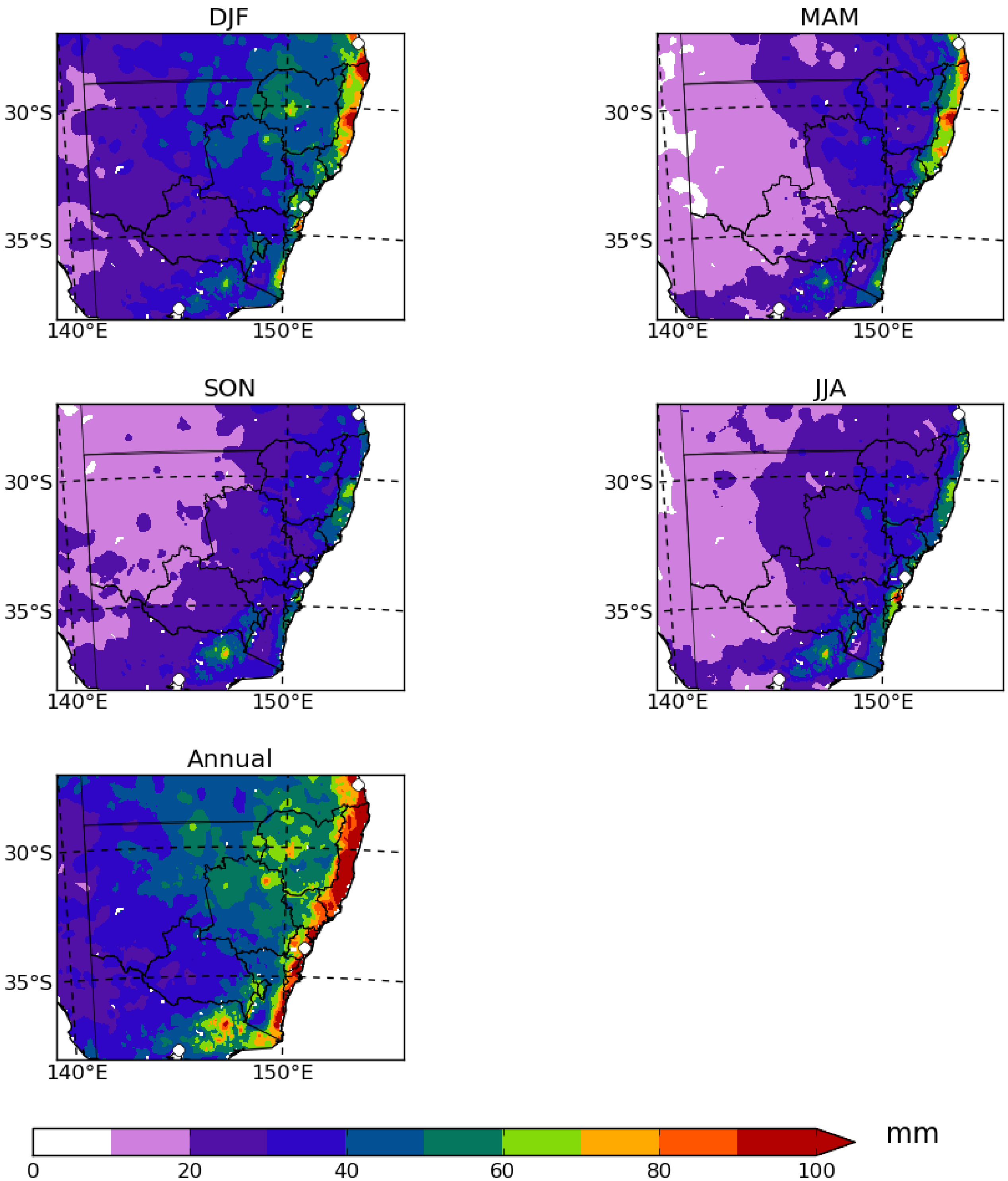

Figure 3.1: Present day (1990-2009) average seasonal and annual maximums of AWAP maximum 1-day preciptation (Rx1day) [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

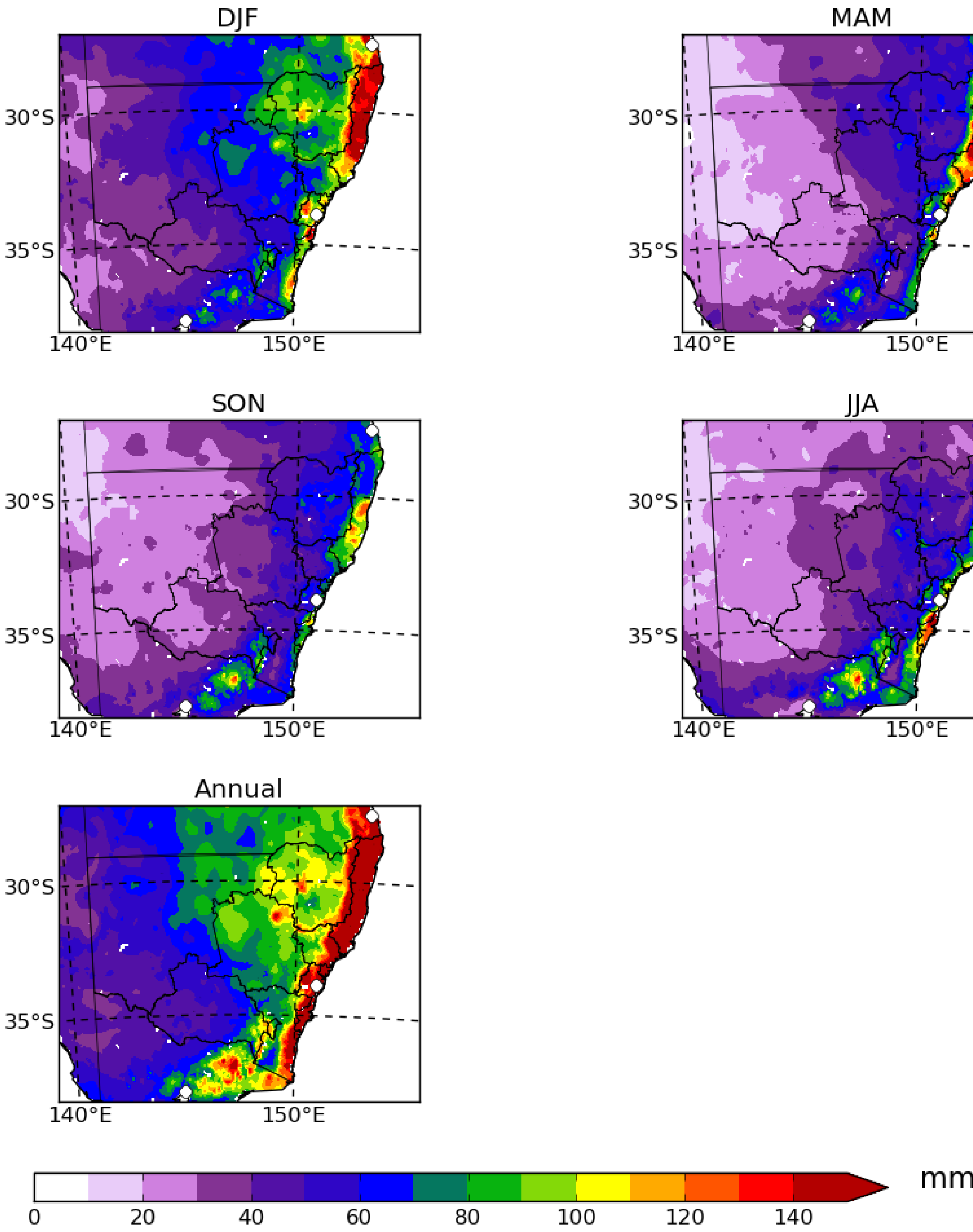

Figure 3.2: Present day (1990-2009) average seasonal and annual maximums of AWAP maximum 5-day preciptation (Rx5day) [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

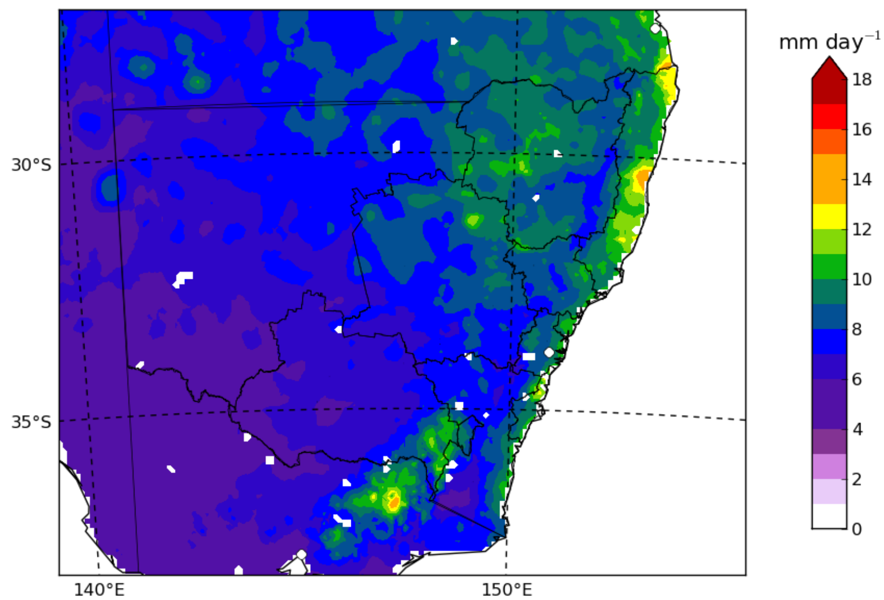

Figure 3.3: Annual means of AWAP simple precipitation intensity index (SDII) for years 1990-2009 [mm day^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

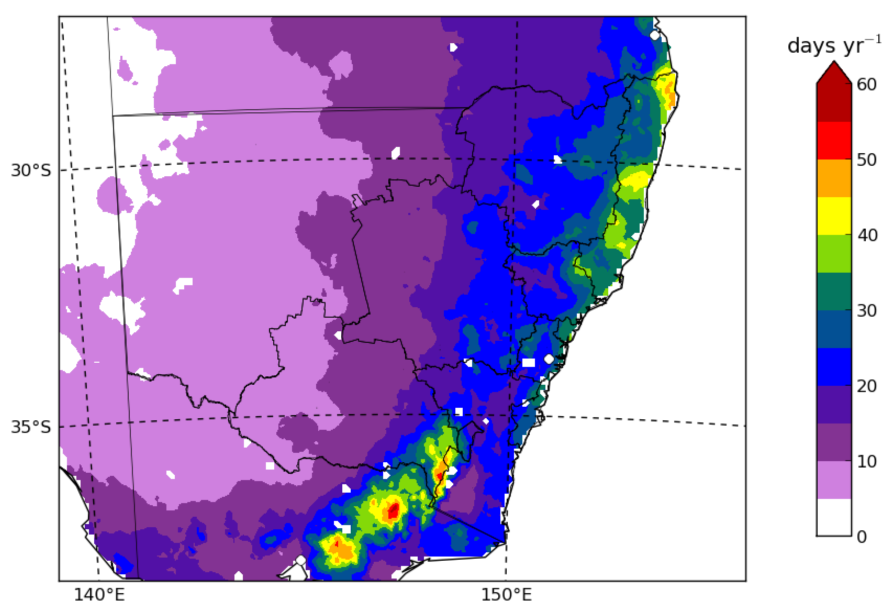

Figure 3.4: Annual means of AWAP number of heavy precipitation days (R10mm) for years 1990-2009 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

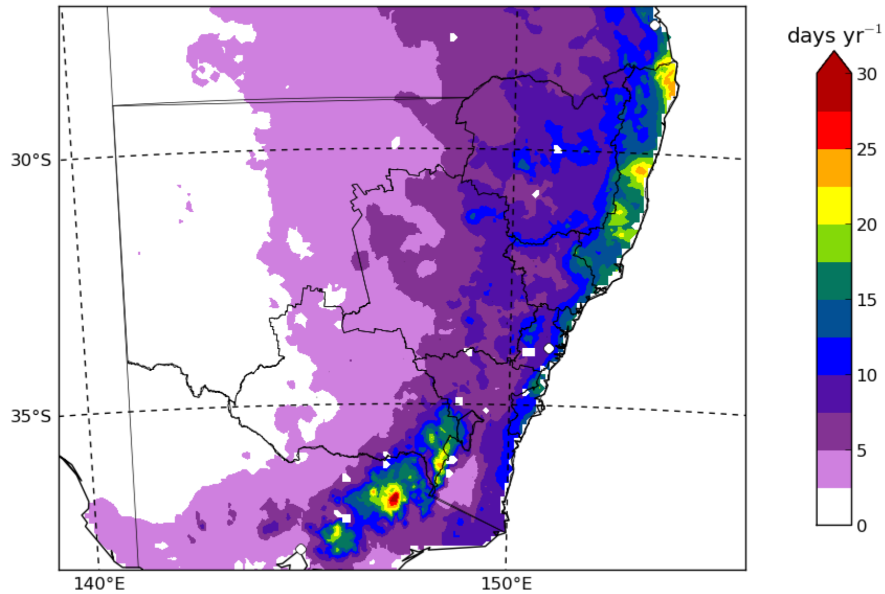

Figure 3.5: Annual means of AWAP number of very heavy precipitation days (R20mm) for years 1990-2009 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

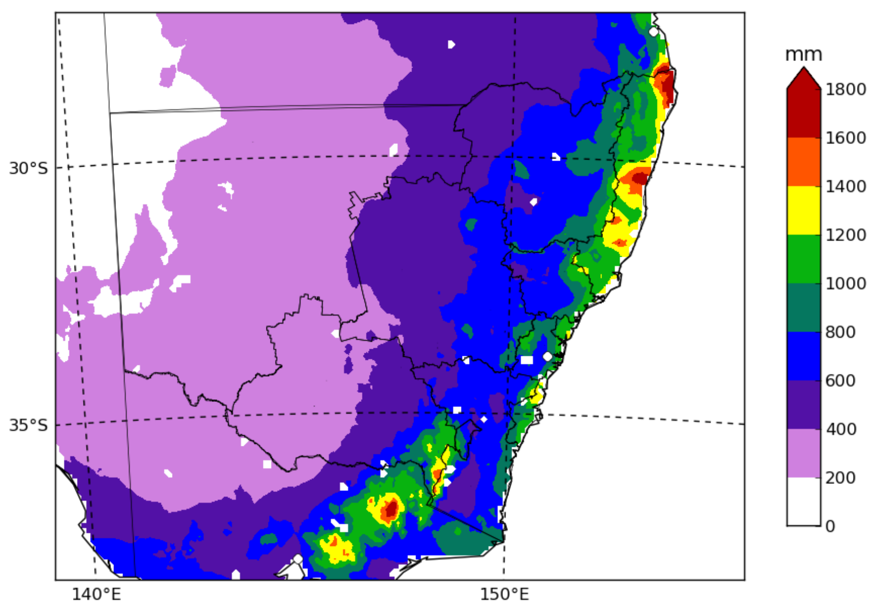

Figure 3.6: Annual means of AWAP annual total wet day precipitation (PRCPTOT) for years 1990-2009 [mm yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

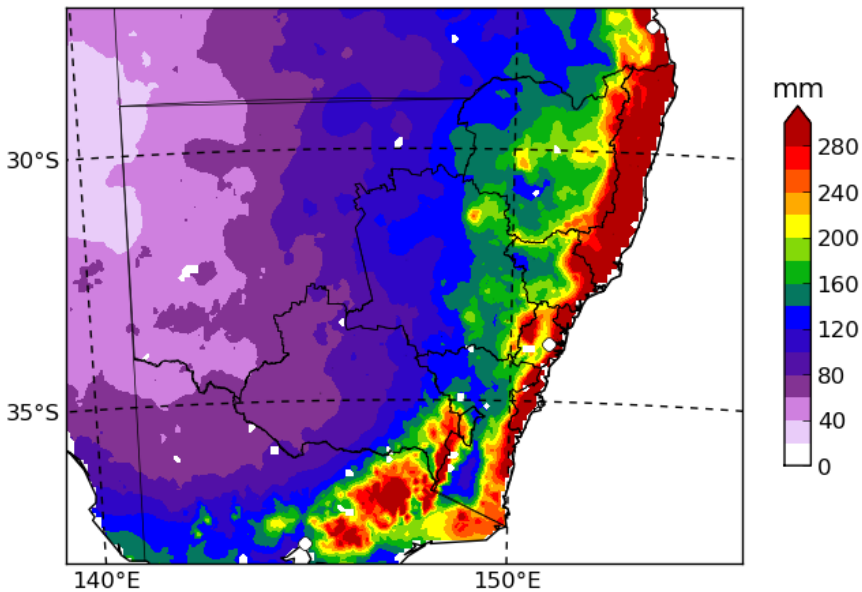

Figure 3.7: Annual means of AWAP contribution from very wet days (R95p) for years 1990-2009 [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

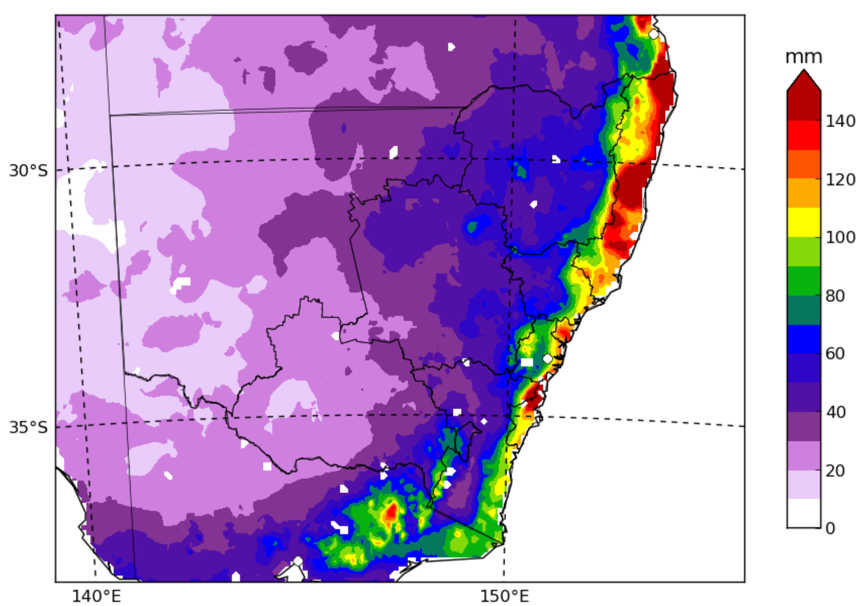

Figure 3.8: Annual means of AWAP contribution from extremely wet days (R99p) for years 1990-2009 [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

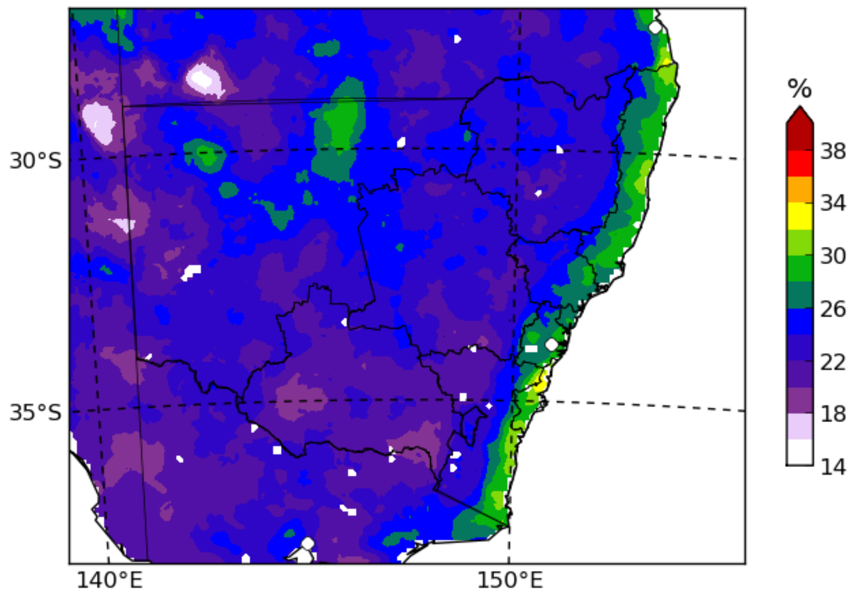

Figure 3.9: Annual means of AWAP contribution from very wet days as % of PRCPTOT (R95pTOT) for years 1990-2009 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

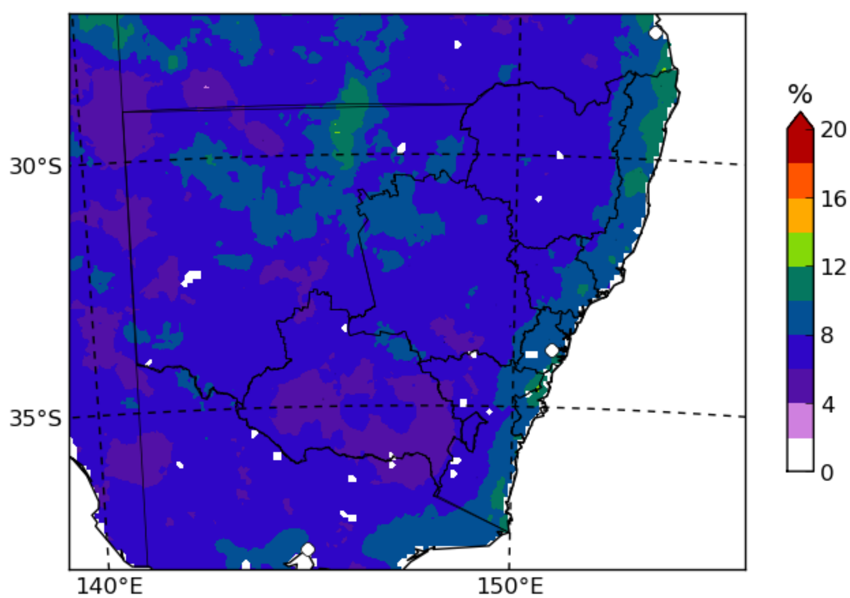

Figure 3.10: Annual means of AWAP contribution from extremely wet days as % of PRCPTOT (R99pTOT) for years 1990-2009 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

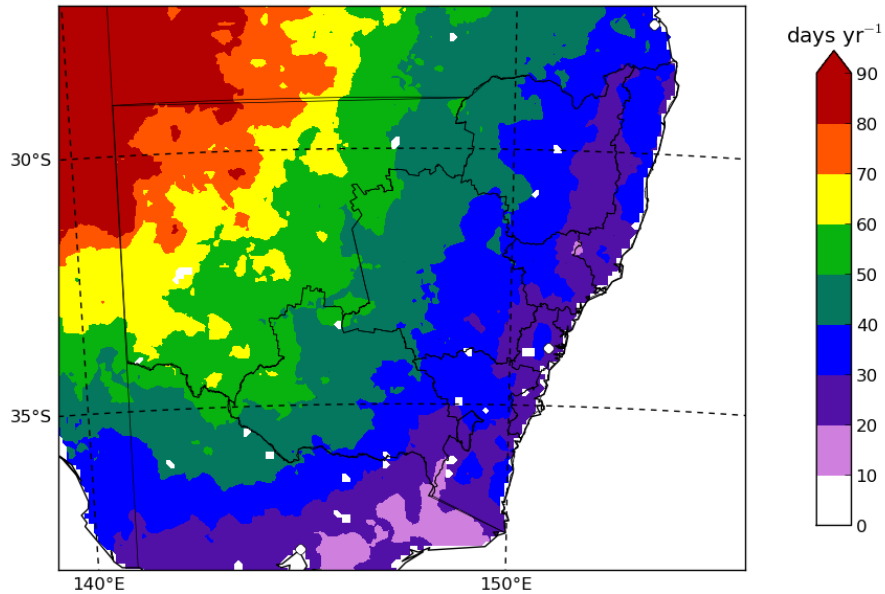

Figure 3.11: Annual means of AWAP consecutive dry days (CDD) for years 1990-2009 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

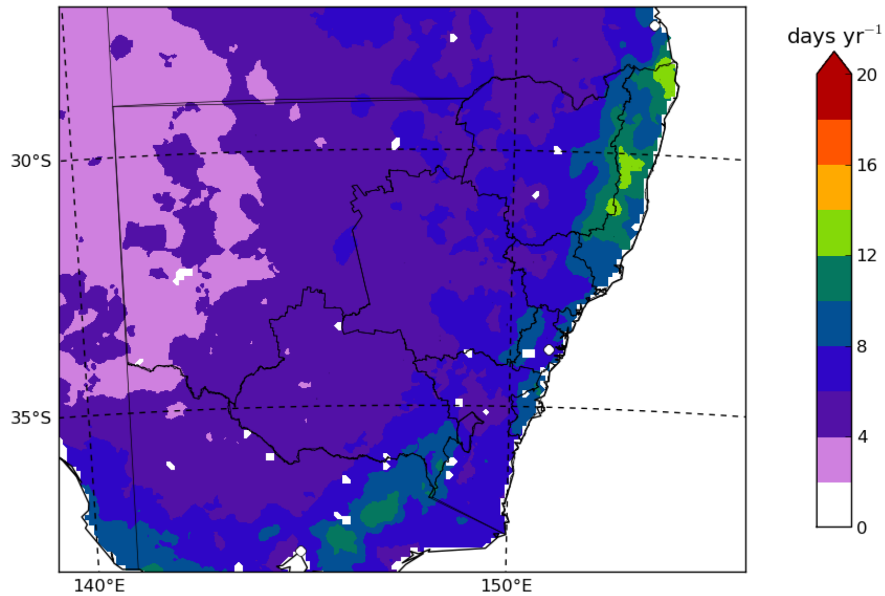

Figure 3.12: Annual means of AWAP consecutive wet days (CWD) for years 1990-2009 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

3.2 Difference Due to Base Period

This subsection contains plots showing the difference in the percentile based indices (R95p, R99p, R95pTOT, R99pTOT) when calculated on the original base period (1961-1990) compared to the NARCliM base period (1990-2009).

The mean difference over the period 1990-2009 is shown in the figures below. Some of the largest differences occur in the north-west of NSW where very few stations exist and AWAP is therefore less reliable. The differences are generally found to be less than 5mm or 8% and are not expected to cause any systematic difference to the interpretation of future changes.

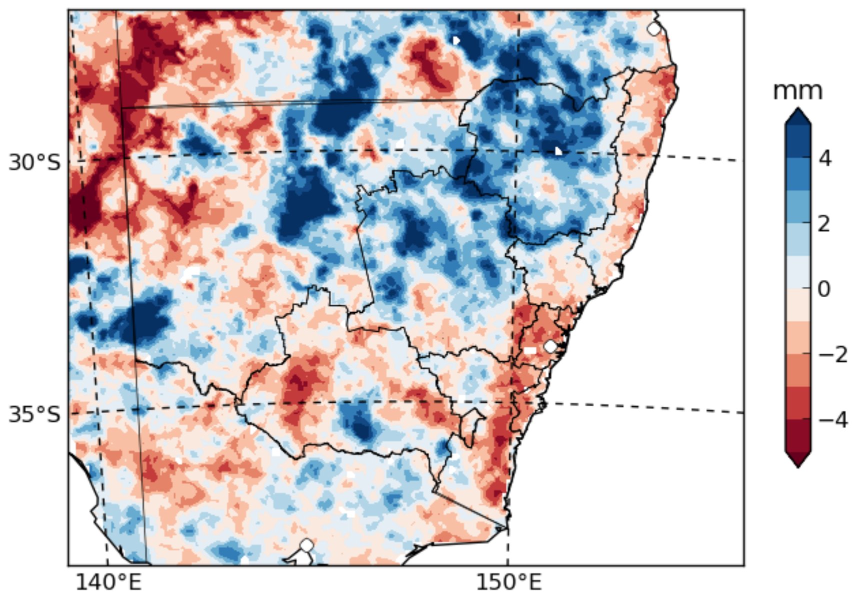

Figure 3.13: Differences in present-climate (1990-2009) contribution from very wet days (R95p) calculated using the 1961-1990 reference period minus contribution from very wet days (R95p) calculated using the 1990-2009 reference period. White circles (top to bottom): Brisbane, Sydney, Melbourne.

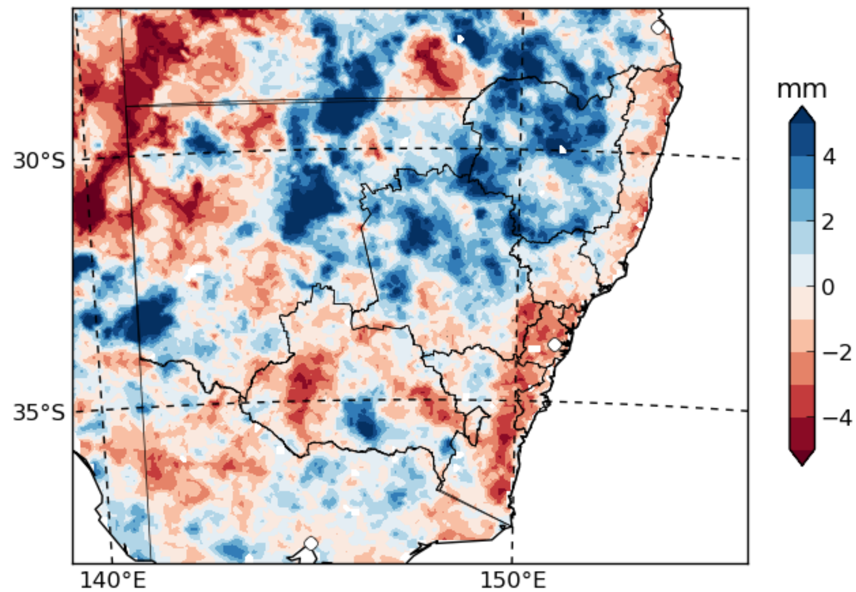

Figure 3.14: Differences in present-climate (1990-2009) contribution from extremely wet days (R99p) calculated using the 1961-1990 reference period minus contribution from extremely wet days (R99p) calculated using the 1990-2009 reference period. White circles (top to bottom): Brisbane, Sydney, Melbourne.

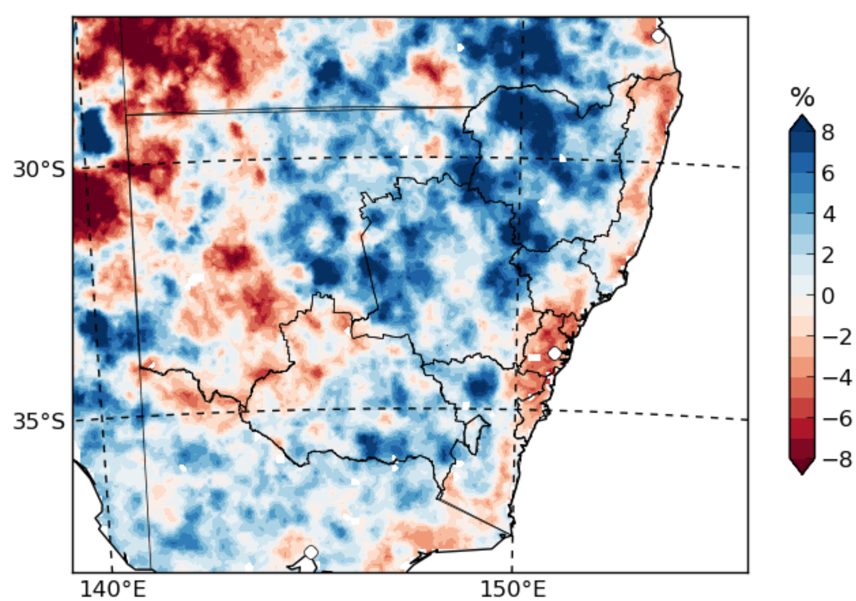

Figure 3.15: Differences in present-climate (1990-2009) contribution from very wet days as % of PRCPTOT (R95pTOT) calculated using the 1961-1990 reference period minus contribution from very wet days as % of PRCPTOT (R95pTOT) calculated using the 1990-2009 reference period. White circles (top to bottom): Brisbane, Sydney, Melbourne.

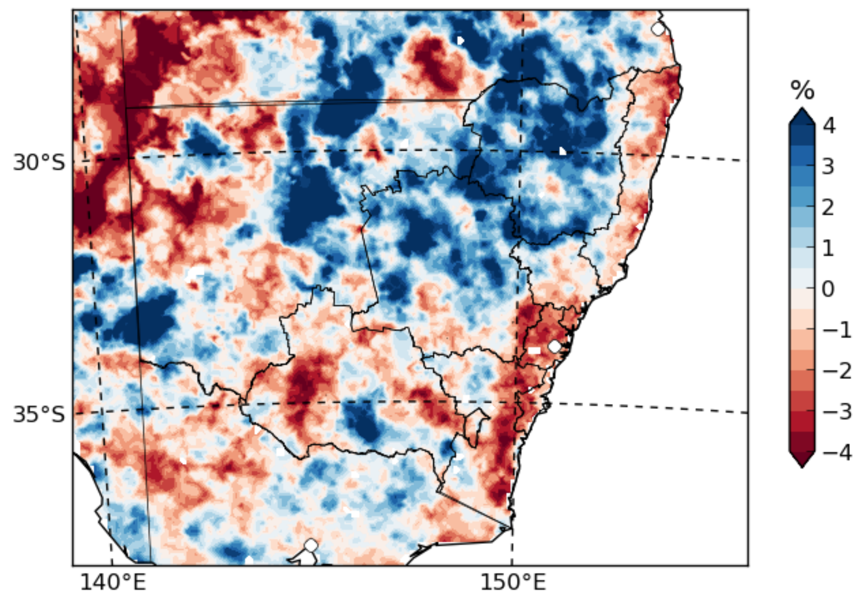

Figure 3.16: Differences in present-climate (1990-2009) contribution from extremely wet days as % of PRCPTOT (R99pTOT) calculated using the 1961-1990 reference period minus contribution from extremely wet days as % of PRCPTOT (R99pTOT) calculated using the 1990-2009 reference period. White circles (top to bottom): Brisbane, Sydney, Melbourne.

3.3 Trends in AWAP Derived Extreme Precipitation Indices from 1911 to 2014

This subsection contains plots showing the trend in the indices calculated from AWAP data over the full record (1911 to 2014). In the resulting maps, trends are estimated using a linear trend model employed in the Intergovernmental Panel on Climate Change Fifth assessment Report [15]. Trend slopes in such a model are the same as those in a standard Ordinary Least Squares regression model but allowing for first-order autocorrelation in the residuals. Statistical significance is tested at the 5% level using a nonparametric Mann-Kendal test. A full description of the method can be obtained from Hartmann et al.[5] .

Most indices have large areas showing significant increases over the last century, and almost no areas with significant decreases. This indicates a consistent intensification of precipitation extremes over this time frame. It is worth noting that the trend in Rx1day 3.17 has no clear longitudinal gradient such that the trends found inland are larger relative to the magnitude of Rx1day than those found near the coast. The only indices with large areas of significant decreases are the maximum consecutive dry days (CDD) and consecutive wet days (CWD) (Figures 3.27 and 3.28). These indicate that the longest dry spell each year is now 10-20 days shorter in many parts of western NSW, and the longest wet spell each year is now a couple of days shorter for some small parts of NSW and much of Victoria.

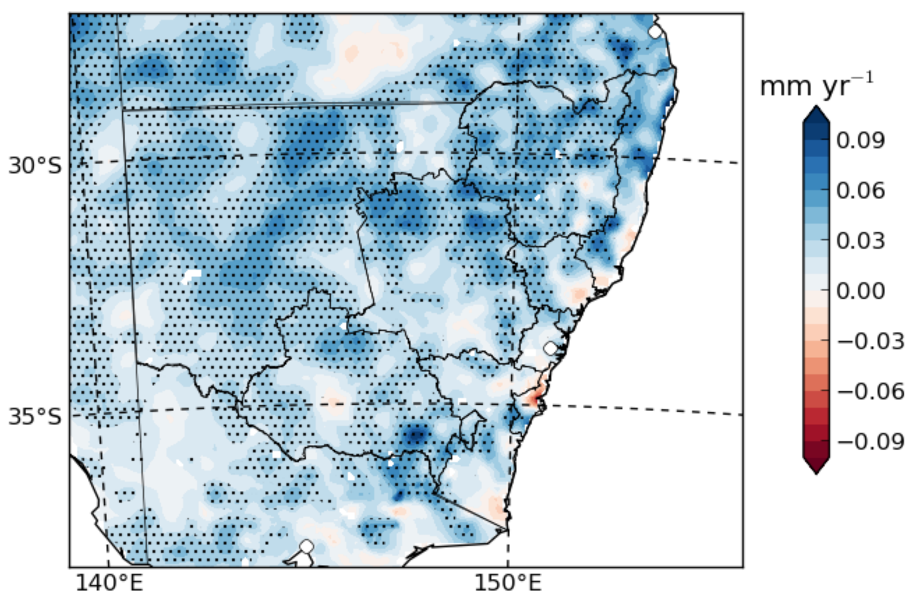

Figure 3.17: Trends from 1911 to 2014 in annual maximum 1-day preciptiation (Rx1day) [mm yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

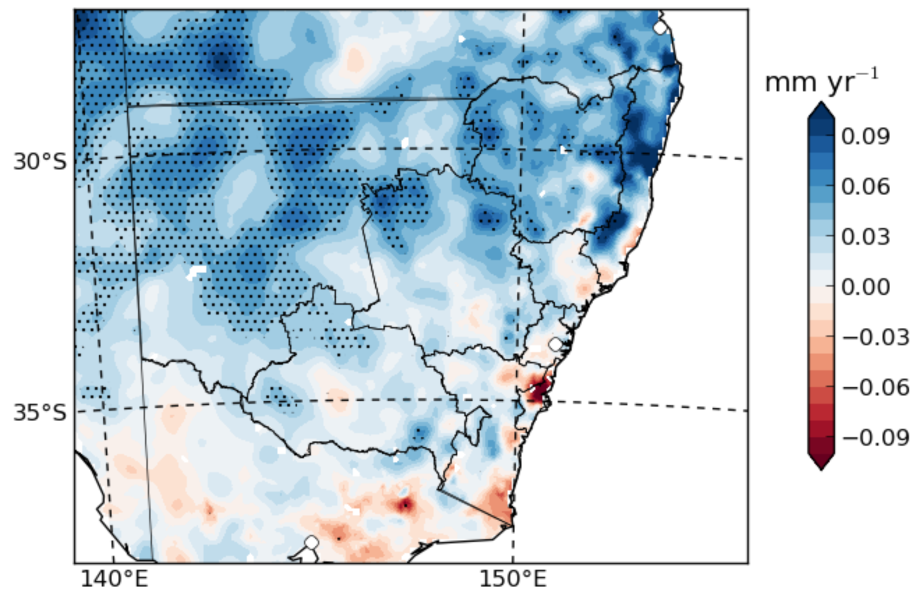

Figure 3.18: Trends from 1911 to 2014 in annual maximum 5-day preciptiation (Rx5day) [mm yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

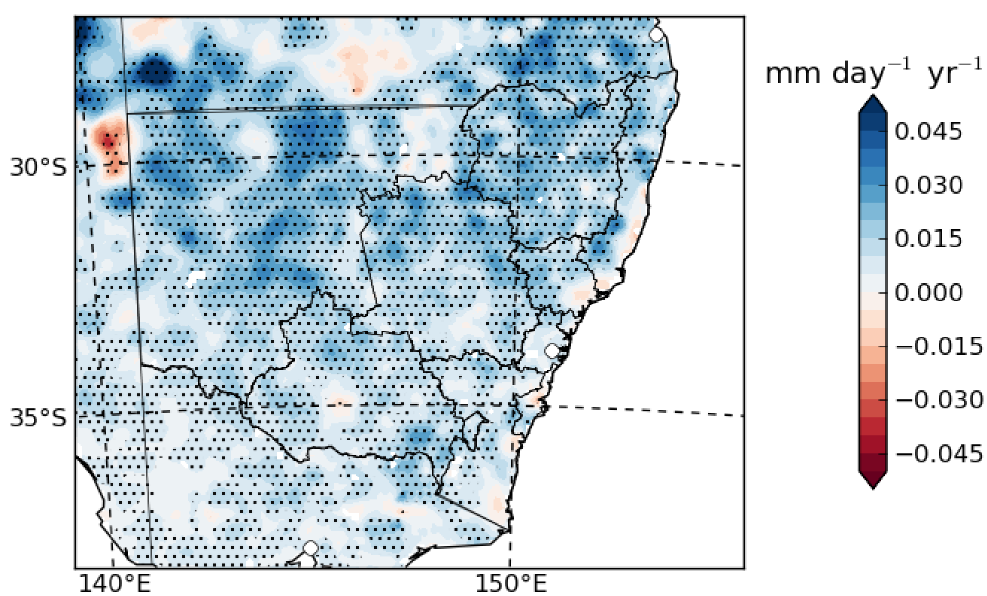

Figure 3.19: Trends from 1911 to 2014 in simple precipitation intensity index (SDII) [mm day^{-1} yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

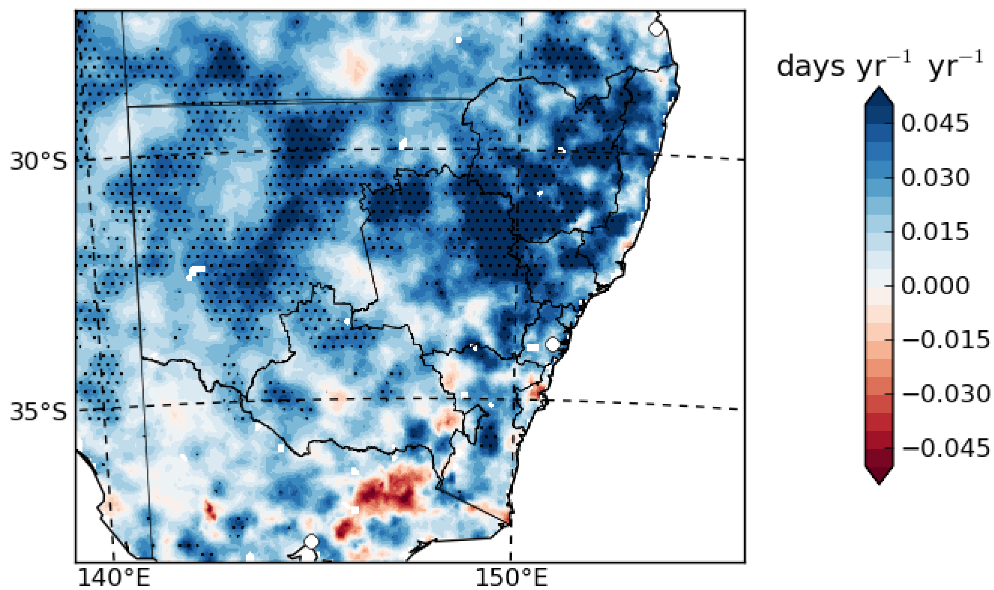

Figure 3.20: Trends from 1911 to 2014 in number of heavy precipitation days (R10mm) [days yr^{-1} yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

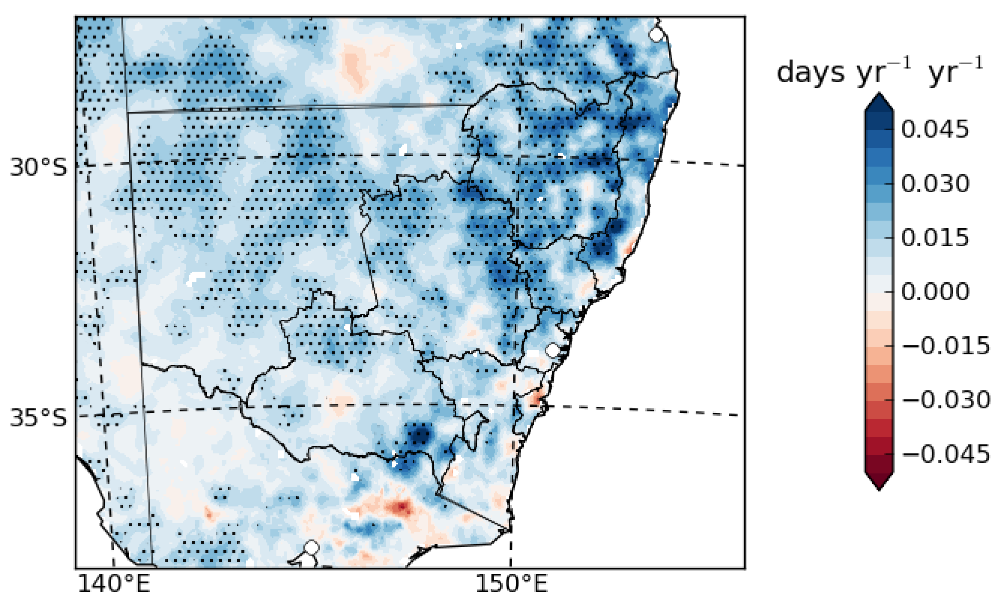

Figure 3.21: Trends from 1911 to 2014 in number of very heavy precipitation days (R20mm) [days yr^{-1} yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

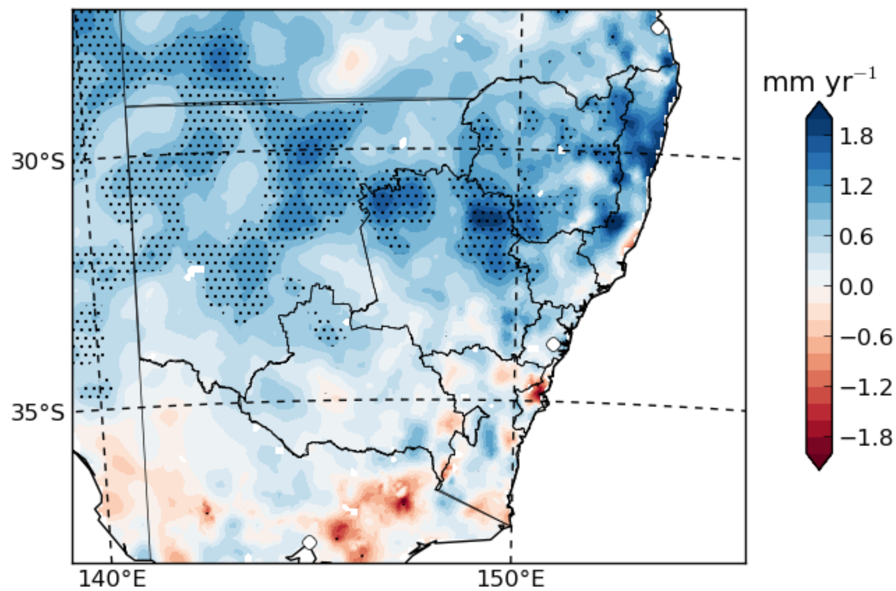

Figure 3.22: Trends from 1911 to 2014 in annual total wet day precipitation (PRCPTOT) [mm yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

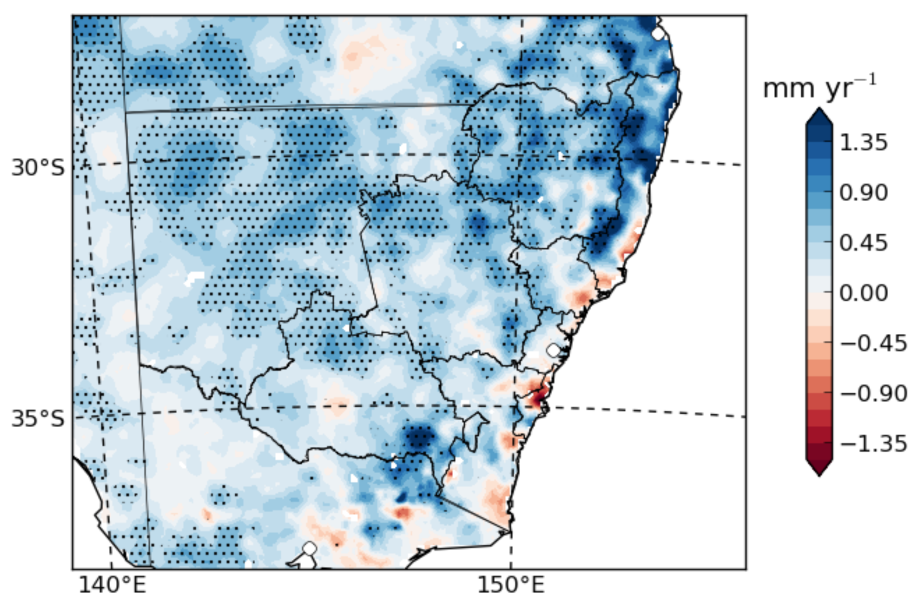

Figure 3.23: Trends from 1911 to 2014 in contribution from very wet days (R95p) [mm yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

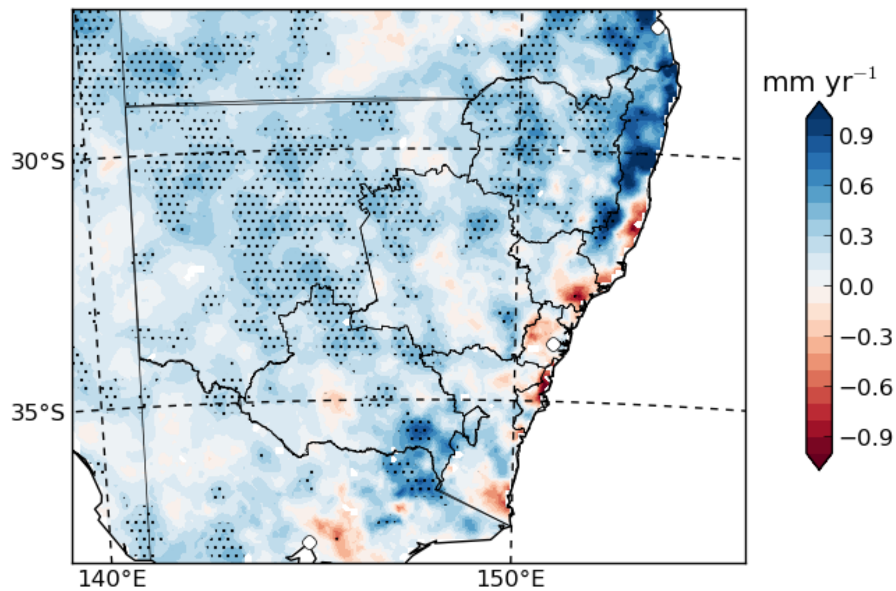

Figure 3.24: Trends from 1911 to 2014 in contribution from extremely wet days (R99p) [mm yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

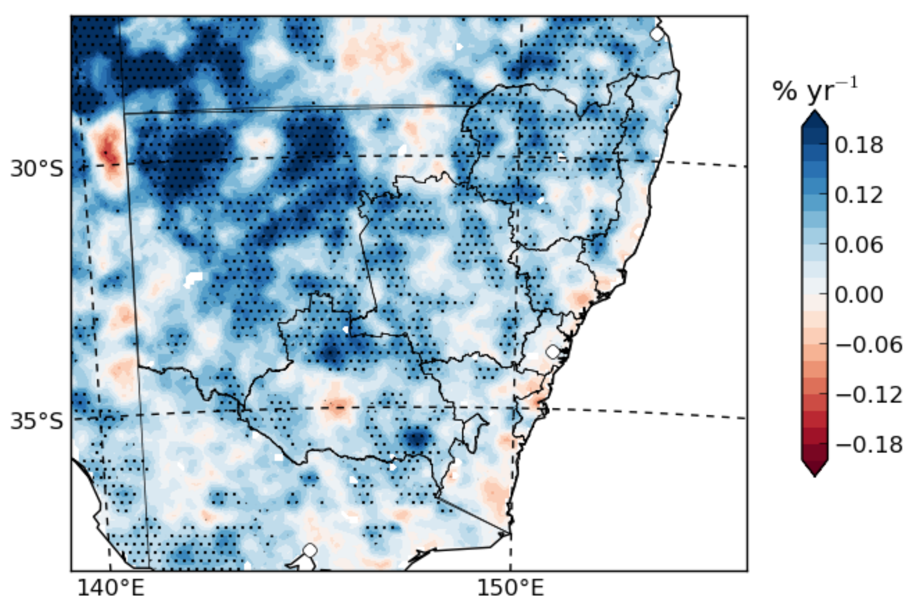

Figure 3.25: Trends from 1911 to 2014 in contribution from very wet days as % of PRCPTOT (R95pTOT) [% yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

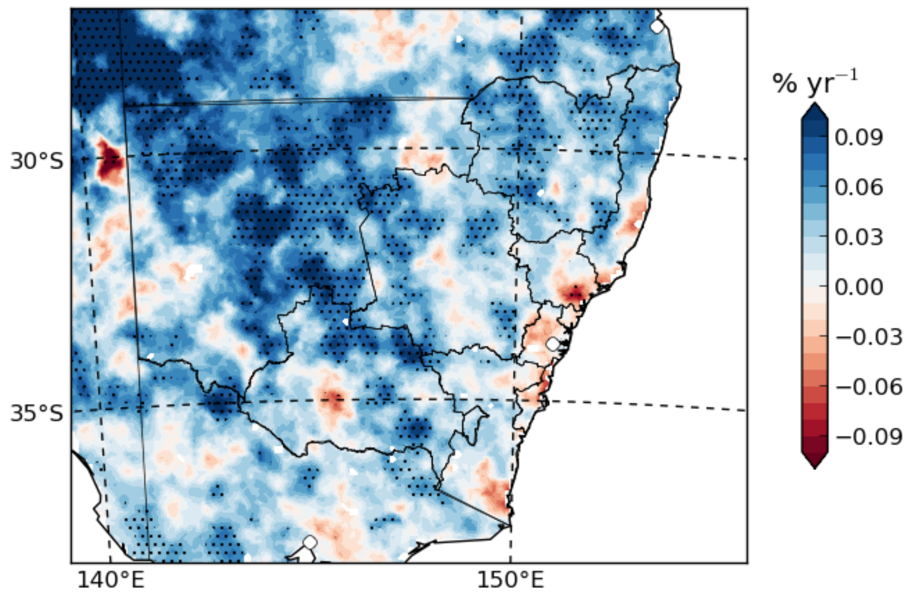

Figure 3.26: Trends from 1911 to 2014 in contribution from extremely wet days as % of PRCPTOT (R99pTOT) [% yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

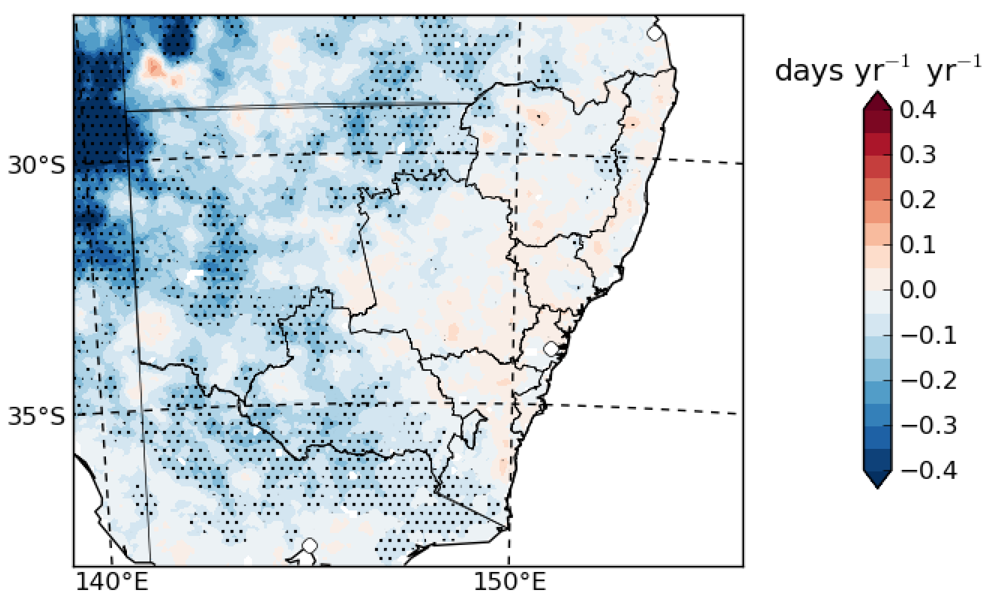

Figure 3.27: Trends from 1911 to 2014 in consecutive dry days (CDD) [days yr^{-1} yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

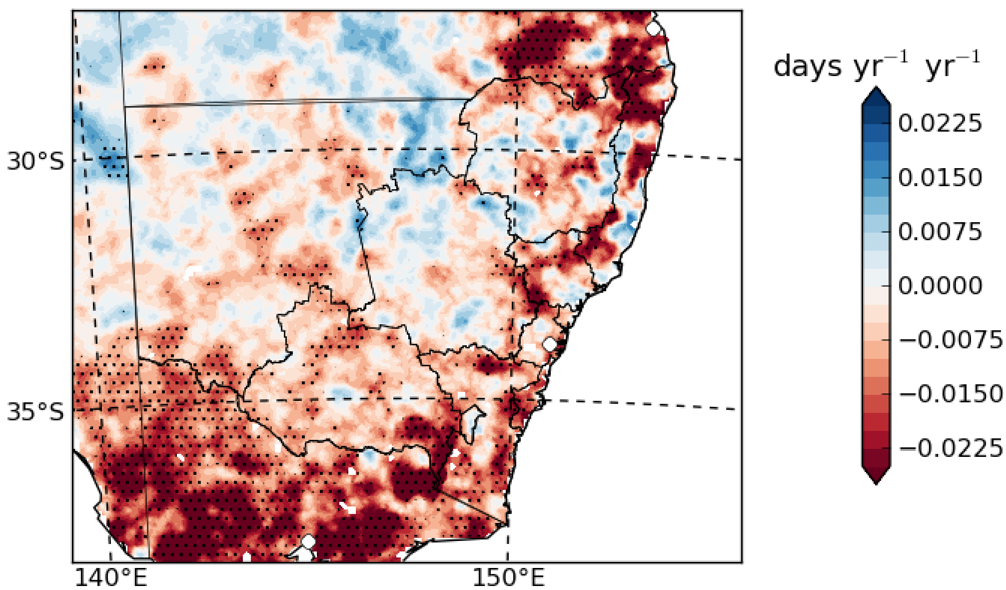

Figure 3.28: Trends from 1911 to 2014 in consecutive wet days (CWD) [days yr^{-1} yr^{-1}]. Stippling indicates the trend is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 4

Present Day (1990-2009) Model Climatologies and Biases

This chapter contains the climatological seasonal and annual means for present-day extreme precipitation indices from the bias-corrected RCM output. The bias-corrected RCM output is the RCM precipitation output corrected for biases between the models and the observations using the methods described in Evans and Argueso (2014) [9]. This method fits theoretical probability distribution functions to the model and observations before correcting the model cumulative distribution function toward the observed cumulative distribution function. This method doesn't provide for a perfect correction of all possible statistics of the distribution but has the advantage of allowing correction of any event regardless of its previous occurrence. This corrected precipitation is then used to calculate the extreme indices. Here we show the multi-model mean climatologies for each variable.

4.1 Present Day Mean Regional Estimates

This subsection contains box plots for each extreme preciptiation index, for each NSW state planning region (see Figure 1.2 which includes the region abbreviations). This region-based representation also shows the variability across NARCliM 12-member GCM/RCM ensemble for each index across the various regions (i.e., box plots). Values from AWAP serve as observational reference and are also included (black square).

Both Rx1day and Rx5day (Figures 4.1 and 4.2) show the NARCliM ensemble is able to capture the regional variability well with the observations falling within the model spread in every region.

Figure 4.3 shows that the observations of SDII are well captured in most regions. Where the observations lie outside the model range (Ill, NC, Hun, CC, MSyd) the models tend to underestimate the precipitation intensity.

For both R10mm and R20mm (Figures 4.4 and 4.5) the NARCliM ensemble captures the observed values everywhere except the Central Coast (CC) where a small underestimate is present.

PRCPTOT is also well captured (Figure 4.6) in most places though the NARCliM ensemble tends to have small overestimates in some regions (e.g. Ill and NC).

For both R95p and R99p (Figures 4.7 and 4.8) the ensemble captures the observations in most regions though it tends to overestimate these index values in Ill, NC, Hun, CC and MSyd. The consecutive wet days also shows a similar response with the ensemble mean value overestimating the index in the same regions as R95p and R99p indices. The consecutive dry days (CDD) however tend to be underestimated by the NARCliM ensemble in most regions.

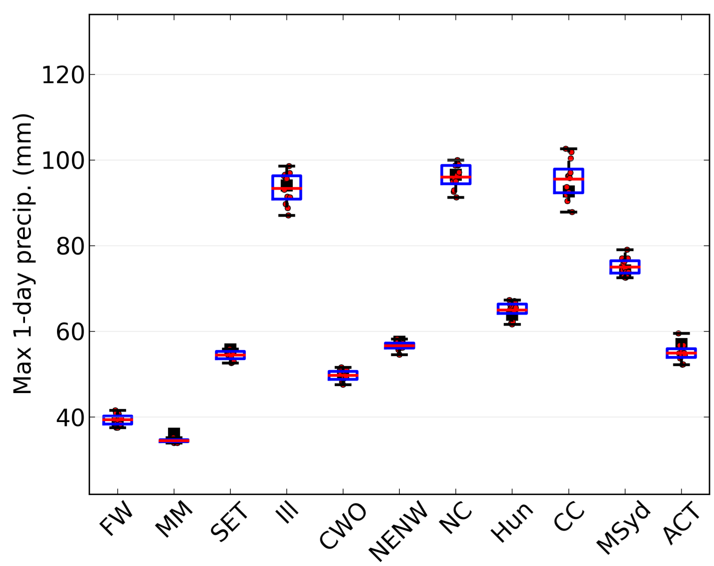

Figure 4.1: Boxplots of monthly maximum 1-day preciptiation (Rx1day) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

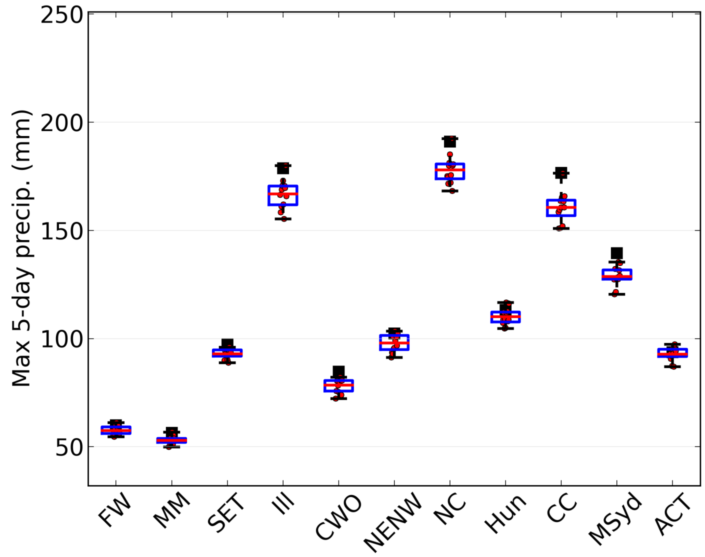

Figure 4.2: Boxplots of monthly maximum 5-day preciptiation (Rx5day) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

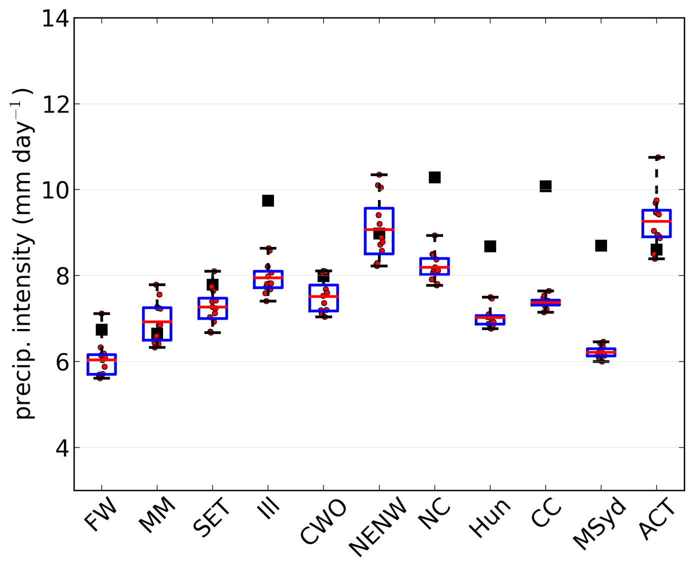

Figure 4.3: Boxplots of simple precipitation intensity index (SDII) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

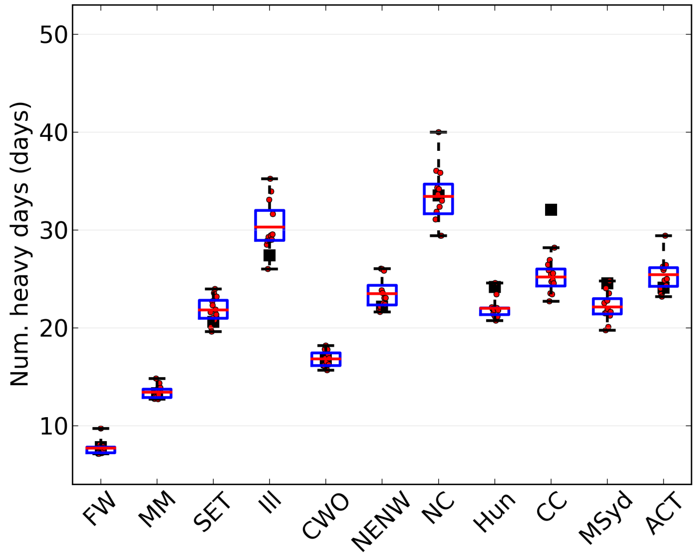

Figure 4.4: Boxplots of number of heavy precipitation days (R10mm) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

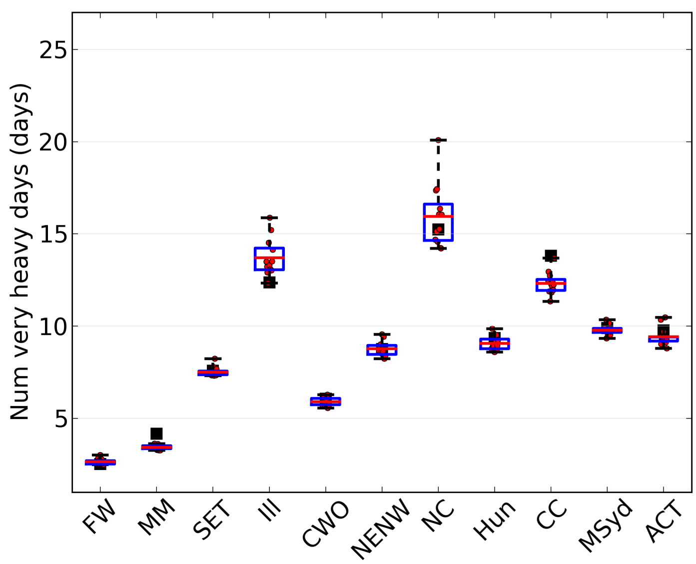

Figure 4.5: Boxplots of number of very heavy precipitation days (R20mm) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

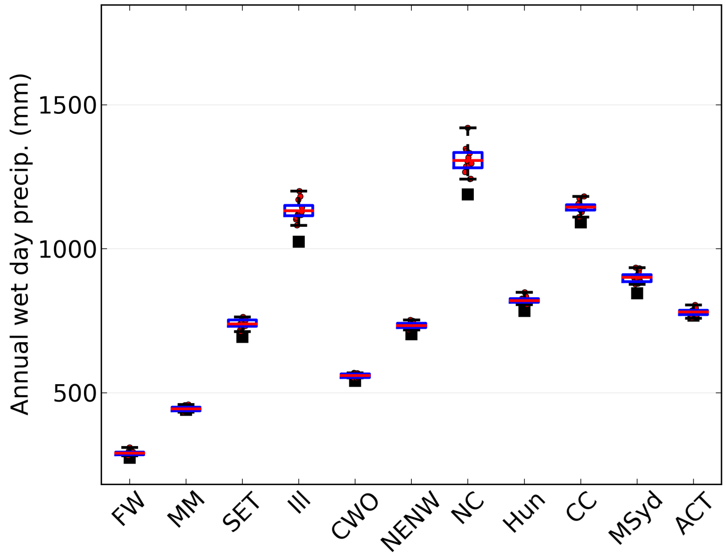

Figure 4.6: Boxplots of annual total wet day precipitation (PRCPTOT) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

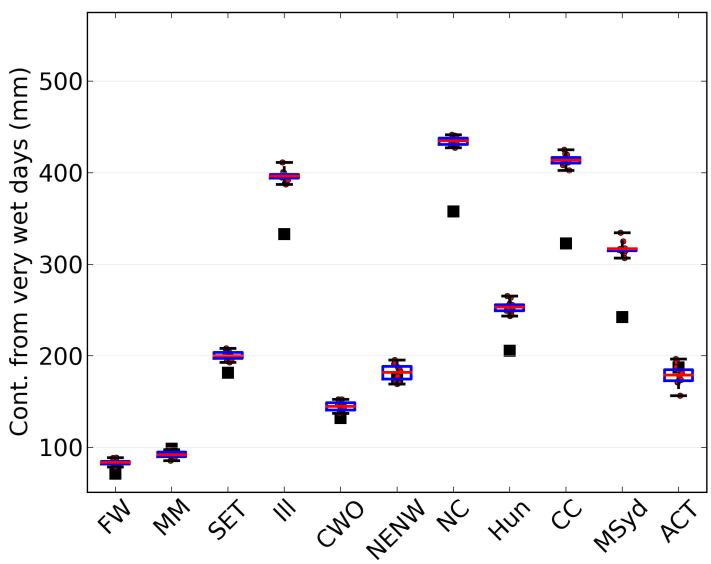

Figure 4.7: Boxplots of contribution from very wet days (R95p) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

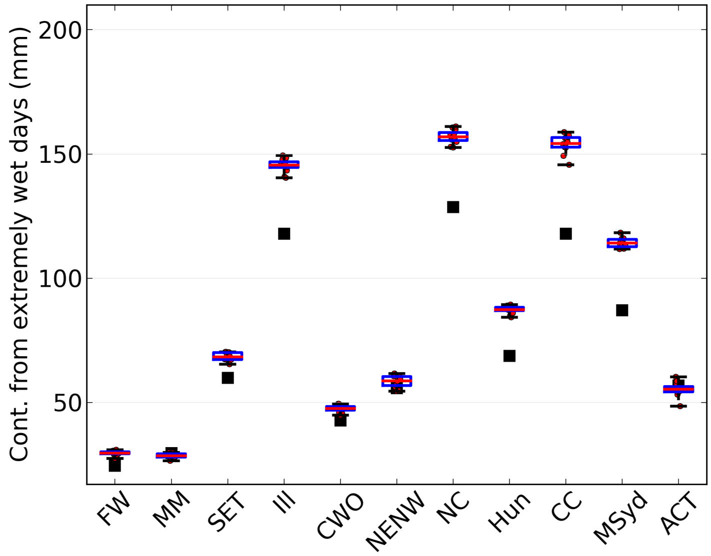

Figure 4.8: Boxplots of contribution from extremely wet days (R99p) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

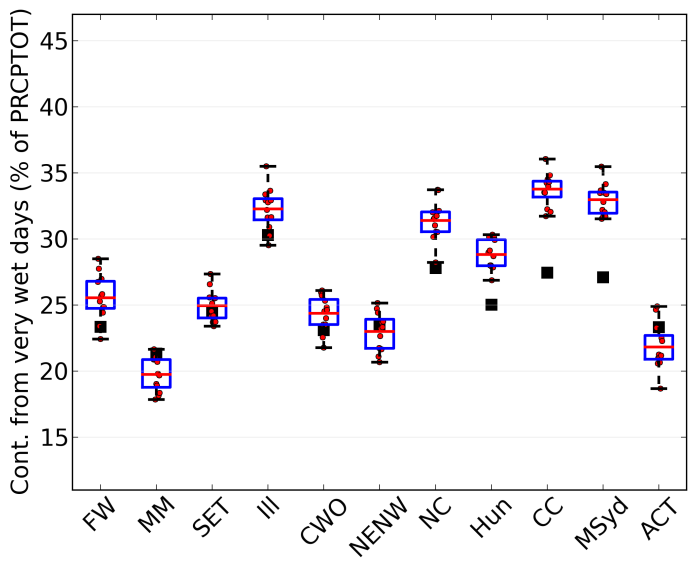

Figure 4.9: Boxplots of contribution from very wet days as % of PRCPTOT (R95pTOT) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

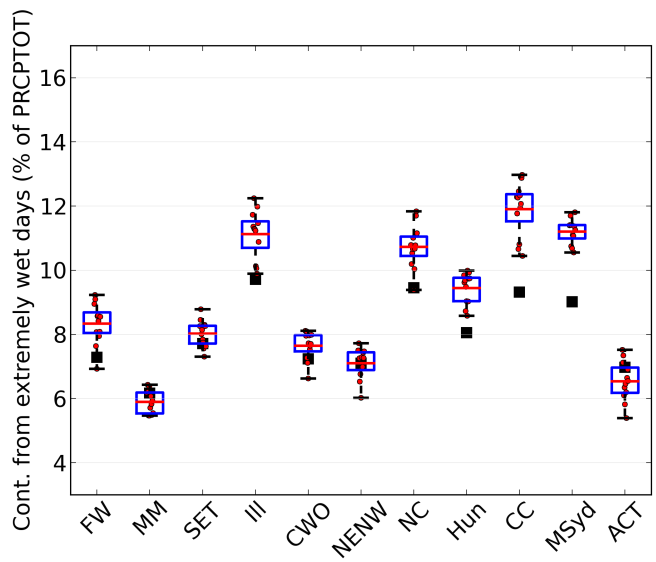

Figure 4.10: Boxplots of contribution from extremely wet days as % of PRCPTOT (R99pTOT) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

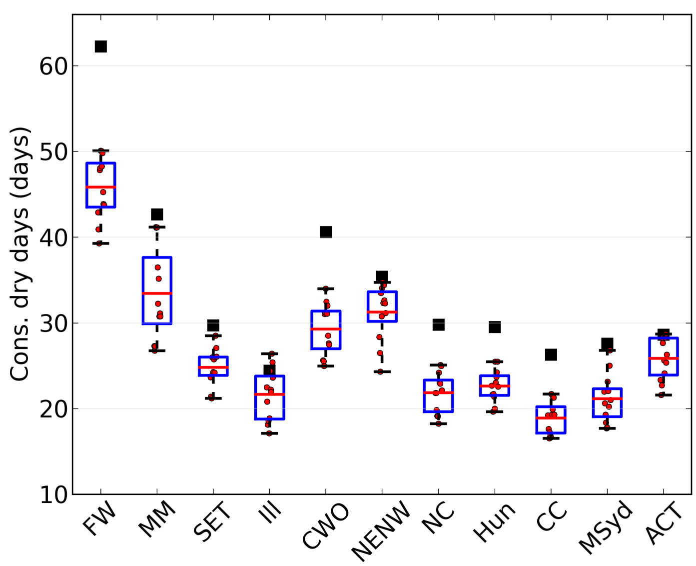

Figure 4.11: Boxplots of consecutive dry days (CDD) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

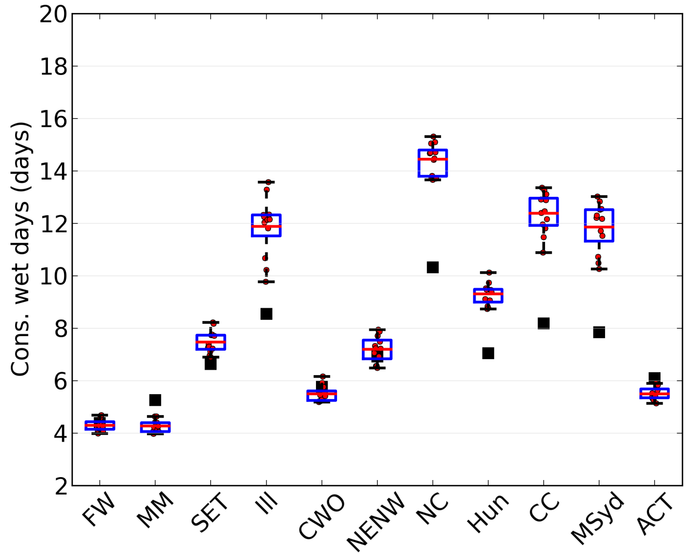

Figure 4.12: Boxplots of consecutive wet days (CWD) for NSW state planning regions (years 1990-2009). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

4.2 Biases: Present Day Models - Observations

This chapter contains climatological seasonal and annual mean biases (models - observations) for present-day (1990-2009) extreme precipitation indices calculated from bias-corrected RCM output. The coloured contours provide information on average model bias, while the stippling provides information on agreement between models.

Individual models are tested for significance using a Student's t-test at 95% confidence level. The multi-model biases are separated into three categories (a) less than half of the models show a significant bias (insignificant areas, multi-model mean change is shown in colour), (b) at least half of the models show a significant bias and at least 80% of significant models agree on the direction of the bias (significant agreeing areas, stippled), and (c) at least half of the models show a significant bias and less than 80% of significant models agree on the direction of the bias (significant disagreeing areas, white).

For biases, insignificant areas indicate a small bias in most models compared to the inter-annual variability, which is the most desired outcome. Significant disagreeing areas indicate that models disagree on the direction of bias, such that the ensemble as a whole spans zero bias. Significant agreeing areas indicate that the ensemble bias tends in one direction, which is the least desired outcome.

These bias maps reflect the information summarised for state planning regions in the boxplots. In most cases the majority of NSW contains insignificant biases compared to the inter-annual variability. There are almost no examples of significant disagreeing biases for any index. There are however a number of cases where significant biases do appear.

For Rx1day and Rx5day (Figures 4.13 and 4.14) large parts of southern NSW have a significant negative bias in winter (JJA). SDII (Figure 4.15) has significant negative biases along the coast and for parts of central north NSW. Consecutive dry days index has a significant negative bias over most of NSW. Consecutive wet days index has a significant positive bias along the coast and areas of significant negative bias in central and southern NSW.

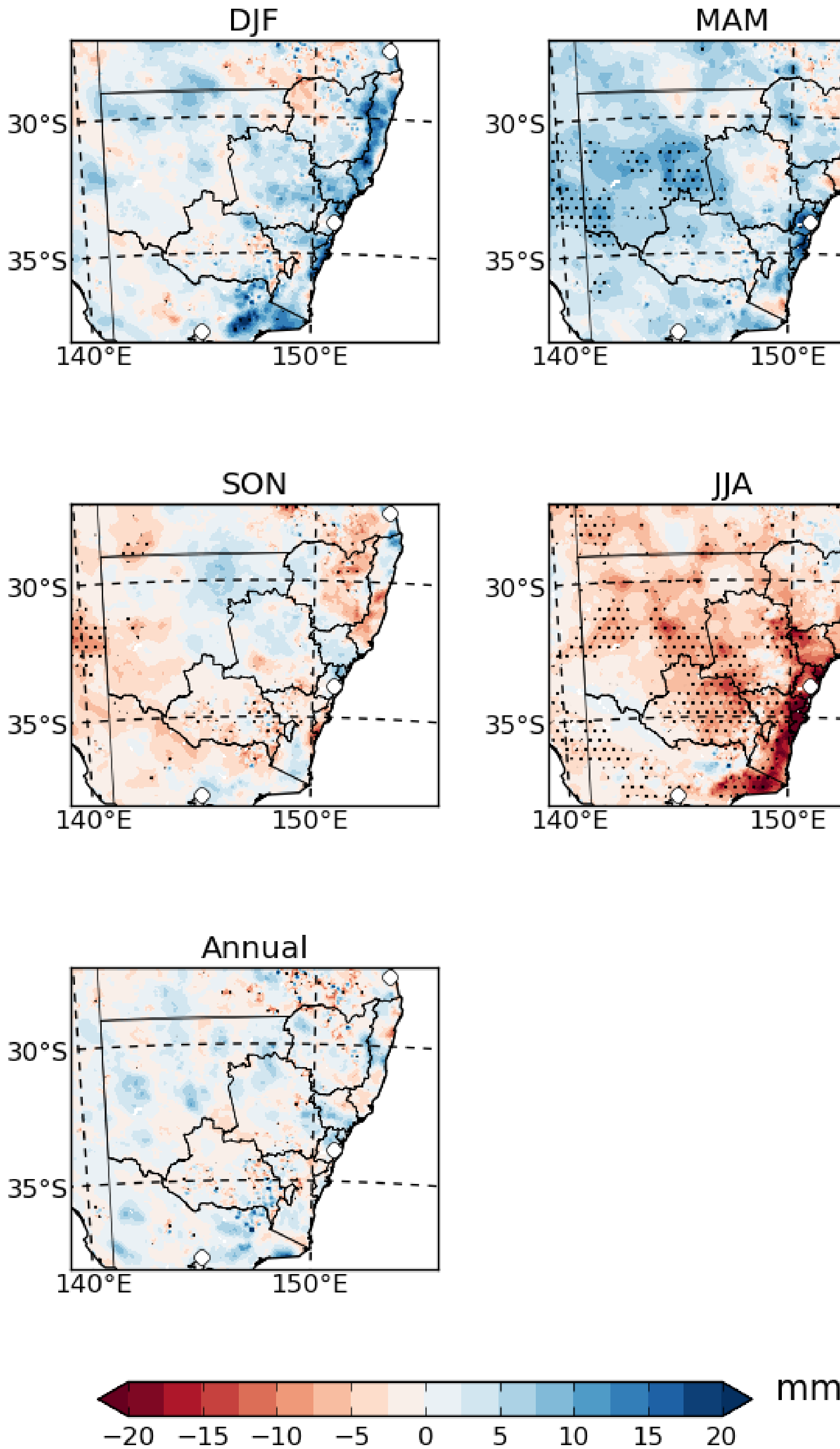

Figure 4.13: Present-day (1990-2009) multi-model average seasonal and annual maximum maximum 1-day precipitation (Rx1day) minus corresponding AWAP observations [mm]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

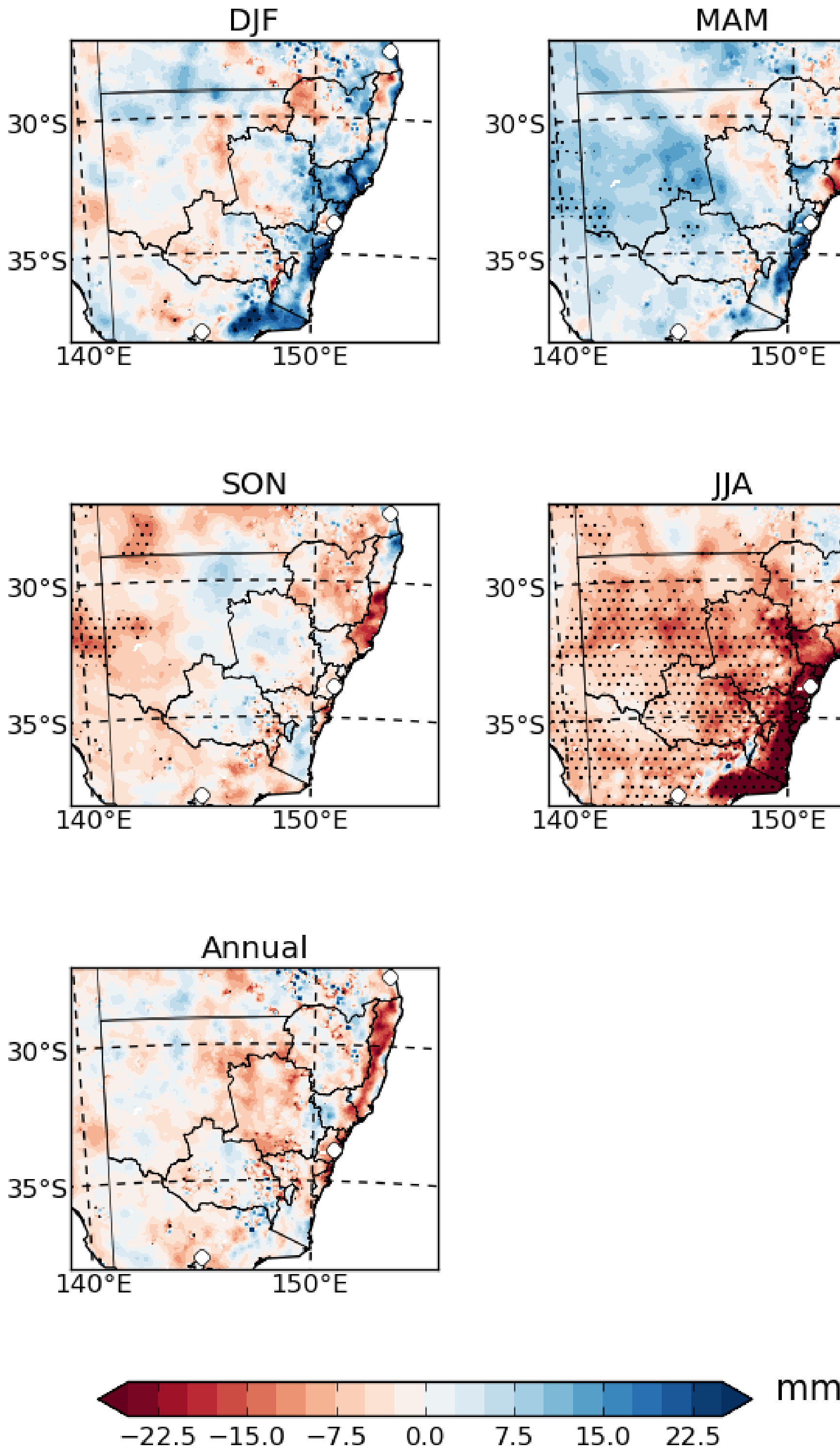

Figure 4.14: Present-day (1990-2009) multi-model average seasonal and annual maximum maximum 5-day precipitation (Rx5day) minus corresponding AWAP observations [mm]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

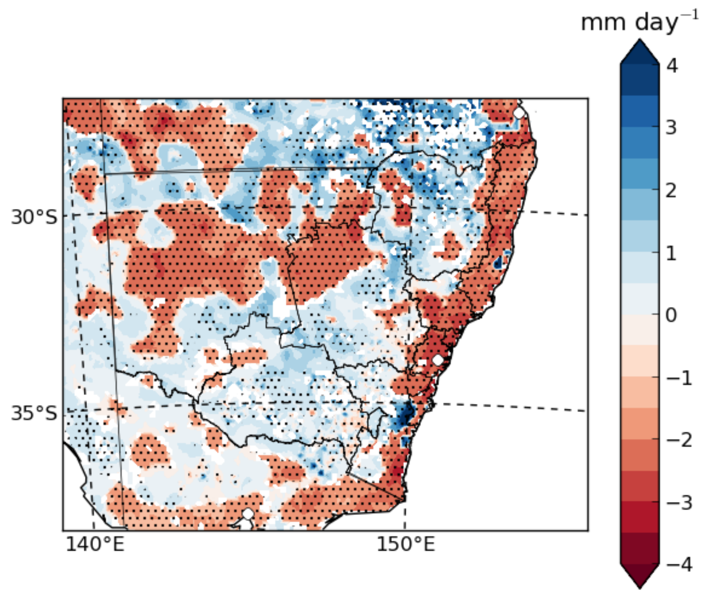

Figure 4.15: Annual multi-model means of bias-corrected WRF minus AWAP simple precipitation intensity index (SDII) for years 1990-2009 [mm day^{-1}]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

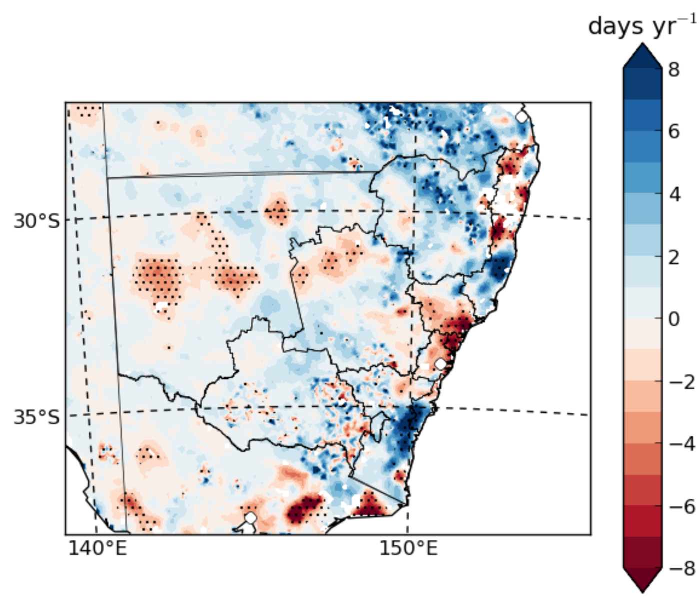

Figure 4.16: Annual multi-model means of bias-corrected WRF minus AWAP number of heavy precipitation days (R10mm) for years 1990-2009 [days yr^{-1}]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

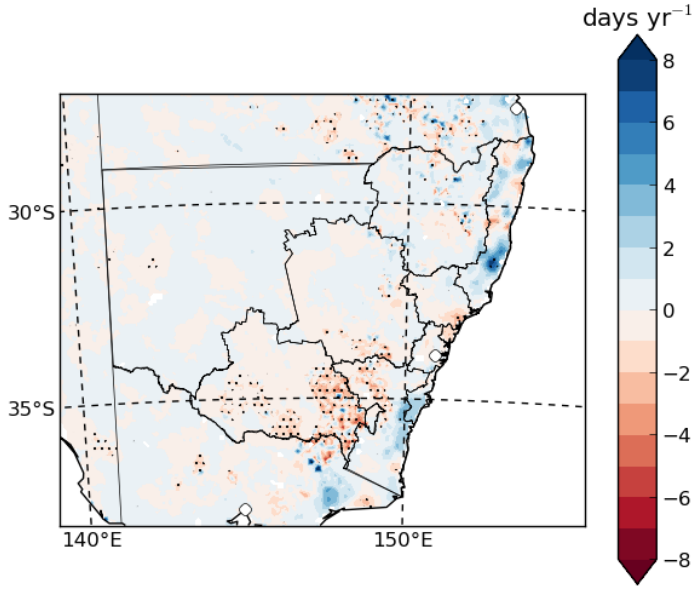

Figure 4.17: Annual multi-model means of bias-corrected WRF minus AWAP number of very heavy precipitation days (R20mm) for years 1990-2009 [days yr^{-1}]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

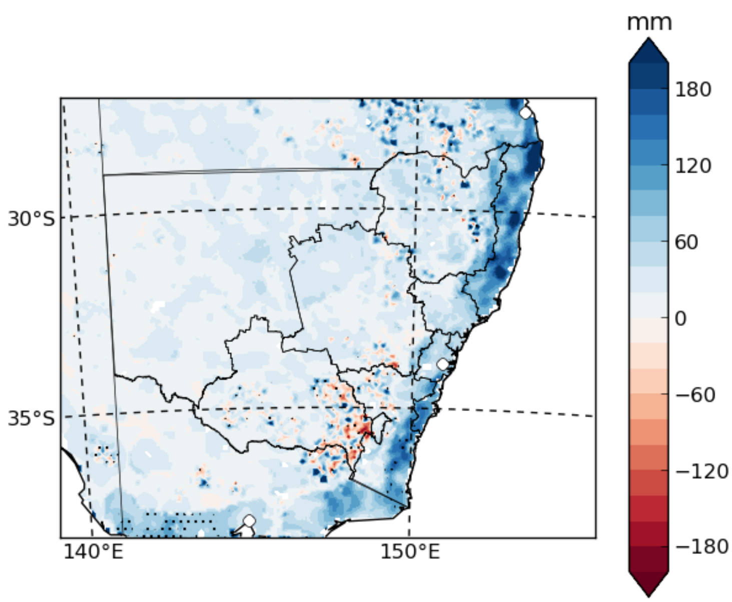

Figure 4.18: Annual multi-model means of bias-corrected WRF minus AWAP annual total wet day precipitation (PRCPTOT) for years 1990-2009 [mm yr^{-1}]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

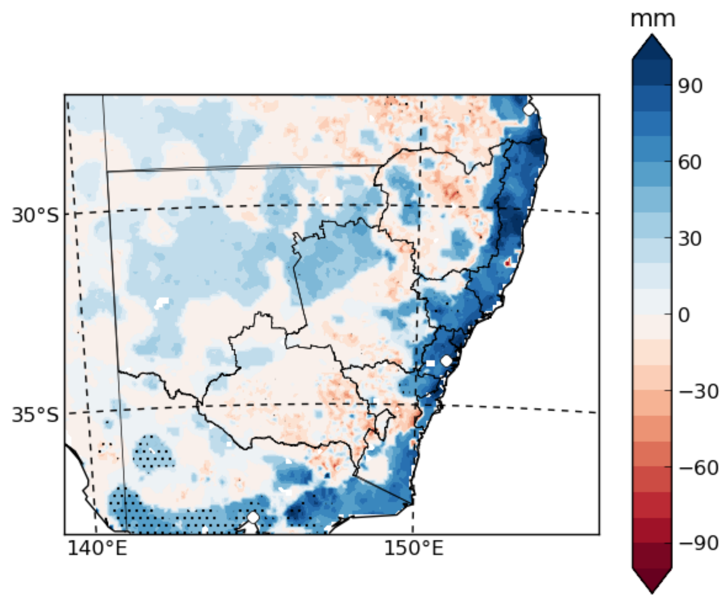

Figure 4.19: Annual multi-model means of bias-corrected WRF minus AWAP contribution from very wet days (R95p) for years 1990-2009 [mm]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

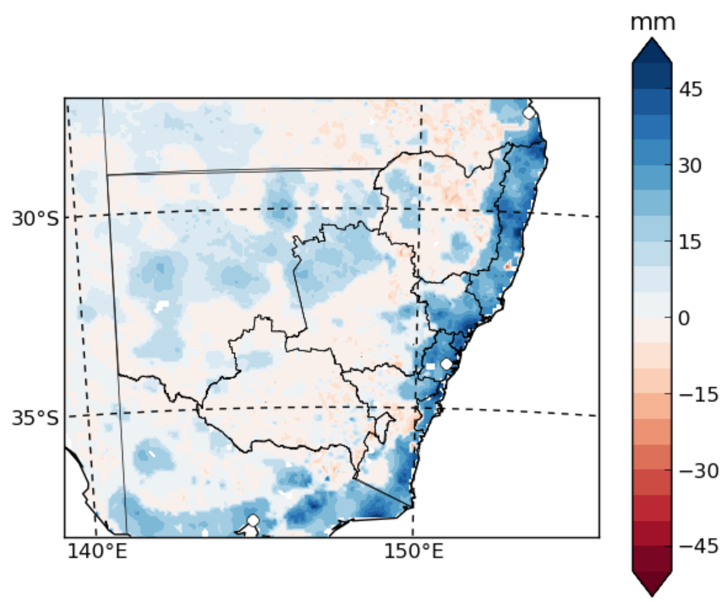

Figure 4.20: Annual multi-model means of bias-corrected WRF minus AWAP contribution from extremely wet days (R99p) for years 1990-2009 [mm]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

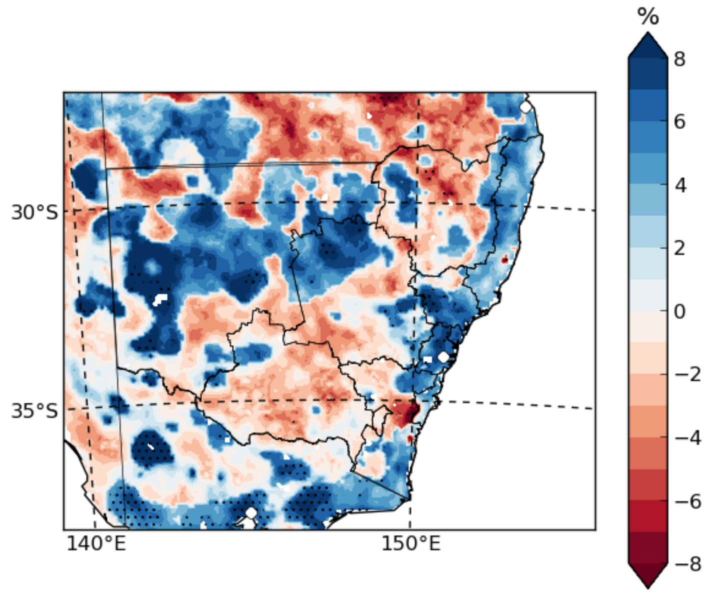

Figure 4.21: Annual multi-model means of bias-corrected WRF minus AWAP contribution from very wet days as % of PRCPTOT (R95pTOT) for years 1990-2009 [%]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

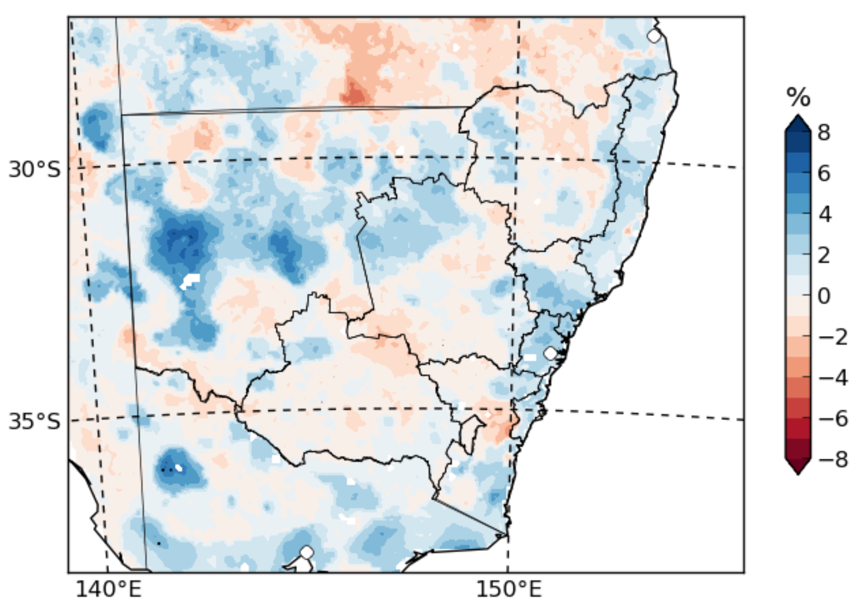

Figure 4.22: Annual multi-model means of bias-corrected WRF minus AWAP contribution from extremely wet days as % of PRCPTOT (R99pTOT) for years 1990-2009 [%]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

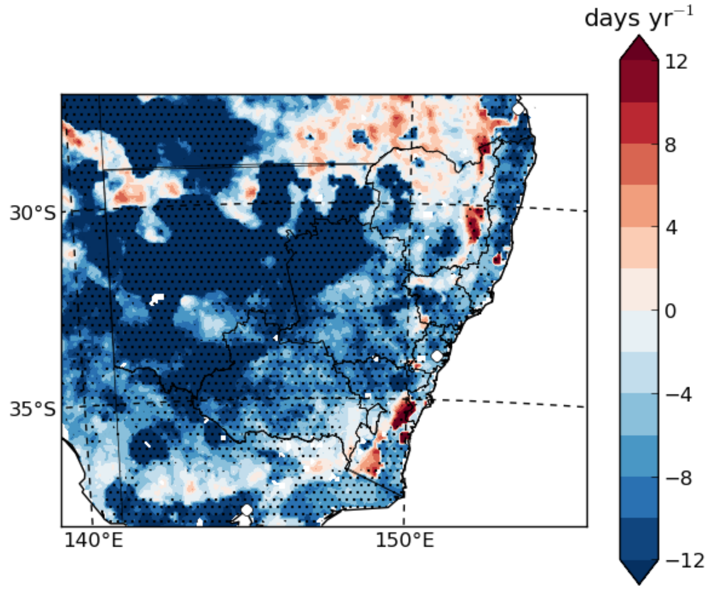

Figure 4.23: Annual multi-model means of bias-corrected WRF minus AWAP consecutive dry days (CDD) for years 1990-2009 [days yr^{-1}]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

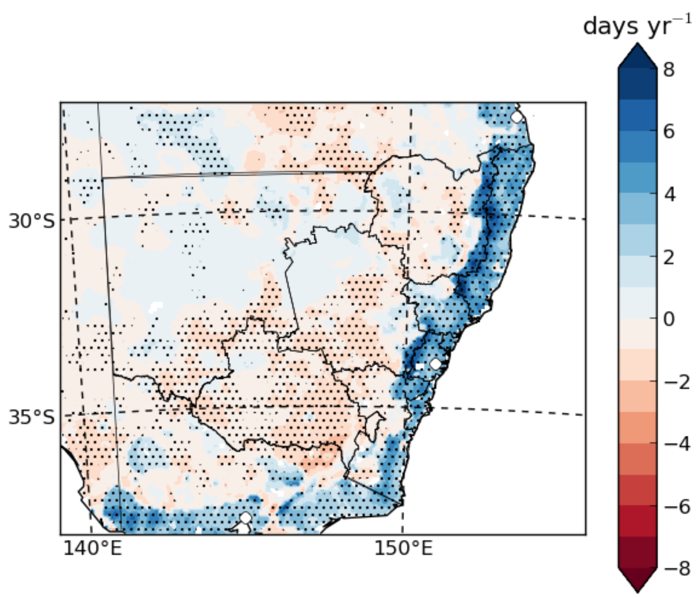

Figure 4.24: Annual multi-model means of bias-corrected WRF minus AWAP consecutive wet days (CWD) for years 1990-2009 [days yr^{-1}]. Stipling indicates the bias is significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 5

Near Future (2020-2039) Model Climatologies and Changes

This chapter contains the climatological seasonal and annual mean projections for the extreme precipitation indices. We show seasonal and annual multi-model mean climatologies for each index.

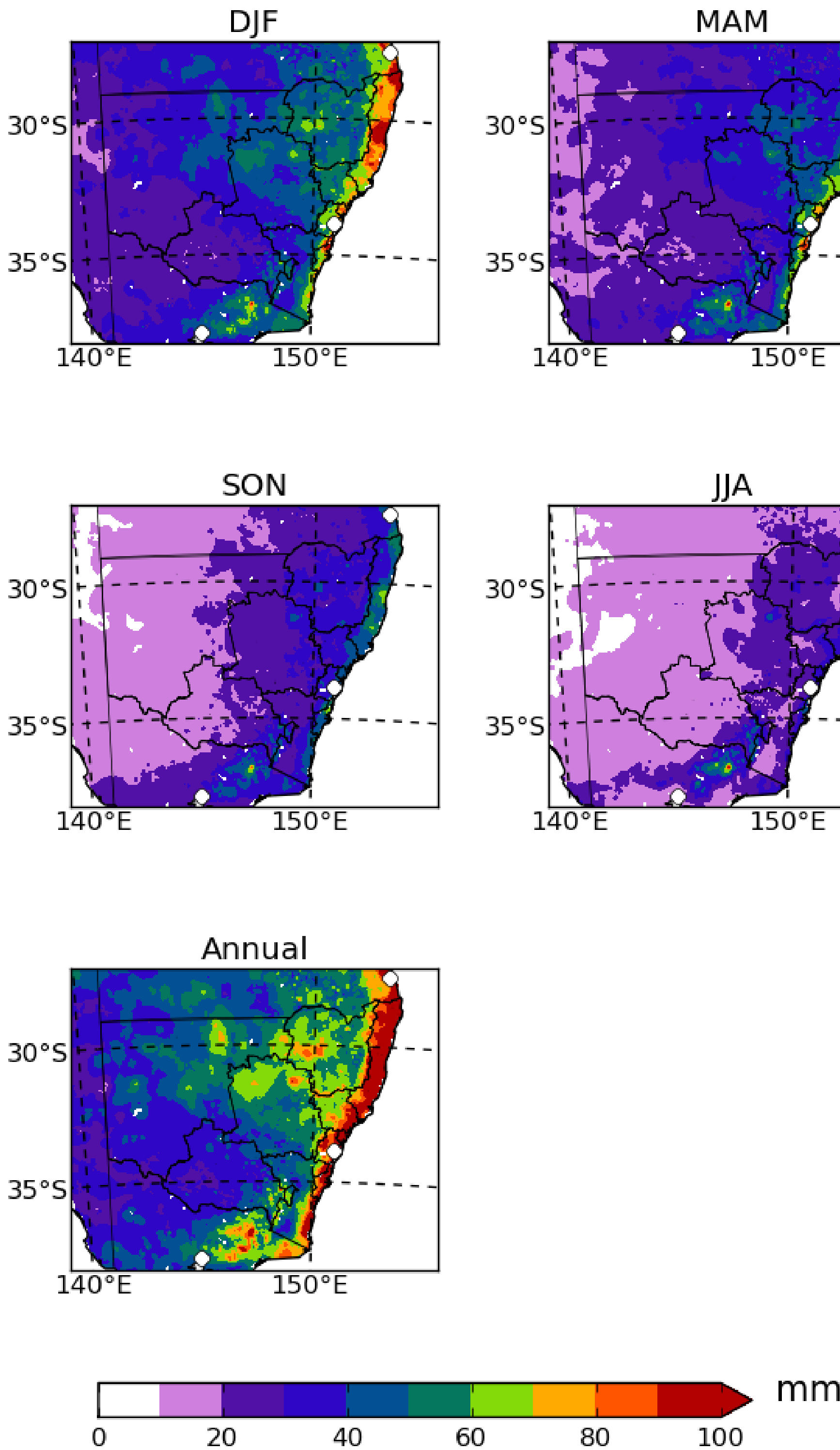

Figure 5.1: Near-future (2020-2039) multi-model average seasonal and annual maximum maximum 1-day precipitation (Rx1day)[mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

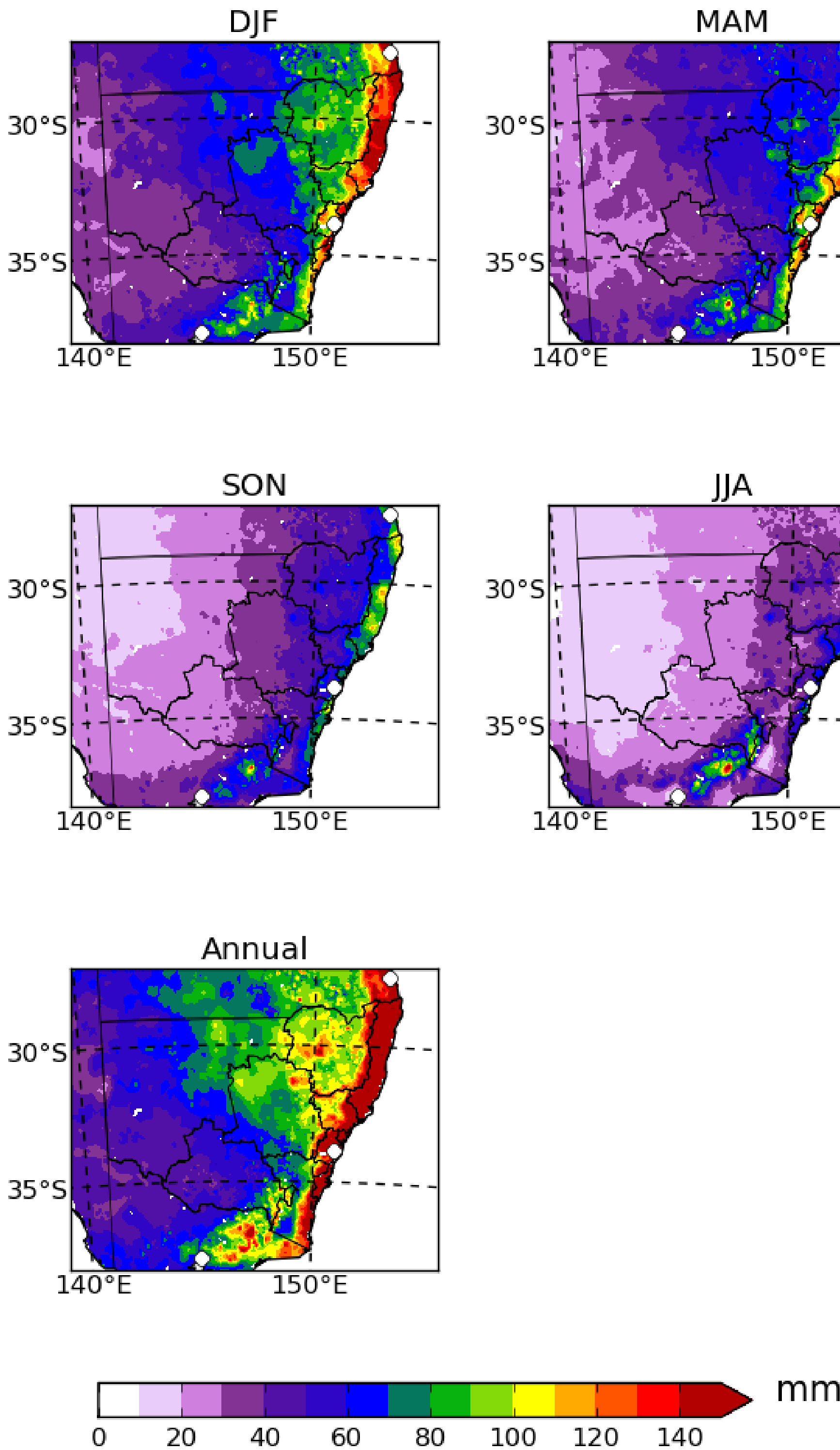

Figure 5.2: Near-future (2020-2039) multi-model average seasonal and annual maximum maximum 5-day precipitation (Rx5day)[mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

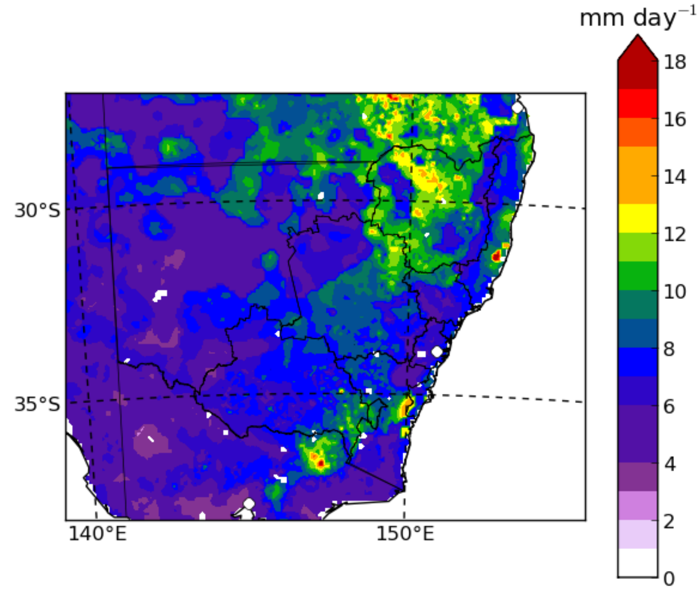

Figure 5.3: Annual multi-model means of simple precipitation intensity index (SDII) for years 2020-2039 [mm day^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

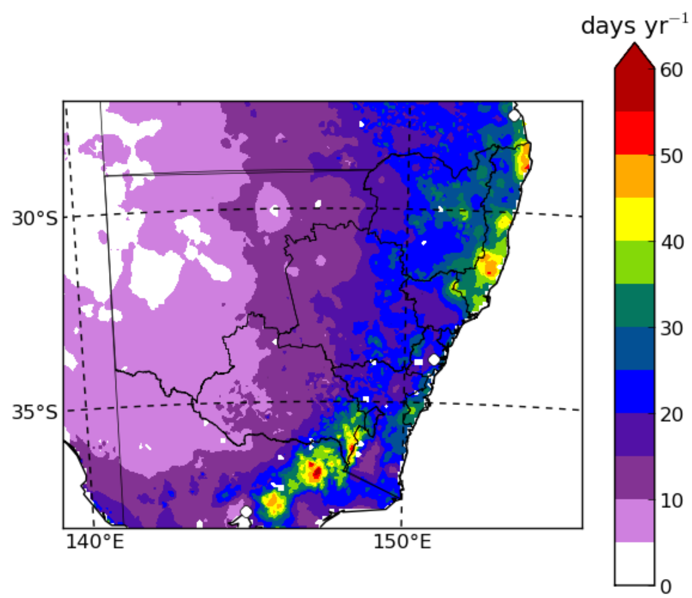

Figure 5.4: Annual multi-model means of number of heavy precipitation days (R10mm) for years 2020-2039 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

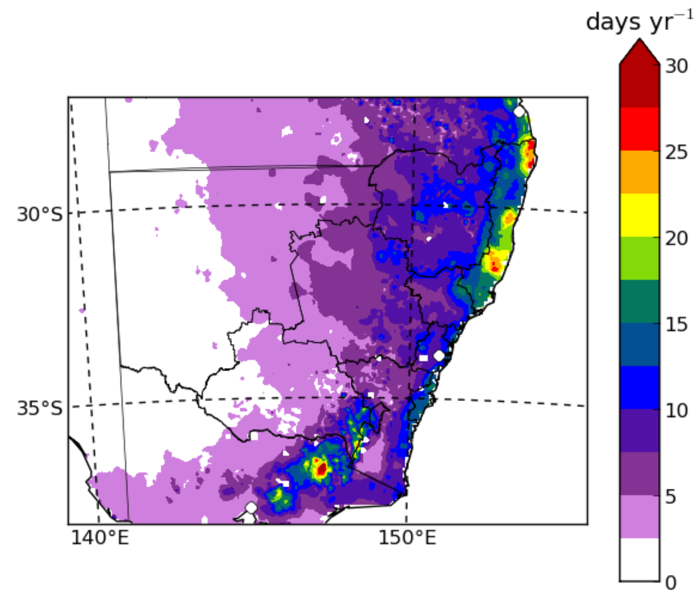

Figure 5.5: Annual multi-model means of number of very heavy precipitation days (R20mm) for years 2020-2039 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

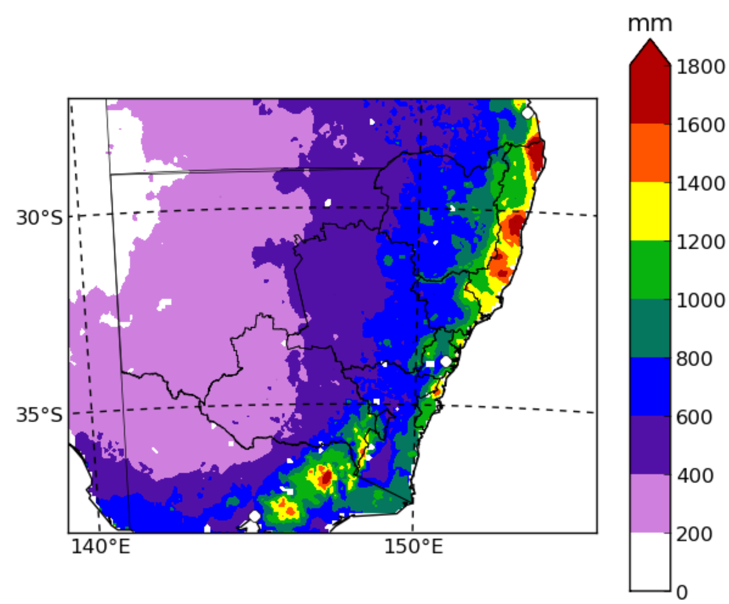

Figure 5.6: Annual multi-model means of annual total wet day precipitation (PRCPTOT) for years 2020-2039 [mm yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

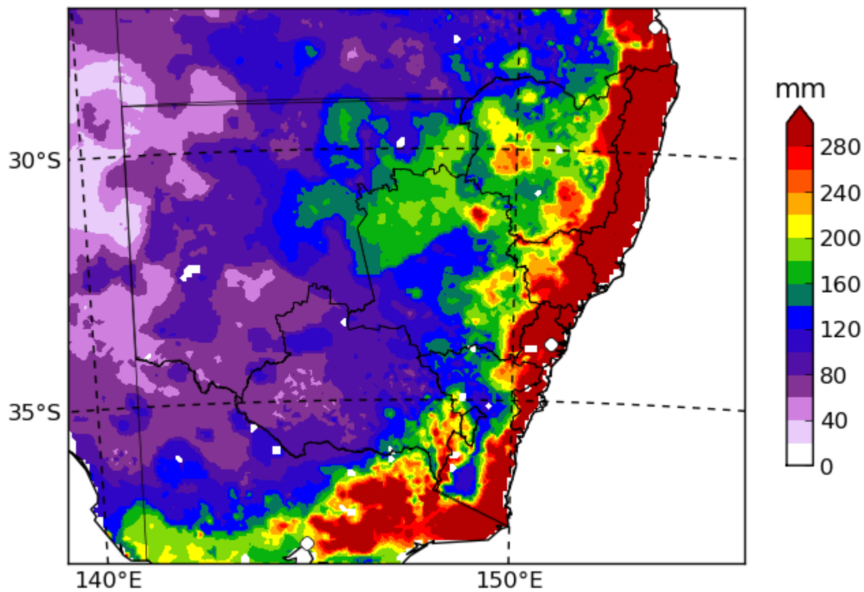

Figure 5.7: Annual multi-model means of contribution from very wet days (R95p) for years 2020-2039 [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

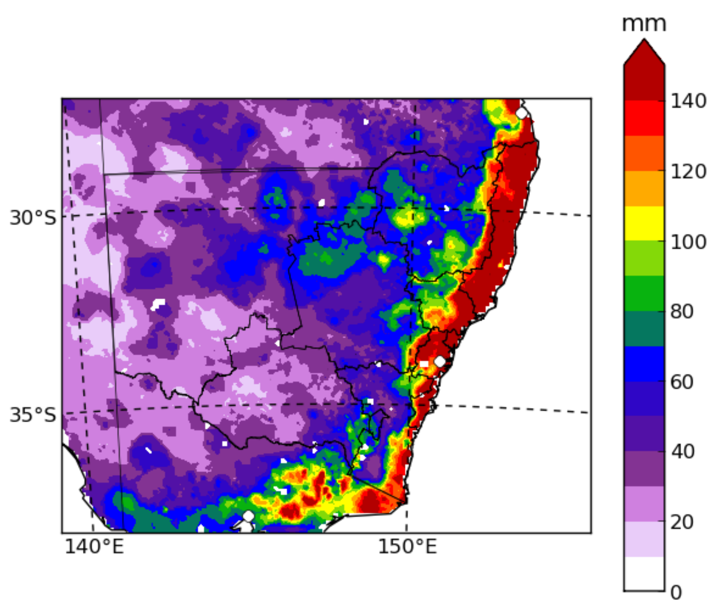

Figure 5.8: Annual multi-model means of contribution from extremely wet days (R99p) for years 2020-2039 [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

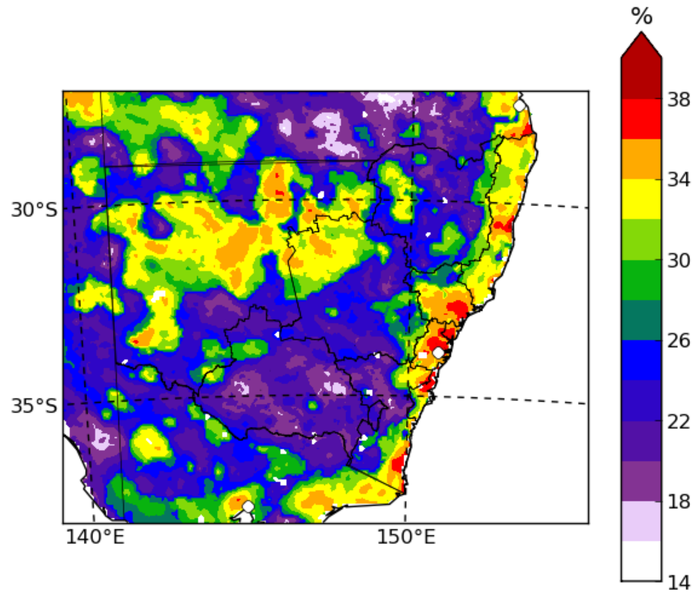

Figure 5.9: Annual multi-model means of contribution from very wet days as % of PRCPTOT (R95pTOT) for years 2020-2039 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

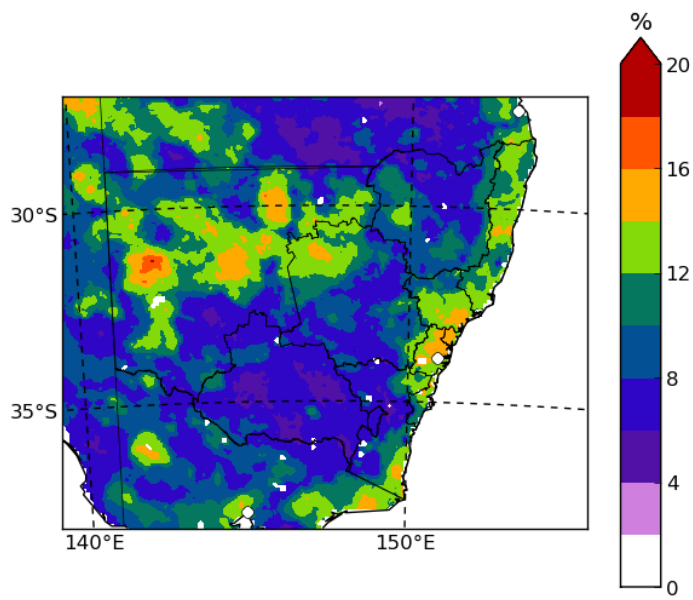

Figure 5.10: Annual multi-model means of contribution from extremely wet days as % of PRCPTOT (R99pTOT) for years 2020-2039 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

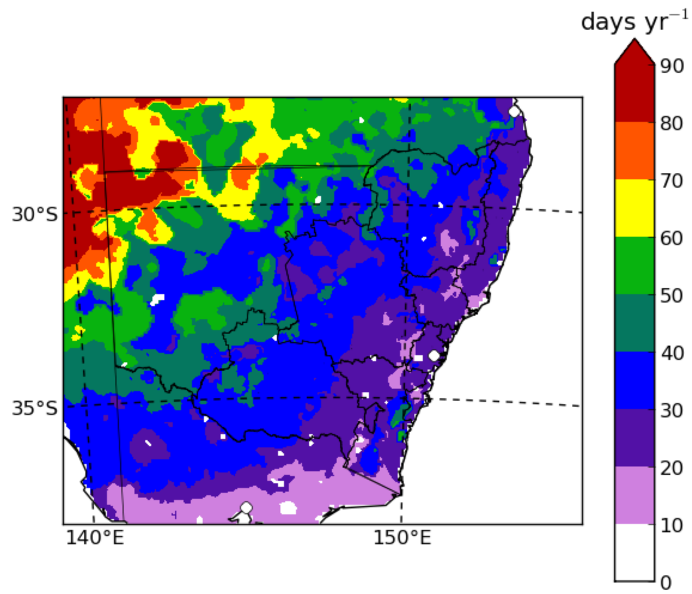

Figure 5.11: Annual multi-model means of consecutive dry days (CDD) for years 2020-2039 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

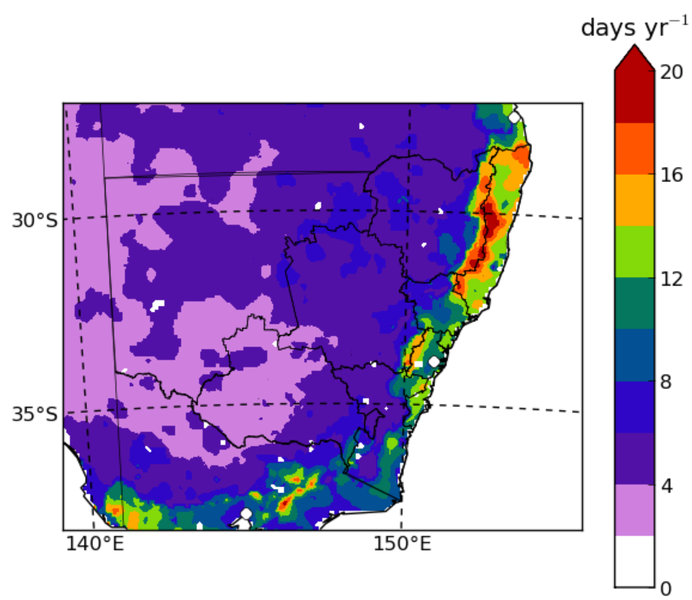

Figure 5.12: Annual multi-model means of consecutive wet days (CWD) for years 2020-2039 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

5.1 Near Future Modeled Changes Compared to the Present Period

This section contains projected seasonal and annual mean changes for the extreme precipitation indices, between present (1990-2009) and near future (2020-2039). The coloured contours provide information on average projected changes, while the stipling indicates the level of model agreement which is an indicator of the level of uncertainty in the projected climate.

An individual model is tested for significance using a Student's t-test with 95% significance applied at each grid point. The multi-model future changes are separated into three categories (a) less than half of the models show a significant change (insignificant areas, multi-model mean change is shown in colour), (b) at least half of the models show a significant change and at least 80% of significant models agree on the direction of change (significant agreeing areas, stippled), and (c) at least half of the models show a significant change and less than 80% of significant models agree on the direction of change (significant disagreeing areas, white).

For future changes, insignificant areas indicate a small projected change in most models compared to the inter-annual variability. Significant agreeing areas indicate that the ensemble is projecting a robust change in a particular direction. Significant disagreeing areas indicate that ensemble members disagree on the direction of change.

For all indices, the projected change in the near future is not significant compared to the inter-annual variability.

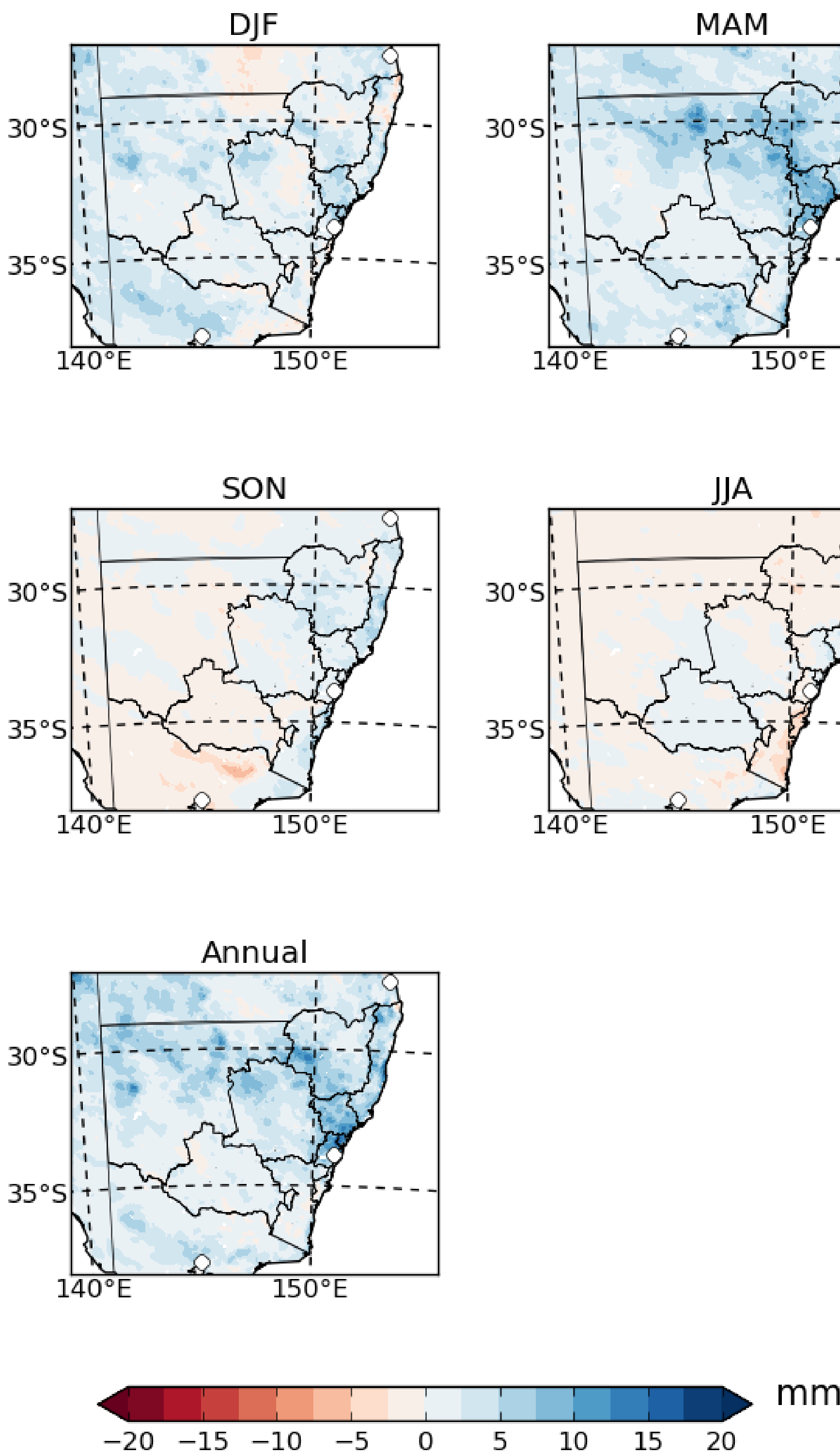

Figure 5.13: Multi-model mean changes between near future (2020-2039) and present (1990-2009) in seasonal and annual maximum 1-day precipitation (Rx1day) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

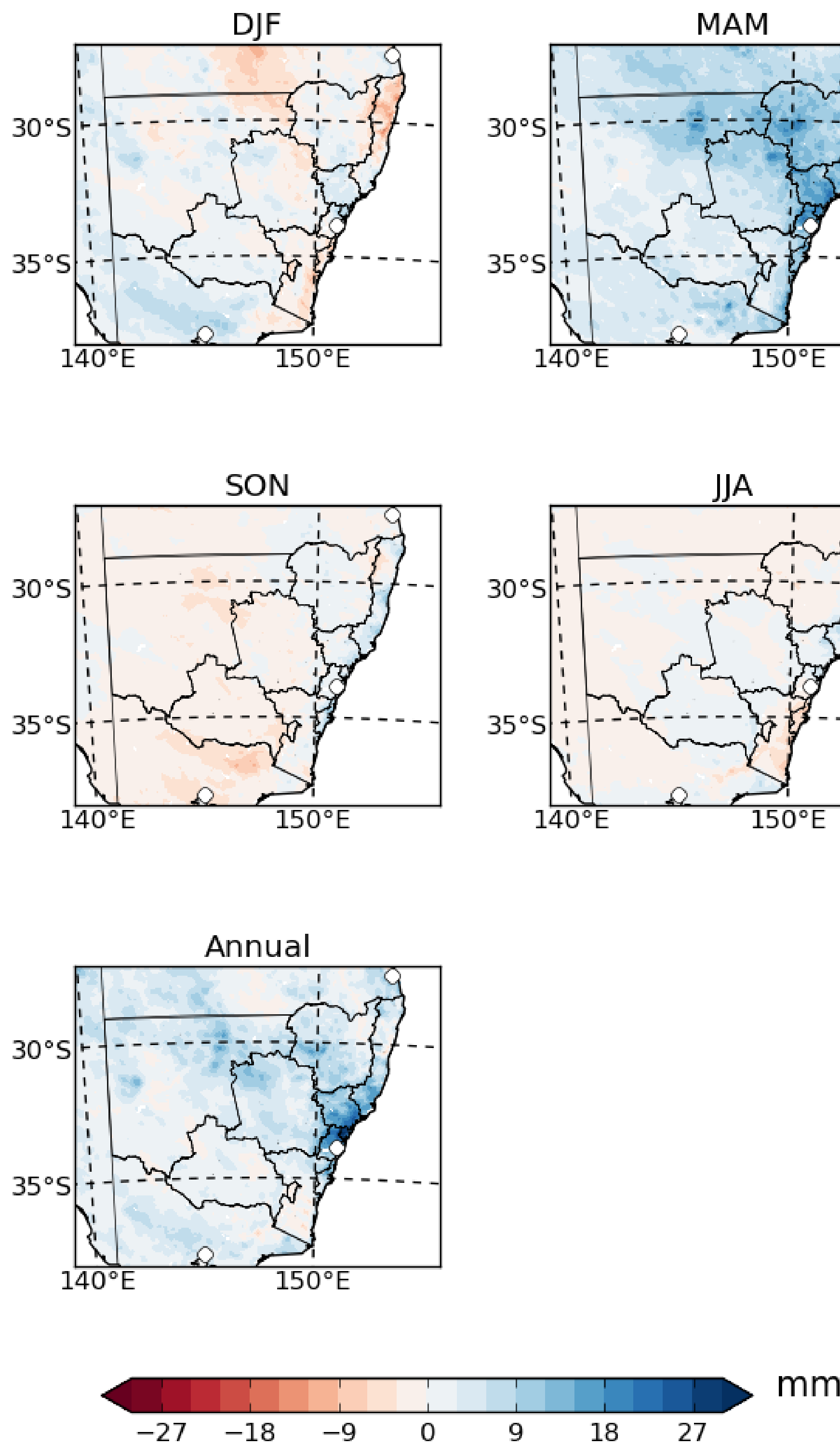

Figure 5.14: Multi-model mean changes between near future (2020-2039) and present (1990-2009) in seasonal and annual maximum 5-day precipitation (Rx5day) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

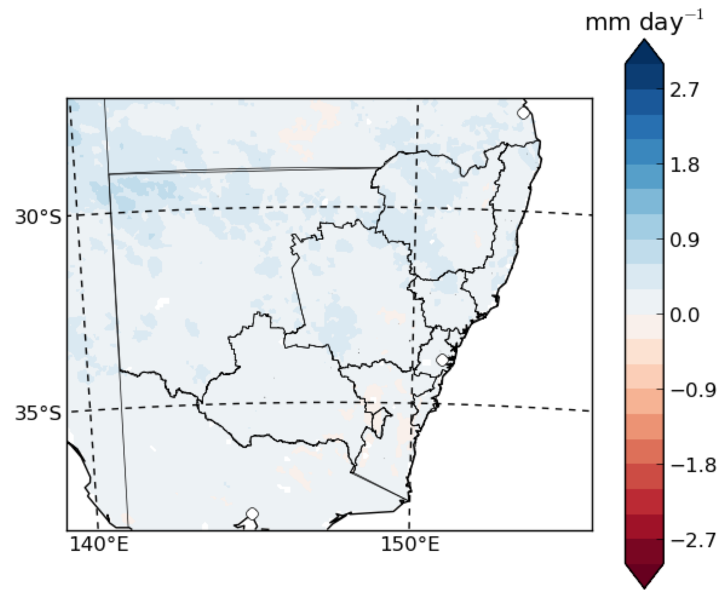

Figure 5.15: Annual multi-model means changes between years 1990-2009 and 2020-2039 for simple precipitation intensity index (SDII) [mm day^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

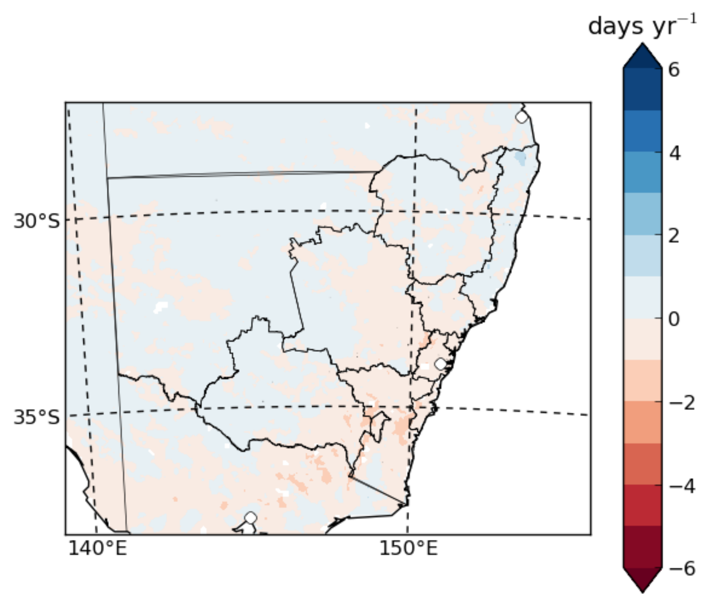

Figure 5.16: Annual multi-model means changes between years 1990-2009 and 2020-2039 for number of heavy precipitation days (R10mm) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

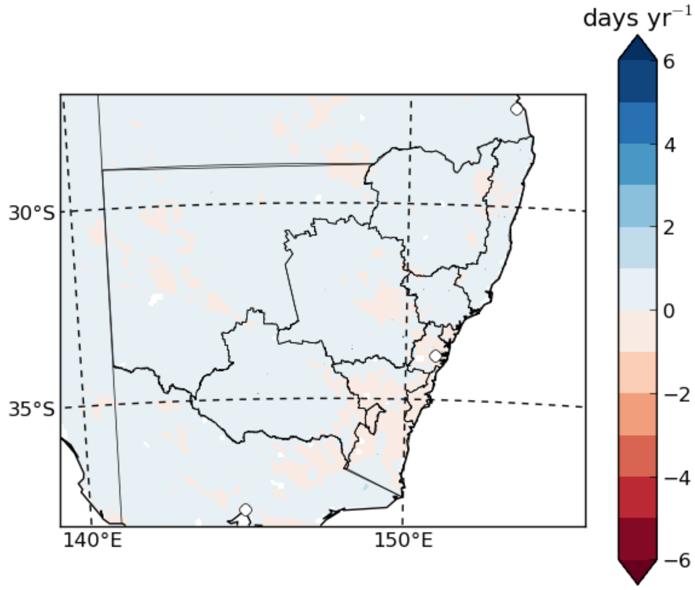

Figure 5.17: Annual multi-model means changes between years 1990-2009 and 2020-2039 for number of very heavy precipitation days (R20mm) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

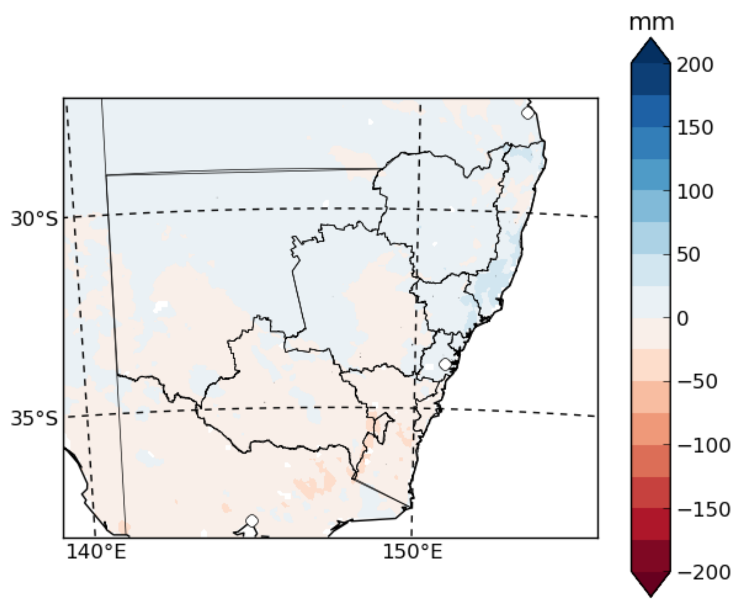

Figure 5.18: Annual multi-model means changes between years 1990-2009 and 2020-2039 for annual total wet day precipitation (PRCPTOT) [mm yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

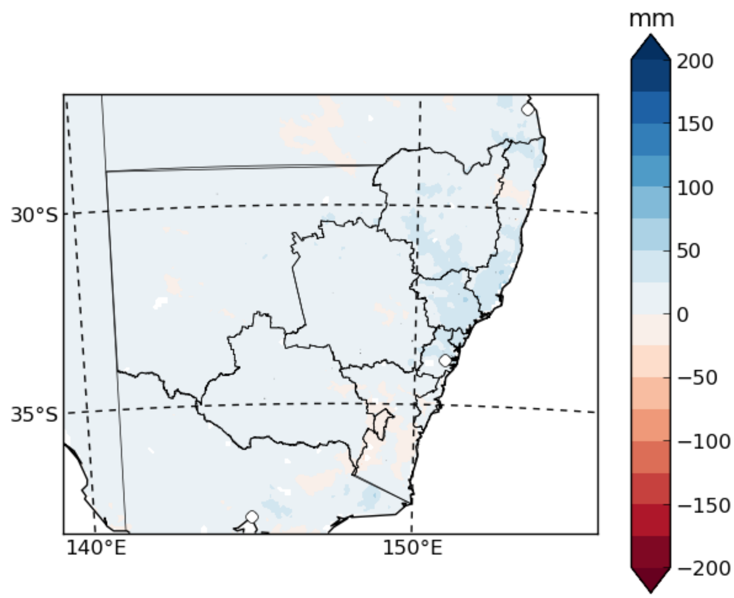

Figure 5.19: Annual multi-model means changes between years 1990-2009 and 2020-2039 for contribution from very wet days (R95p) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

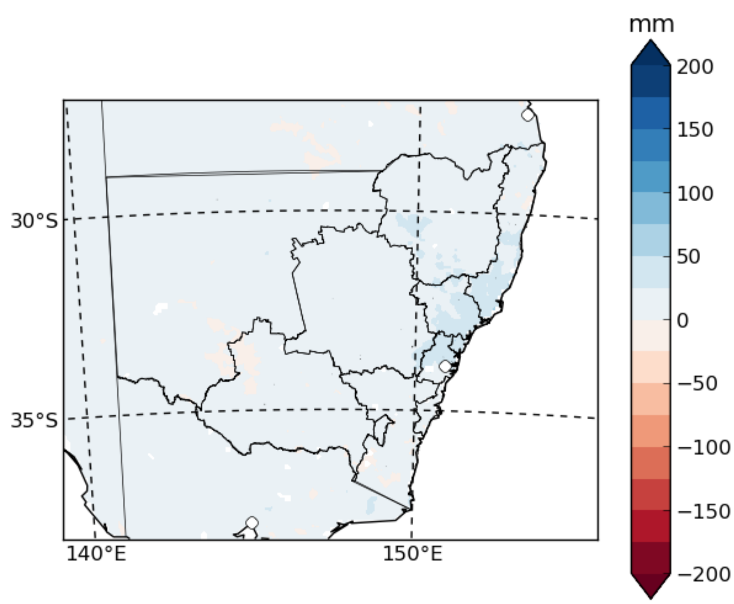

Figure 5.20: Annual multi-model means changes between years 1990-2009 and 2020-2039 for contribution from extremely wet days (R99p) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

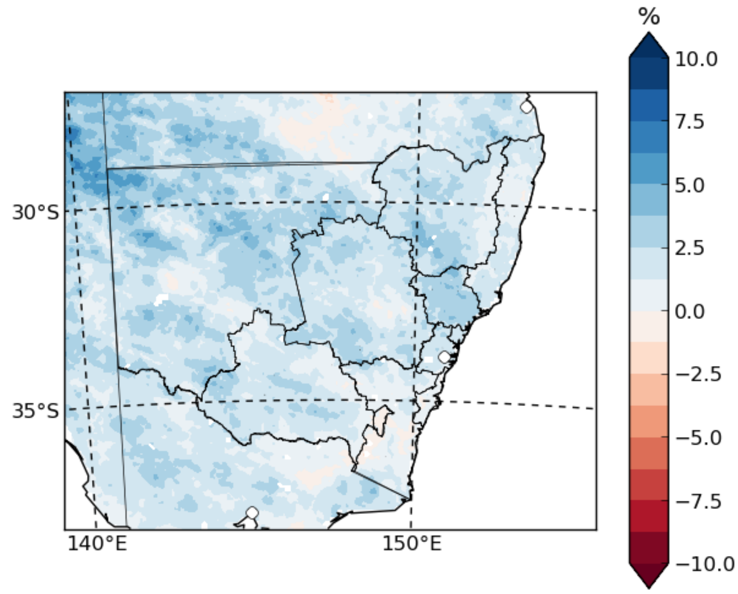

Figure 5.21: Annual multi-model means changes between years 1990-2009 and 2020-2039 for contribution from very wet days as % of PRCPTOT (R95pTOT) [%]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

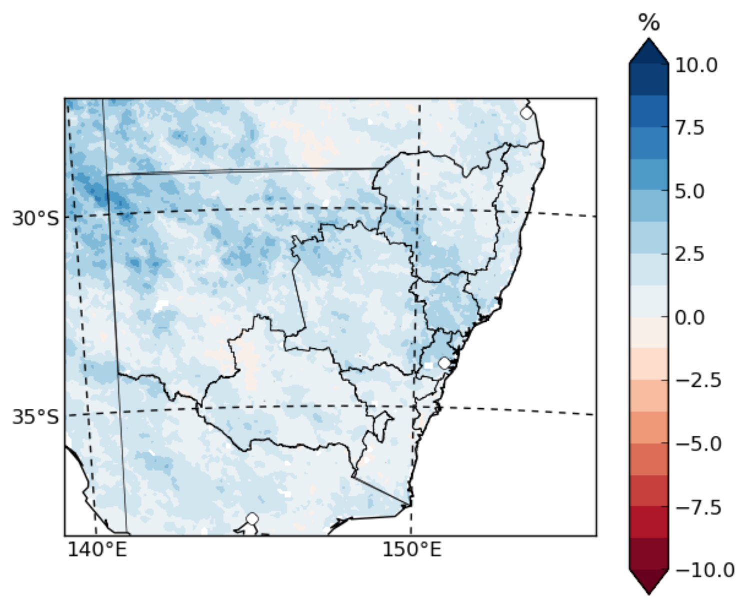

Figure 5.22: Annual multi-model means changes between years 1990-2009 and 2020-2039 for contribution from extremely wet days as % of PRCPTOT (R99pTOT) [%]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

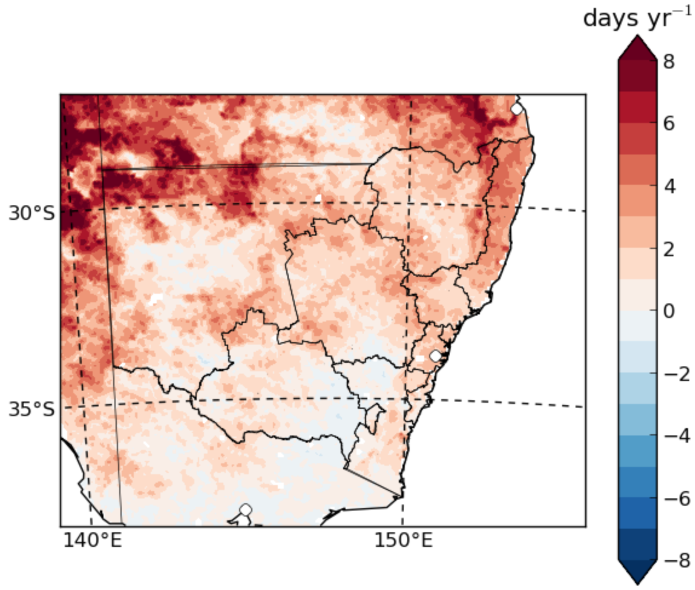

Figure 5.23: Annual multi-model means changes between years 1990-2009 and 2020-2039 for consecutive dry days (CDD) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

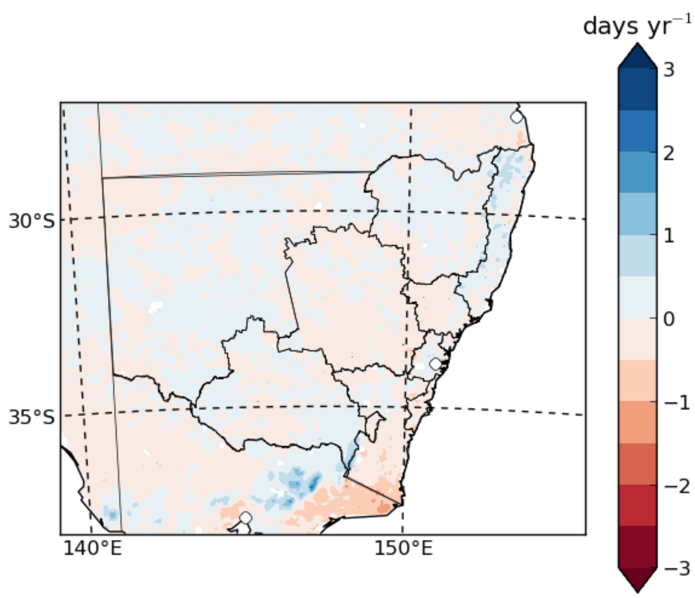

Figure 5.24: Annual multi-model means changes between years 1990-2009 and 2020-2039 for consecutive wet days (CWD) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

5.2 Near Future Changes in Mean Regional Estimates

This subsection contains box plots for each extreme precipitation index, for each NSW state planning region (see Figure 1.2 which includes the region abbreviations). This region-based representation also shows the variability across NARCliM ensemble members for each index across the various regions (i.e., box plots).

In agreement with the spatial analysis shown in section 5.1, almost all region based changes span zero change in the near future. The only exception is the consecutive dry days for the Central Coast (CC) and Metropolitan Sydney (MSyd) where small increases are projected.

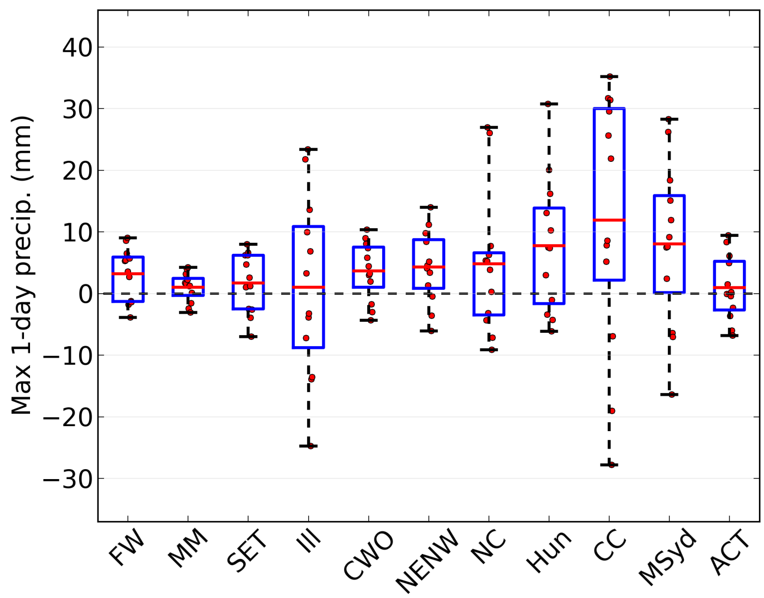

Figure 5.25: Boxplots of annual maximum 1-day preciptiation (Rx1day) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

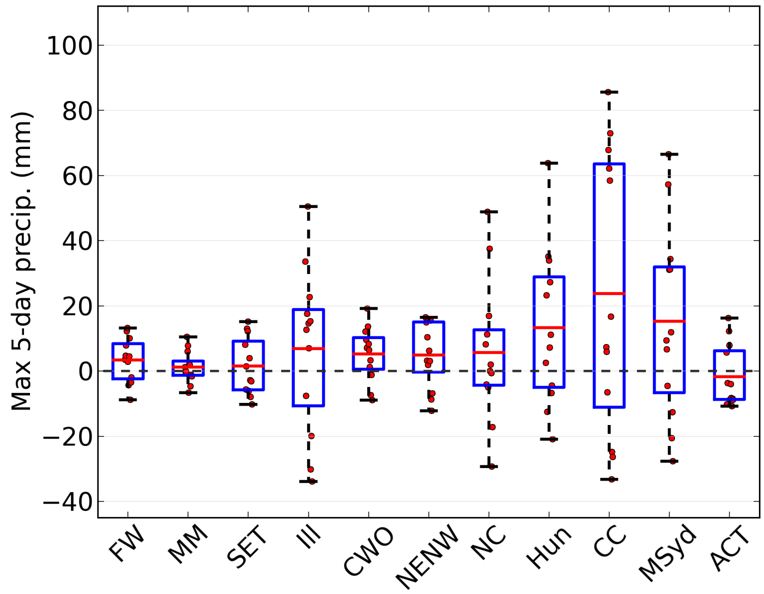

Figure 5.26: Boxplots of annual maximum 5-day preciptiation (Rx5day) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

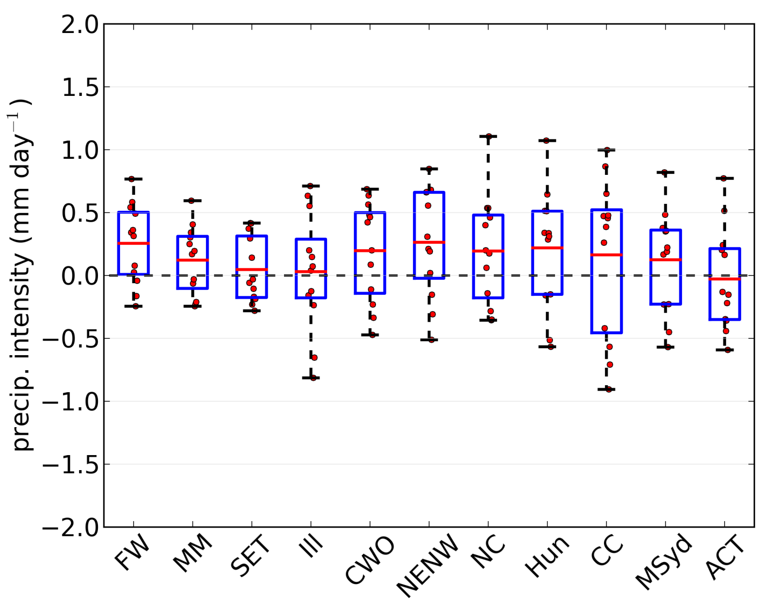

Figure 5.27: Boxplots of simple precipitation intensity index (SDII) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

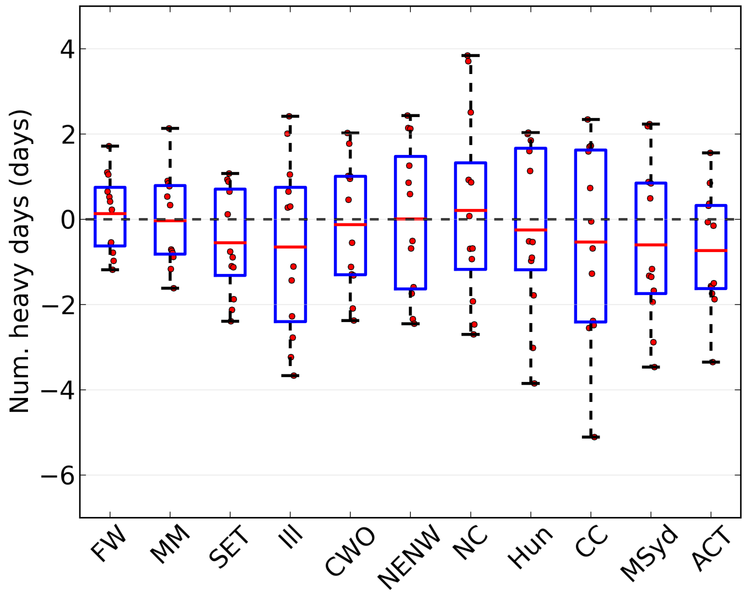

Figure 5.28: Boxplots of number of heavy precipitation days (R10mm) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

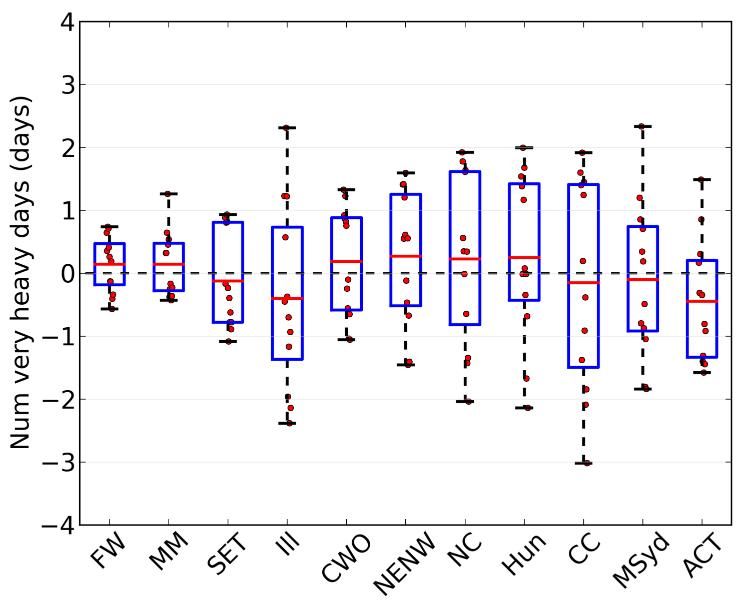

Figure 5.29: Boxplots of number of very heavy precipitation days (R20mm) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

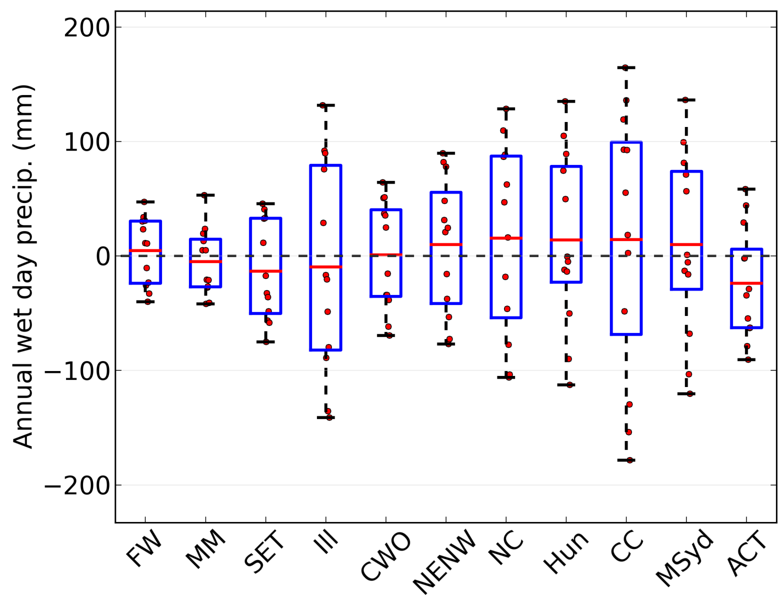

Figure 5.30: Boxplots of annual total wet day precipitation (PRCPTOT) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

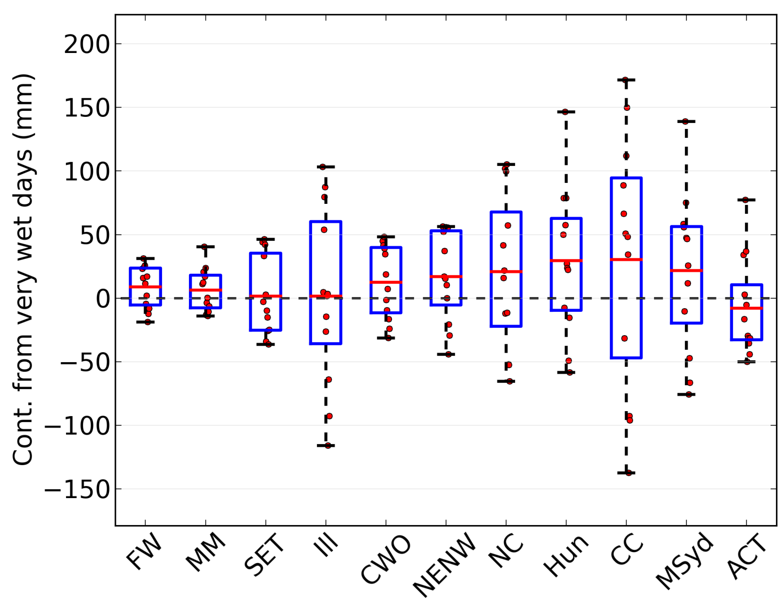

Figure 5.31: Boxplots of contribution from very wet days (R95p) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

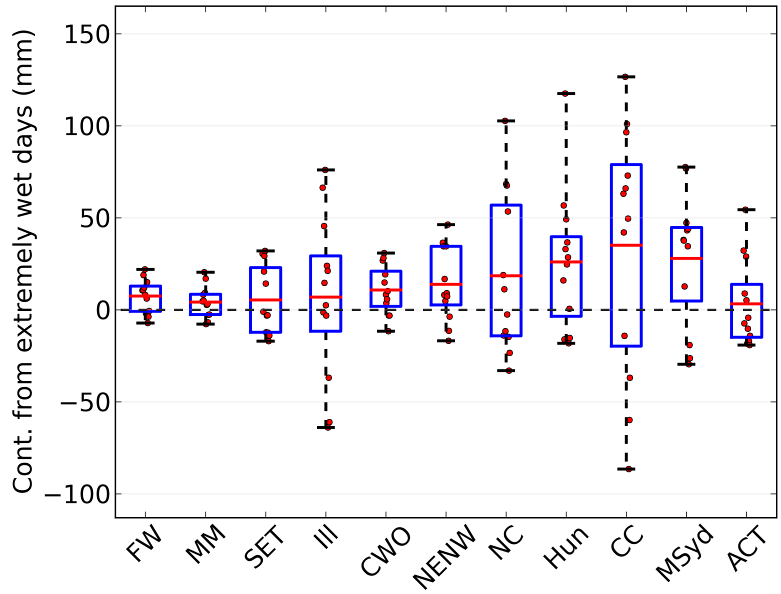

Figure 5.32: Boxplots of contribution from extremely wet days (R99p) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

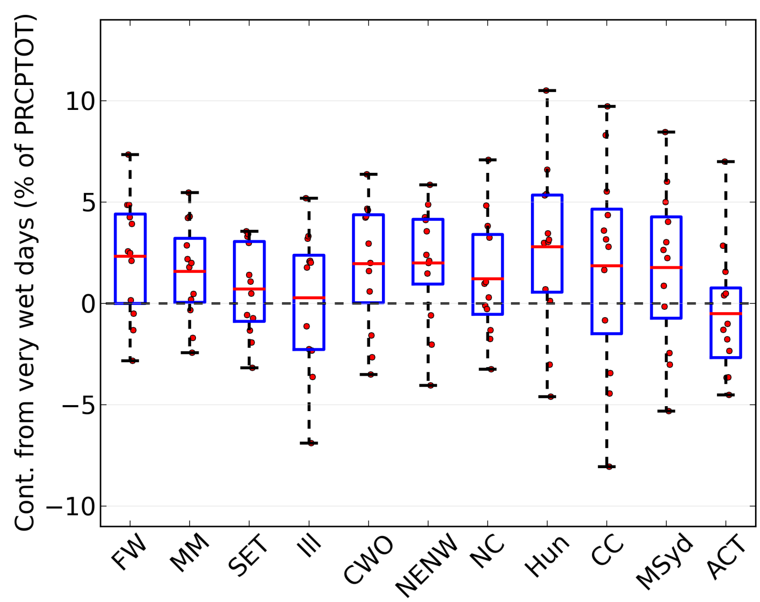

Figure 5.33: Boxplots of contribution from very wet days as % of PRCPTOT (R95pTOT) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

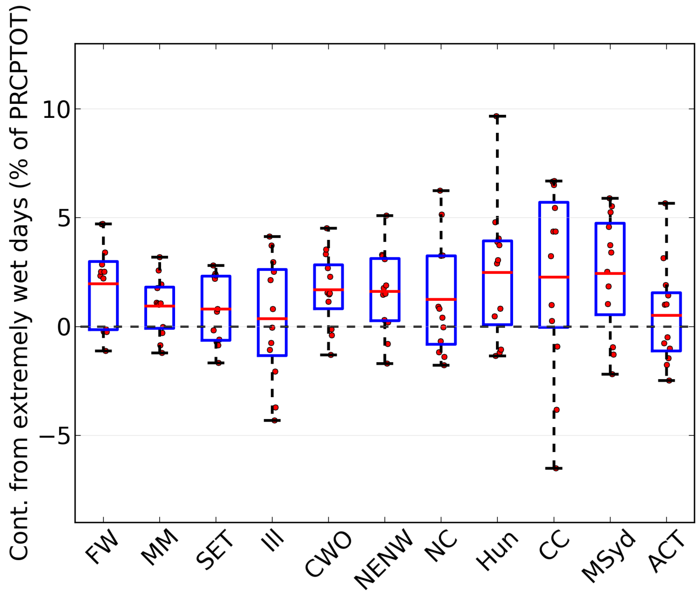

Figure 5.34: Boxplots of contribution from extremely wet days as % of PRCPTOT (R99pTOT) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

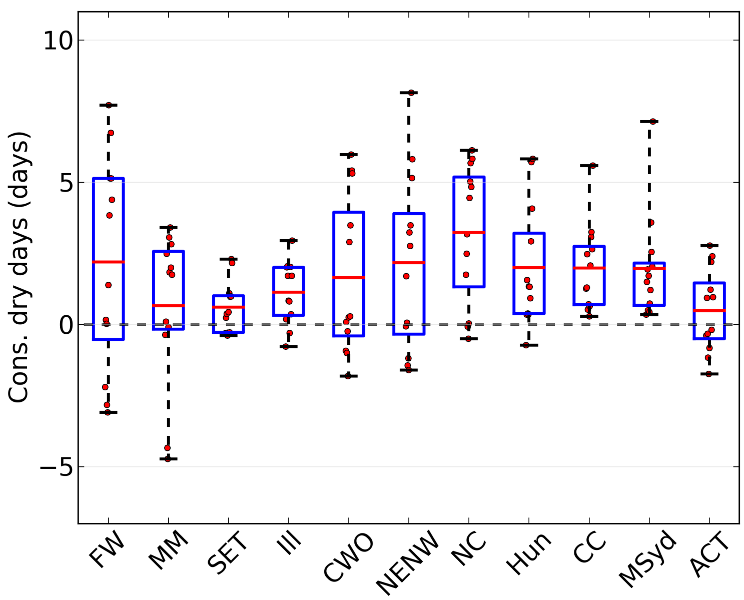

Figure 5.35: Boxplots of consecutive dry days (CDD) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

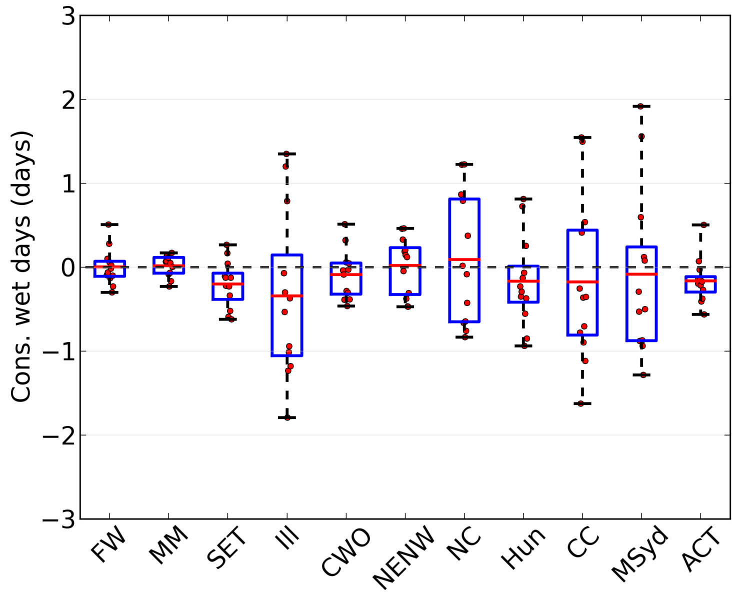

Figure 5.36: Boxplots of consecutive wet days (CWD) for NSW state planning regions (years 2020-2039). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

Chapter 6

Far Future (2060-2079) Model Climatologies and Changes

This chapter contains the climatological seasonal and annual mean projections for the extreme precipitation indices. We show seasonal and annual multi-model mean climatologies for each index.

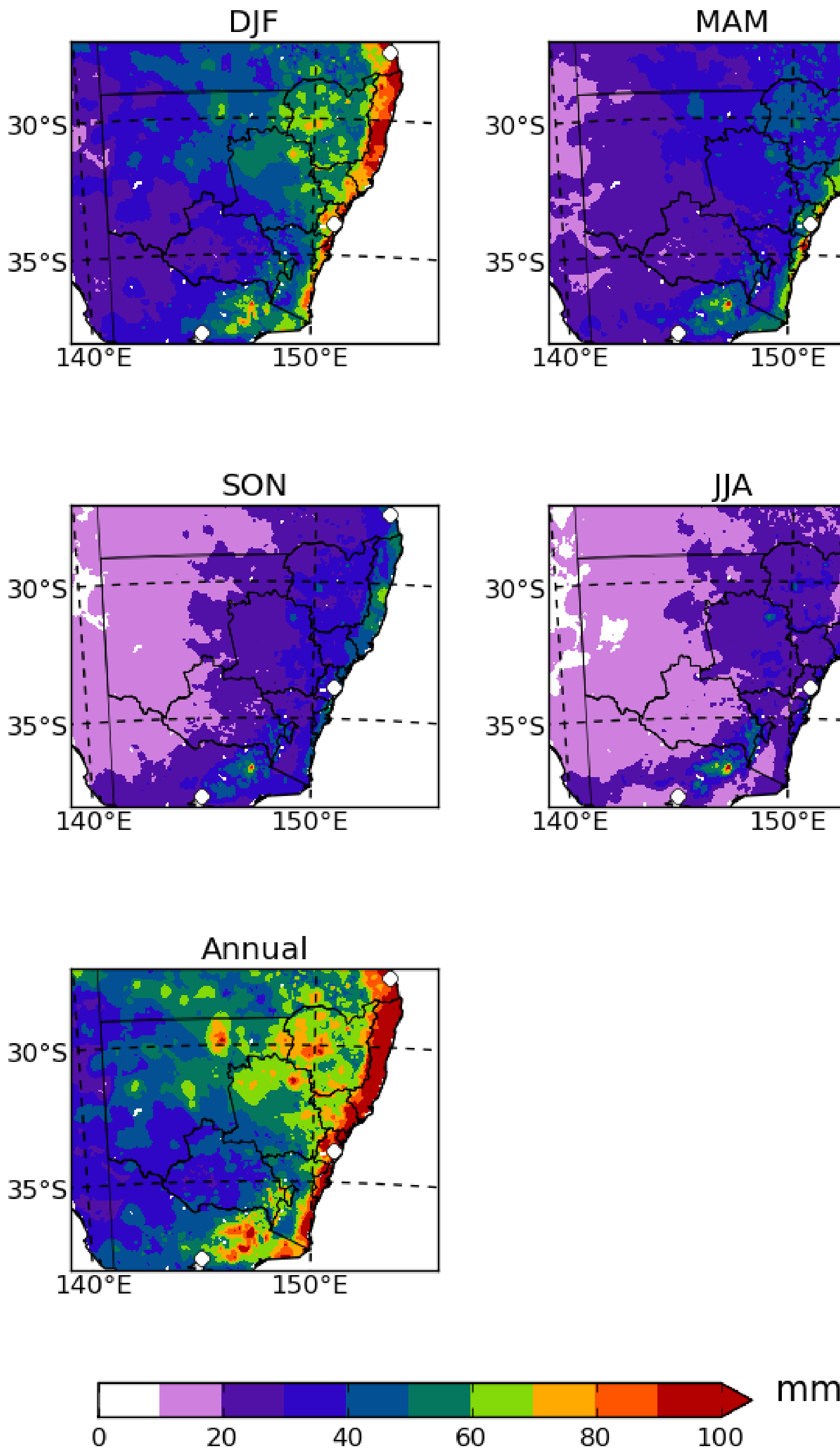

Figure 6.1: Far-future (2060-2079) multi-model average seasonal and annual maximummaximum 1-day preciptiation (Rx1day)[mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

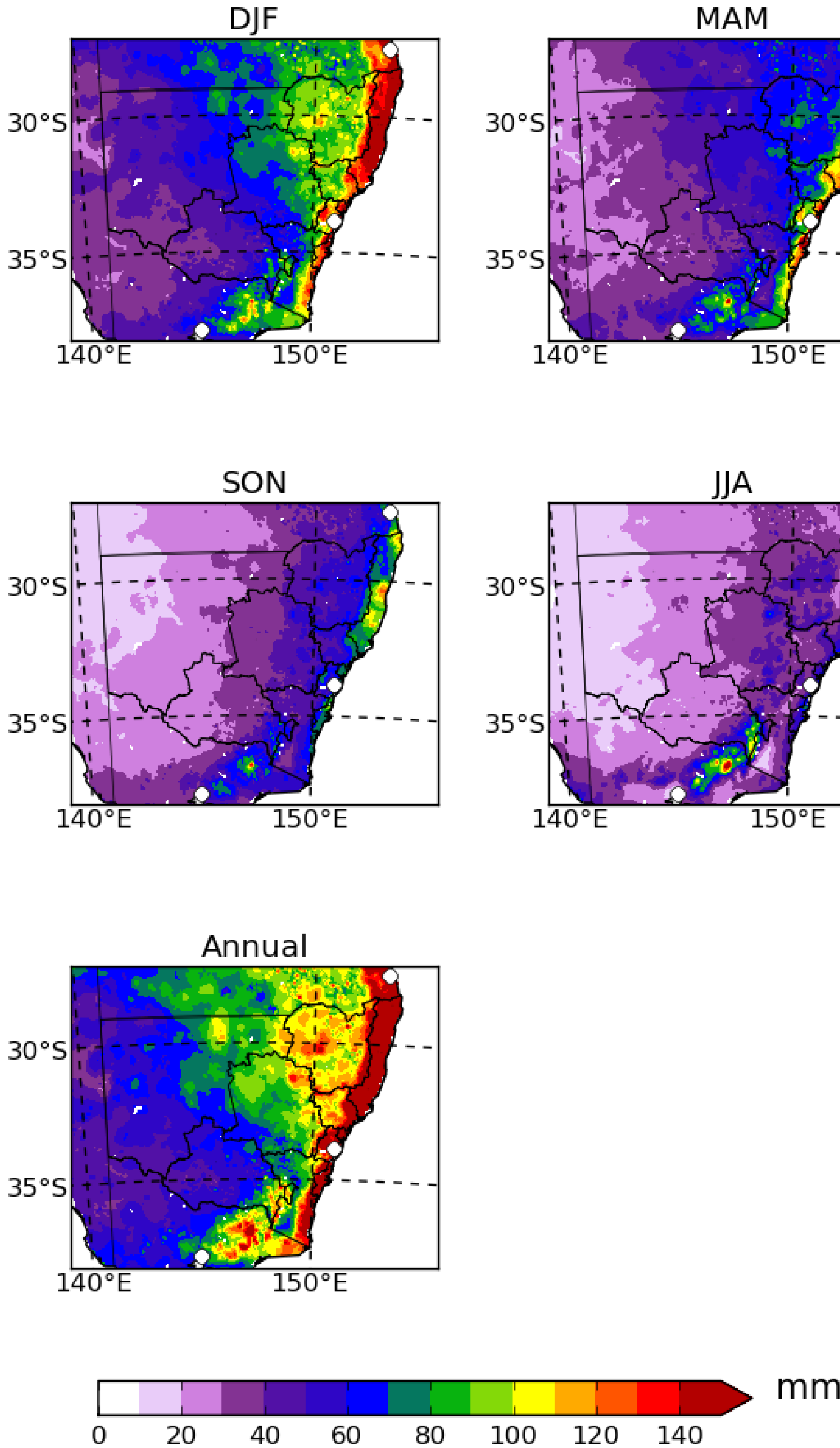

Figure 6.2: Far-future (2060-2079) multi-model average seasonal and annual maximummaximum 5-day preciptiation (Rx5day)[mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

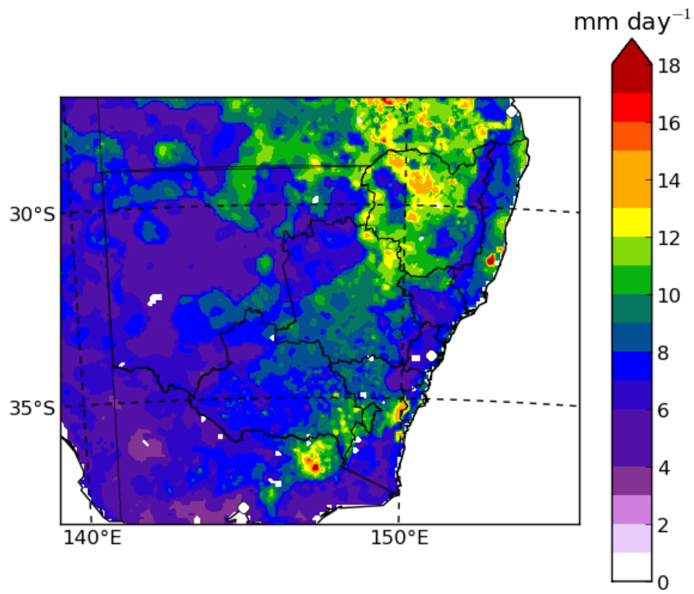

Figure 6.3: Annual multi-model means of simple precipitation intensity index (SDII) for years 2060-2079 [mm day^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

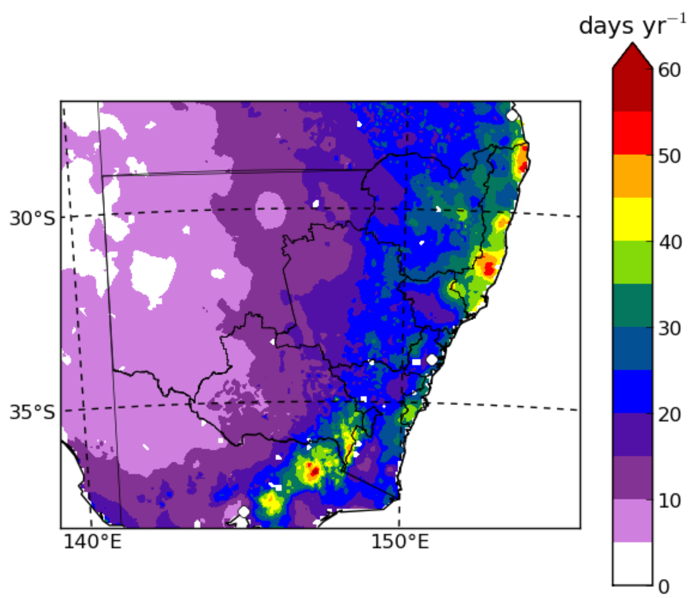

Figure 6.4: Annual multi-model means of number of heavy precipitation days (R10mm) for years 2060-2079 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

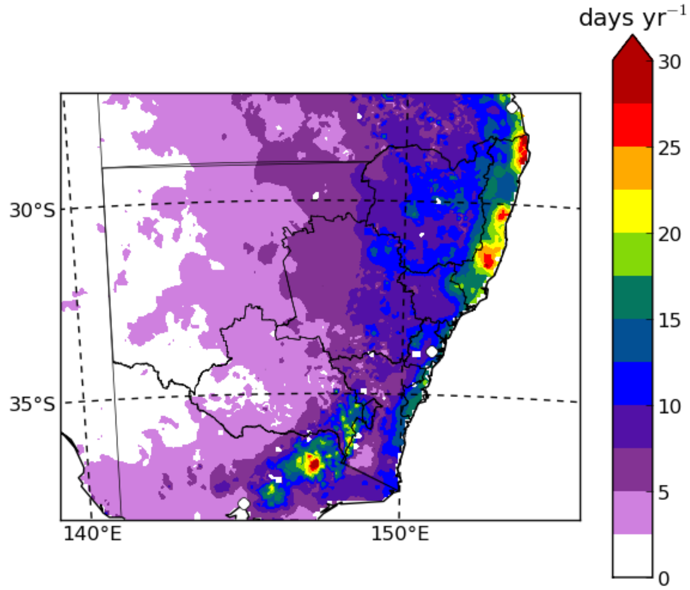

Figure 6.5: Annual multi-model means of number of very heavy precipitation days (R20mm) for years 2060-2079 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

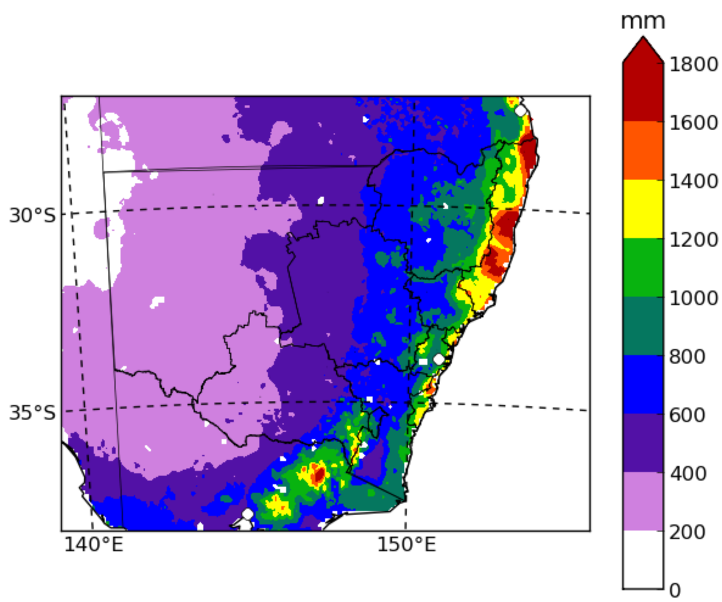

Figure 6.6: Annual multi-model means of annual total wet day precipitation (PRCPTOT) for years 2060-2079 [mm yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

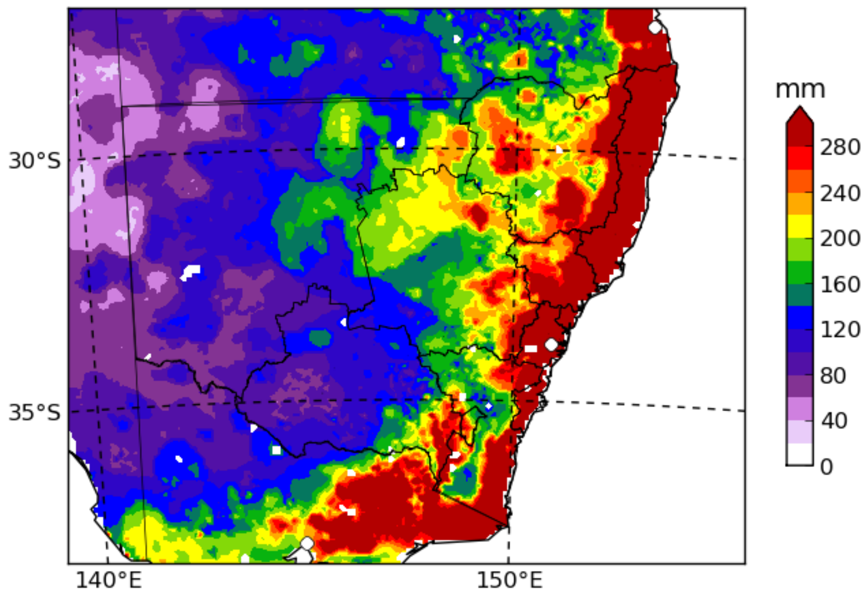

Figure 6.7: Annual multi-model means of contribution from very wet days (R95p) for years 2060-2079 [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

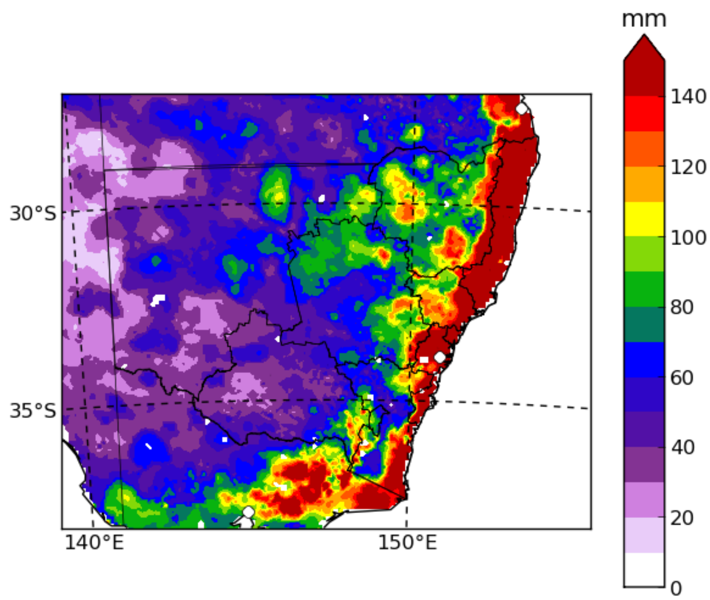

Figure 6.8: Annual multi-model means of contribution from extremely wet days (R99p) for years 2060-2079 [mm]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

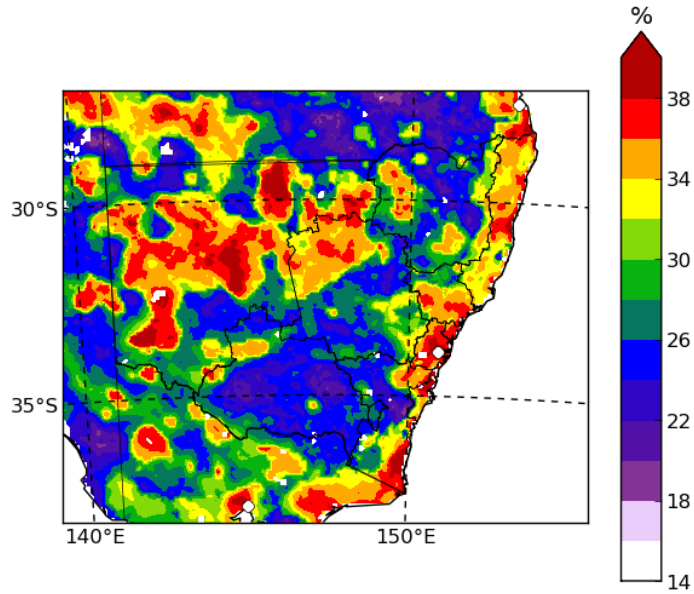

Figure 6.9: Annual multi-model means of contribution from very wet days as % of PRCPTOT (R95pTOT) for years 2060-2079 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

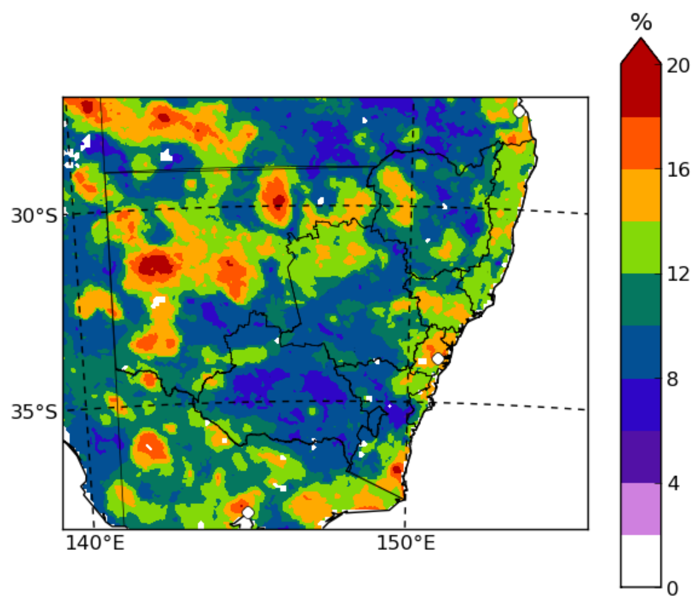

Figure 6.10: Annual multi-model means of contribution from extremely wet days as % of PRCPTOT (R99pTOT) for years 2060-2079 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

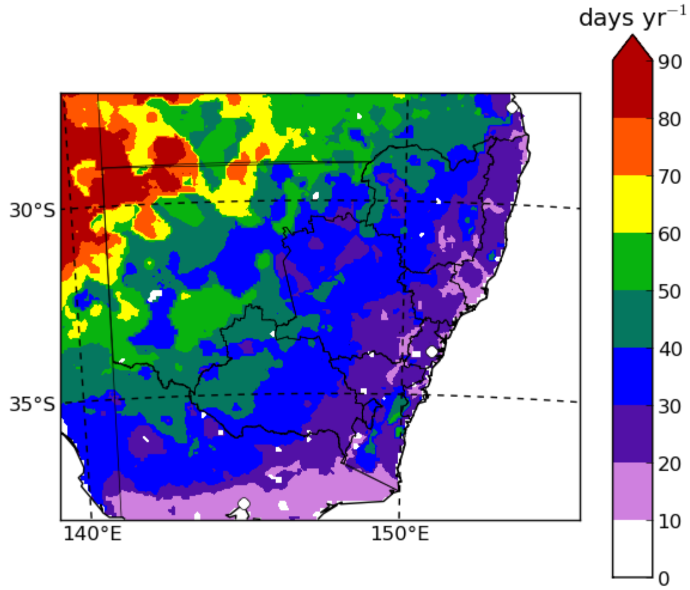

Figure 6.11: Annual multi-model means of consecutive dry days (CDD) for years 2060-2079 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

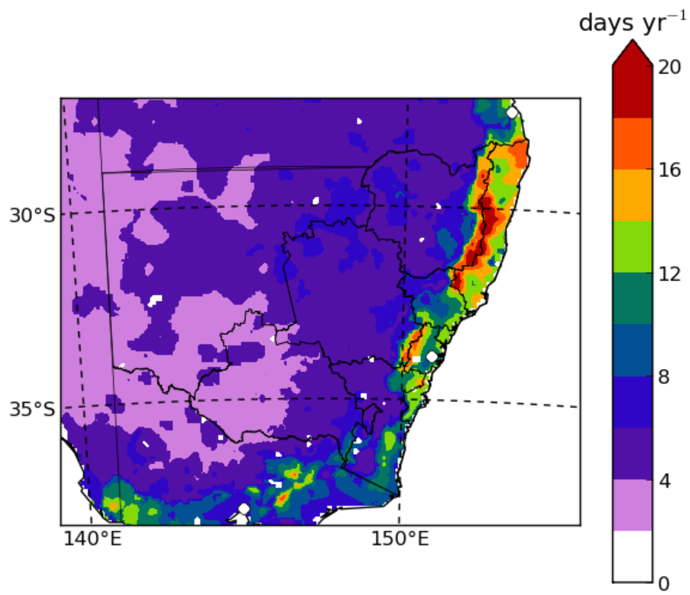

Figure 6.12: Annual multi-model means of consecutive wet days (CWD) for years 2060-2079 [days yr^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

6.1 Far Future Modeled Changes Compared to the Present Period

This section contains projected seasonal and annual mean changes for the extreme precipitation indices, between present (1990-2009) and far future (2060-2079). The coloured contours provide information on average projected changes, while the stippling indicates the level of model agreement which is an indicator of the level of uncertainty in the projected climate.

An individual model is tested for significance using a Student's t-test at the 95% significant level. The multi-model future changes are separated into three categories (a) less than half of the models show a significant change (insignificant areas, multi-model mean change is shown in colour), (b) at least half of the models show a significant change and at least 80% of significant models agree on the direction of change (significant agreeing areas, stippled), and (c) at least half of the models show a significant change and less than 80% of significant models agree on the direction of change (significant disagreeing areas, white).

For future changes, insignificant areas indicate a small projected change in most models compared to the inter-annual variability. Significant agreeing areas indicate that the ensemble is projecting a robust change in a particular direction. Significant disagreeing areas indicate that ensemble members disagree on the direction of change.

In the far future most changes in these extreme precipitation indices remain non-significant. Exceptions to this include: SDII increasing significantly for regions west of the Great Dividing Range and in southern NSW; and smaller scattered zones of significant increase for R10mm, R20mm, PRCPTOT, R95p and R95pTOT.

While the changes are not significant it is worth noting that statewide there is very little change in the maximum number of consecutive wet days each year but there is an increase in the maximum consecutive dry days. This is indicative of longer dry spells between rainfall events.

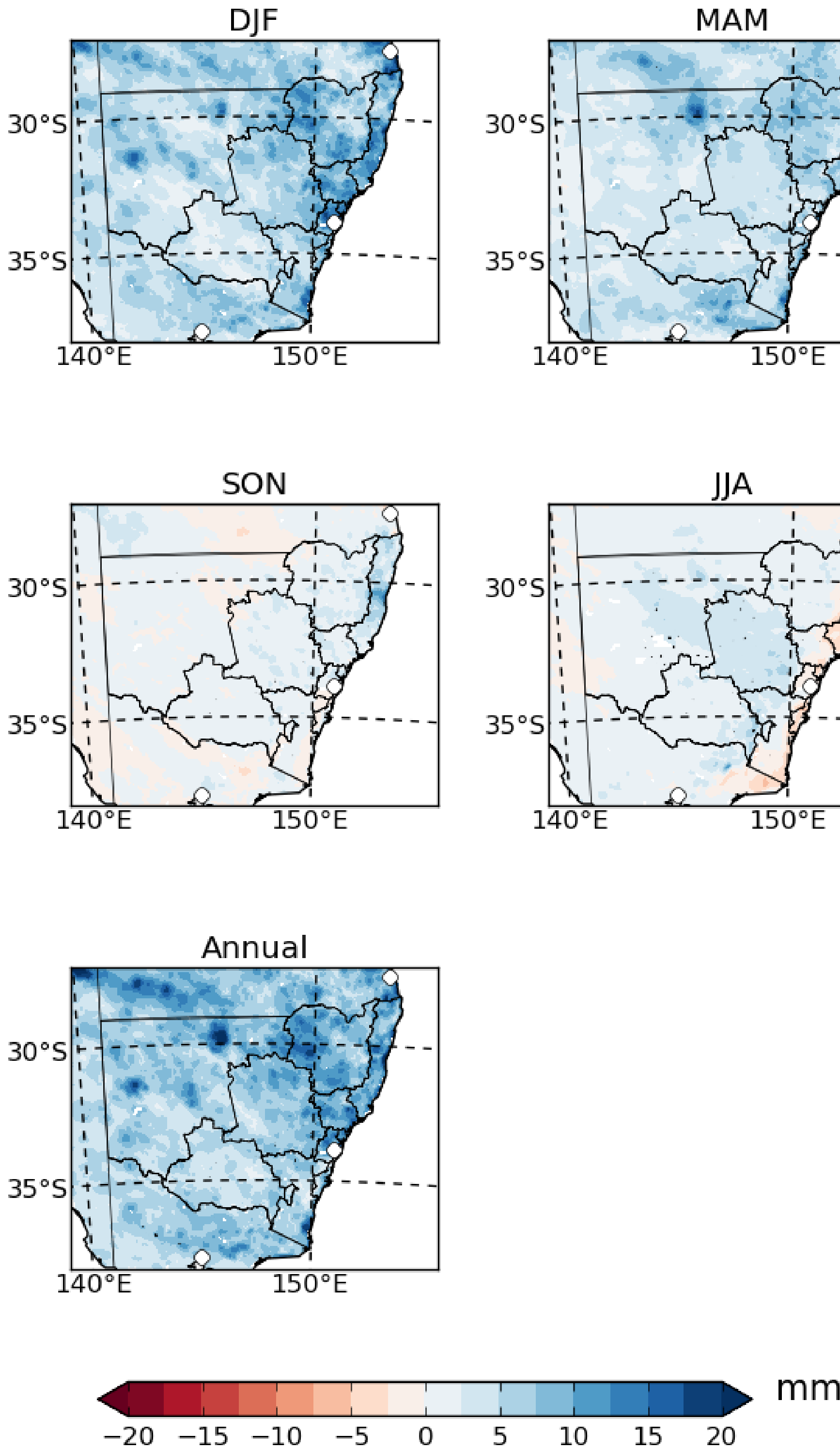

Figure 6.13: Multi-model mean changes between far future (2060-2079) and present (1990-2009) in seasonal and annual maximum maximum 1-day preciptiation (Rx1day) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

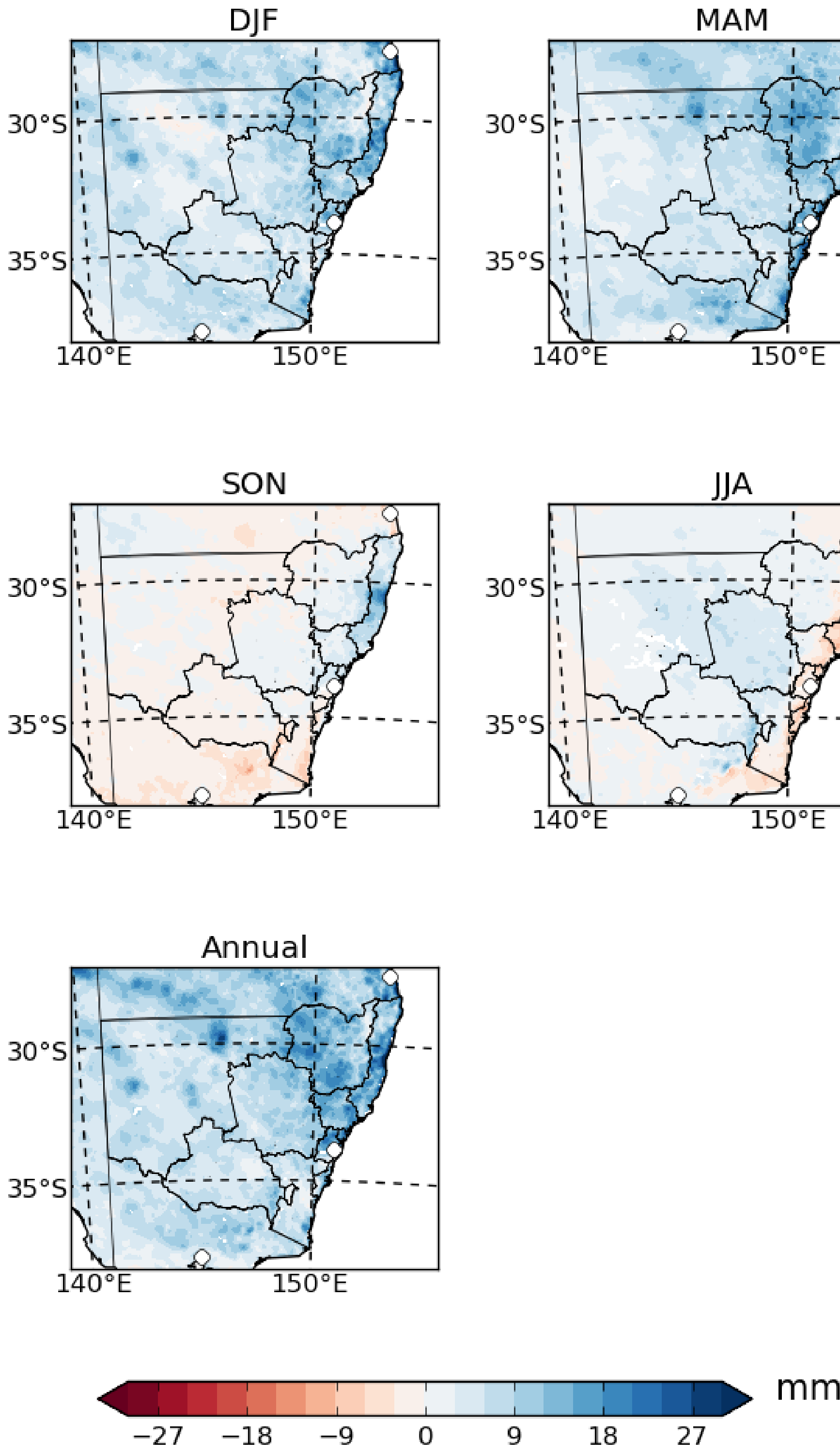

Figure 6.14: Multi-model mean changes between far future (2060-2079) and present (1990-2009) in seasonal and annual maximum maximum 5-day preciptiation (Rx5day) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

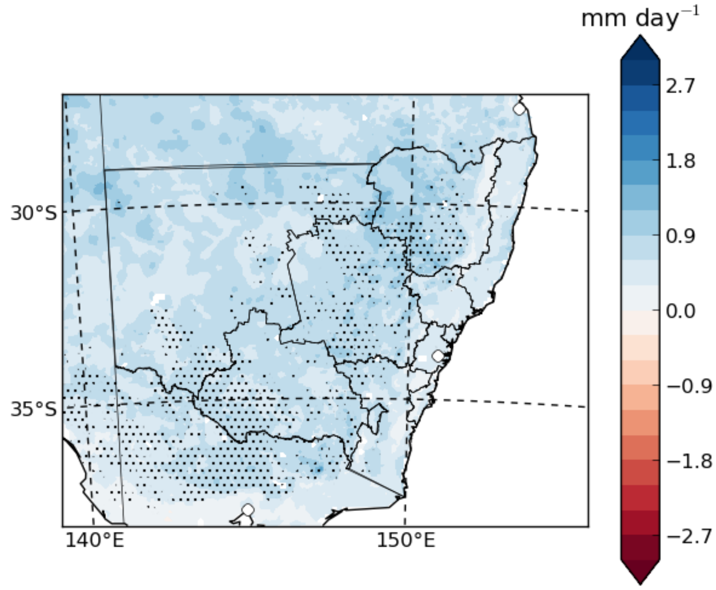

Figure 6.15: Annual multi-model means changes between years 1990-2009 and 2060-2079 for simple precipitation intensity index (SDII) [mm day^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

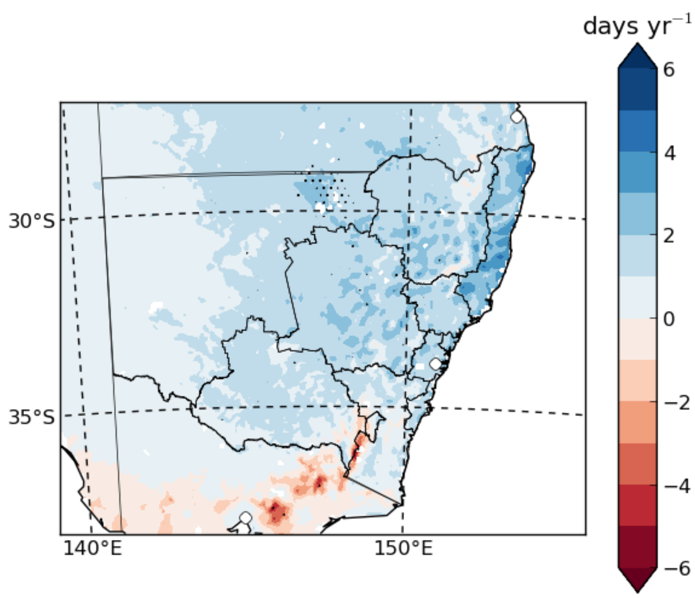

Figure 6.16: Annual multi-model means changes between years 1990-2009 and 2060-2079 for number of heavy precipitation days (R10mm) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

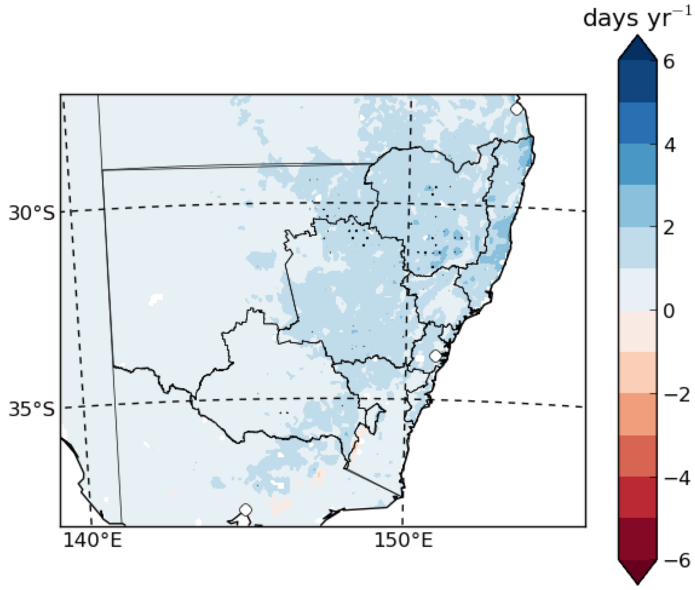

Figure 6.17: Annual multi-model means changes between years 1990-2009 and 2060-2079 for number of very heavy precipitation days (R20mm) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

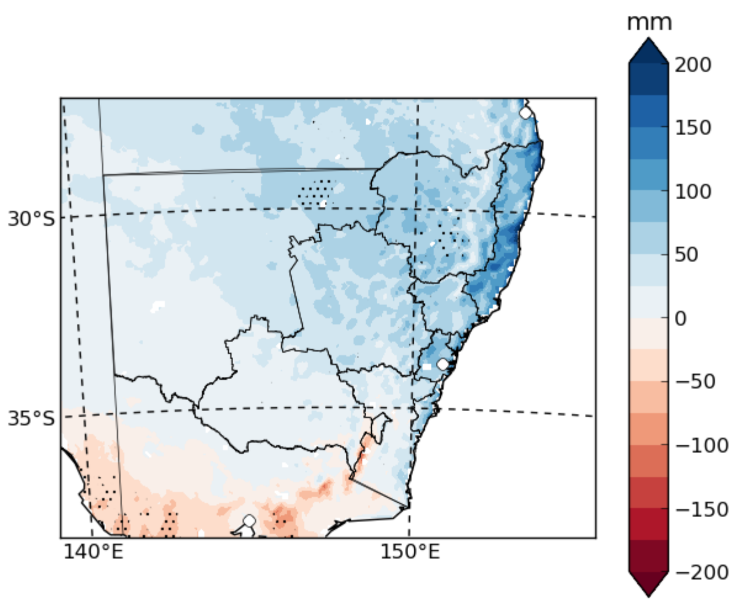

Figure 6.18: Annual multi-model means changes between years 1990-2009 and 2060-2079 for annual total wet day precipitation (PRCPTOT) [mm yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

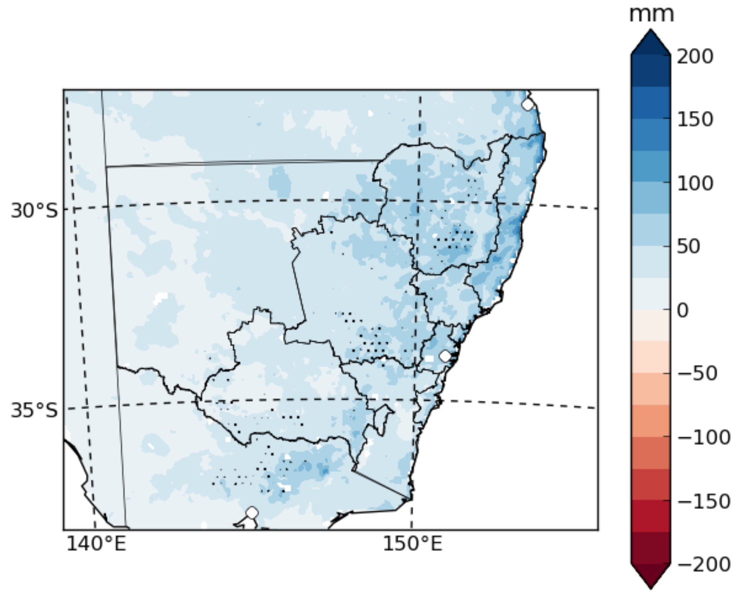

Figure 6.19: Annual multi-model means changes between years 1990-2009 and 2060-2079 for contribution from very wet days (R95p) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

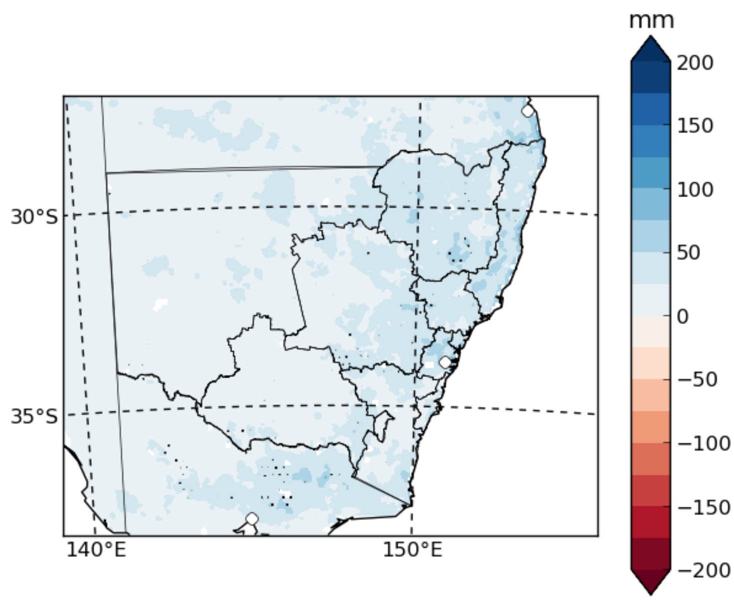

Figure 6.20: Annual multi-model means changes between years 1990-2009 and 2060-2079 for contribution from extremely wet days (R99p) [mm]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

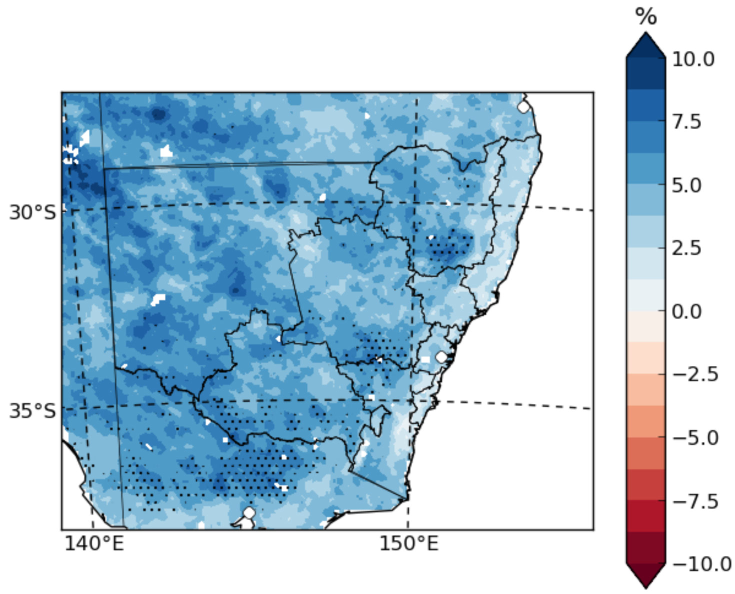

Figure 6.21: Annual multi-model means changes between years 1990-2009 and 2060-2079 for contribution from very wet days as % of PRCPTOT (R95pTOT) [%]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

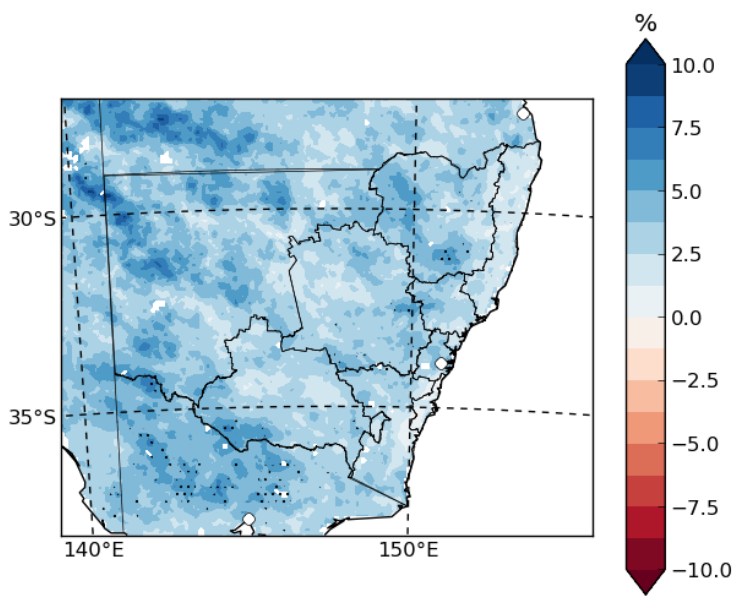

Figure 6.22: Annual multi-model means changes between years 1990-2009 and 2060-2079 for contribution from extremely wet days as % of PRCPTOT (R99pTOT) [%]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

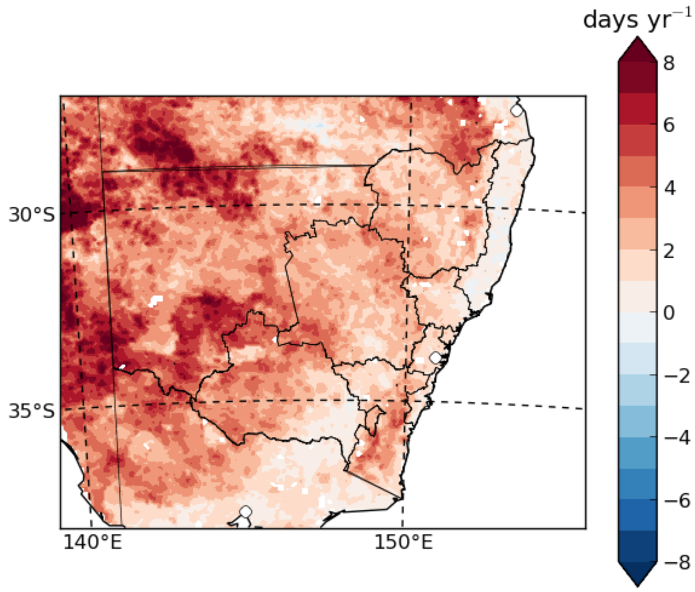

Figure 6.23: Annual multi-model means changes between years 1990-2009 and 2060-2079 for consecutive dry days (CDD) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

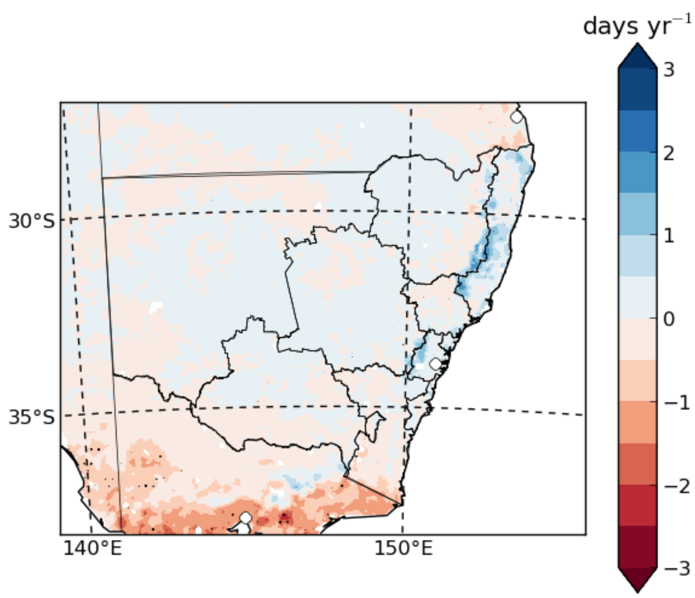

Figure 6.24: Annual multi-model means changes between years 1990-2009 and 2060-2079 for consecutive wet days (CWD) [days yr^{-1}]. Stipling indicates that the changes are significant at the 5% level. White circles (top to bottom): Brisbane, Sydney, Melbourne.

6.2 Far Future Changes in Mean Regional Estimates

This subsection contains box plots for each extreme precipitation index, for each NSW state planning region (see Figure 1.2 which includes the region abbreviations). This region-based representation also shows the variability across NARCliM ensemble members for each index across the various regions (i.e., box plots).

Like the results for the near future, most changes projected by the ensemble for the far future span zero change. All exceptions are increases and include: Rx1day in FW, MM and NENW; Rx5day in FW, NENW and Hun; SDII in FW and MM; R99p in FW, MM and NENW; R95pTOT in FW, MM, SET; and R99pTOT in FW, MM, NENW and Hun. This suggests that for these regions one may expect a small increase in the rainfall intensity, particularly for the more extreme events.

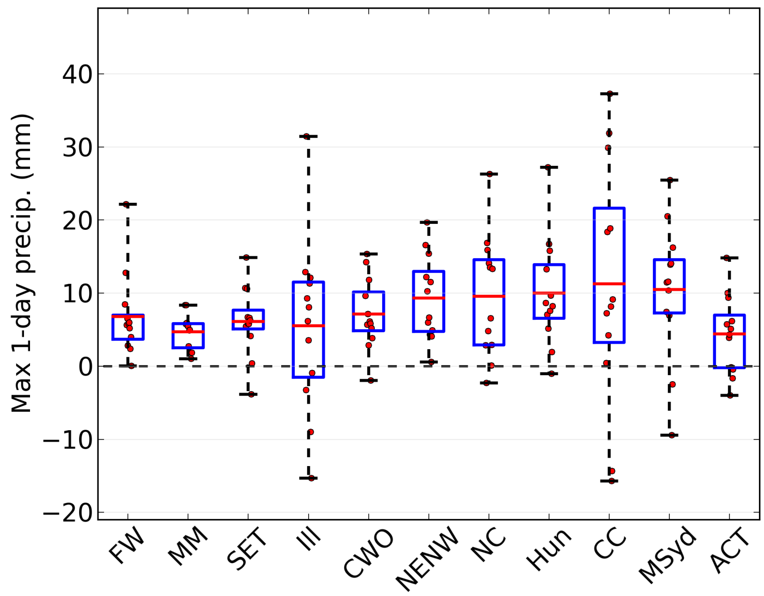

Figure 6.25: Boxplots of monthly maximum 1-day precipitation (Rx1day) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

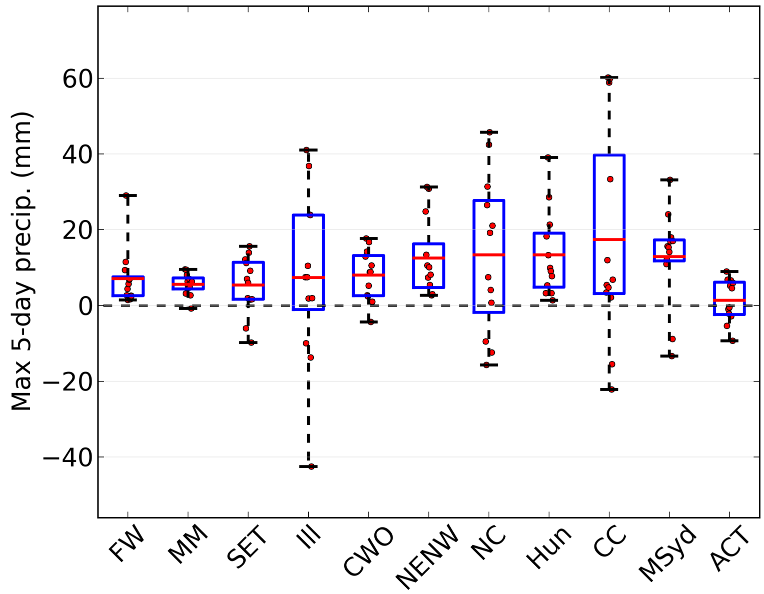

Figure 6.26: Boxplots of monthly maximum 5-day precipitation (Rx5day) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

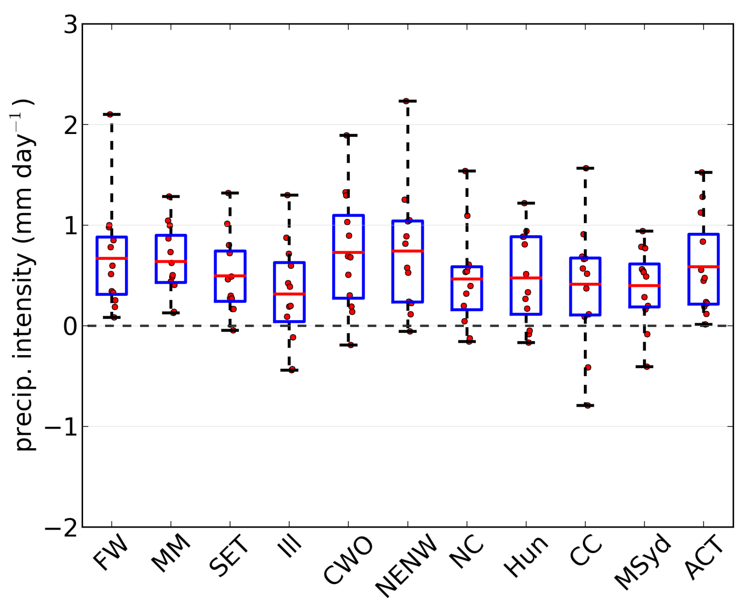

Figure 6.27: Boxplots of simple precipitation intensity index (SDII) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

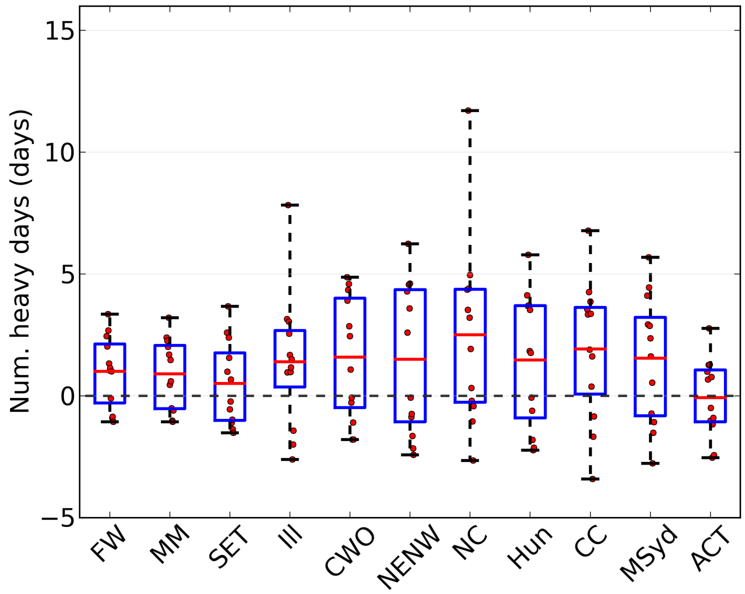

Figure 6.28: Boxplots of number of heavy precipitation days (R10mm) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

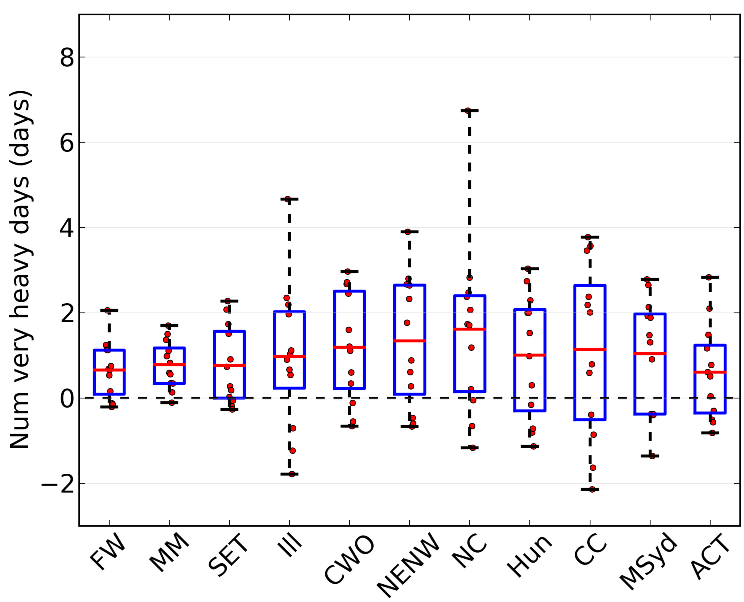

Figure 6.29: Boxplots of number of very heavy precipitation days (R20mm) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

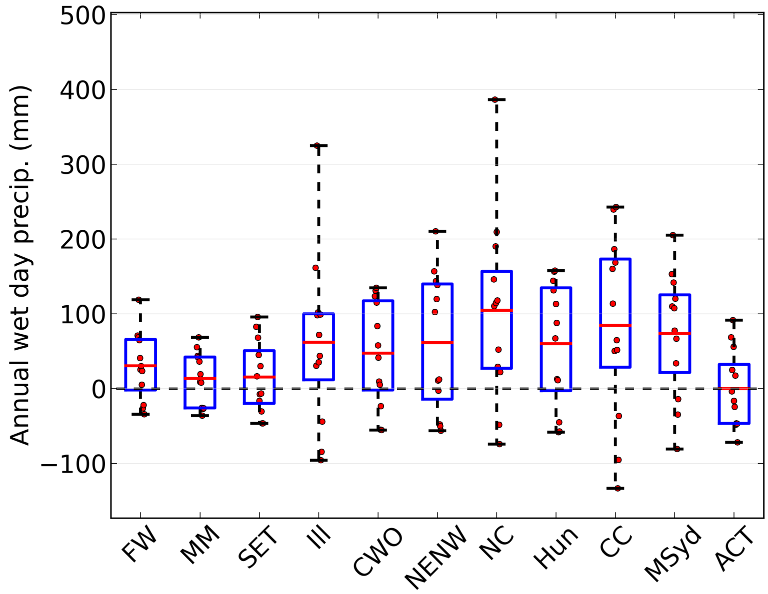

Figure 6.30: Boxplots of annual total wet day precipitation (PRCPTOT) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

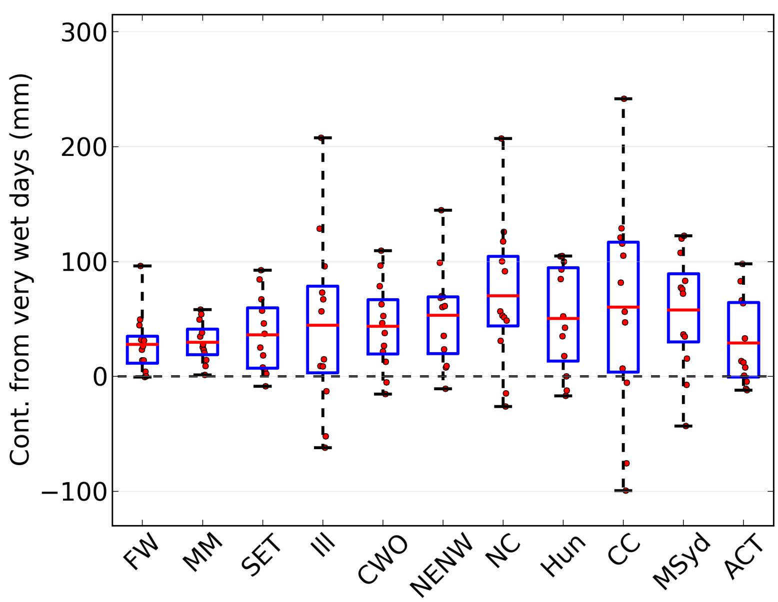

Figure 6.31: Boxplots of contribution from very wet days (R95p) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

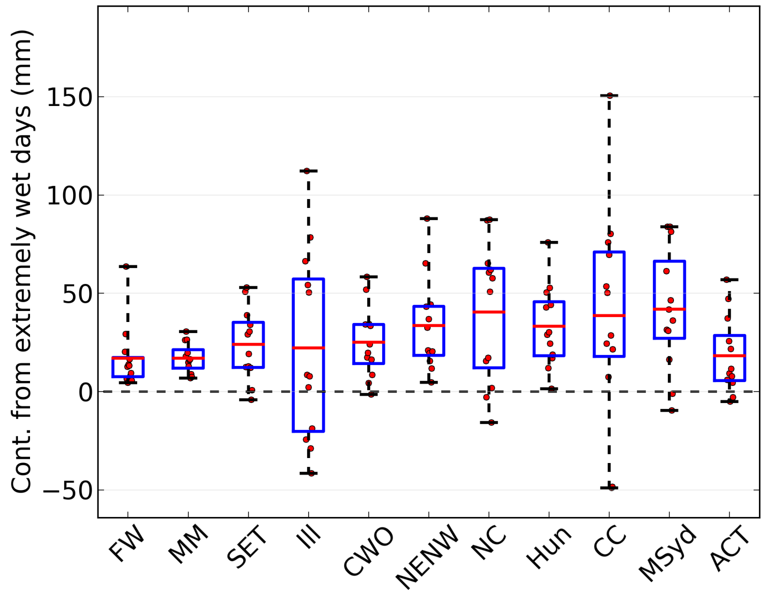

Figure 6.32: Boxplots of contribution from extremely wet days (R99p) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

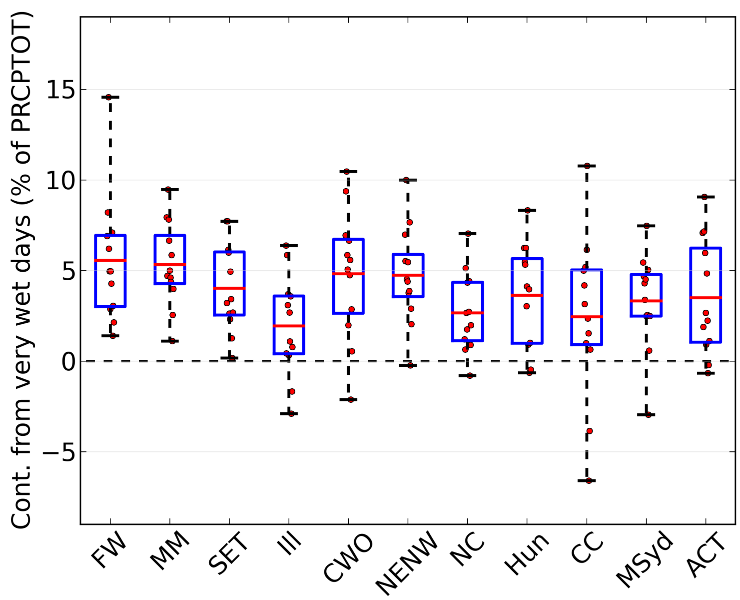

Figure 6.33: Boxplots of contribution from very wet days as % of PRCPTOT (R95pTOT) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

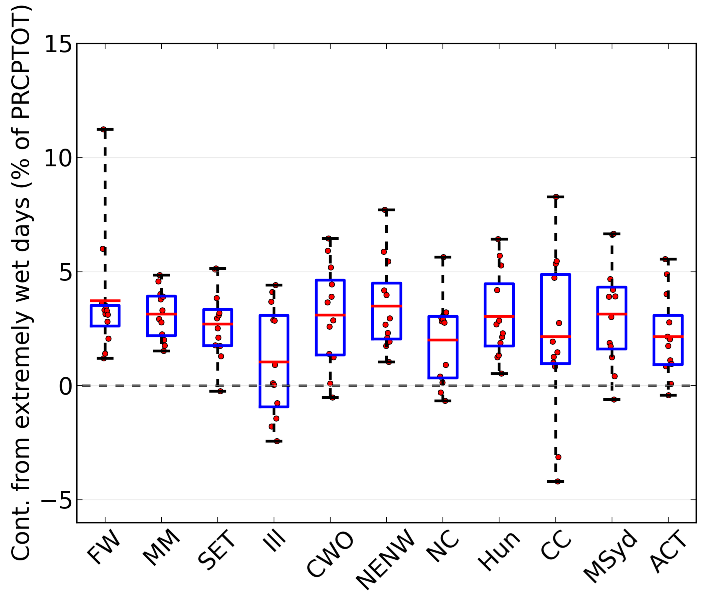

Figure 6.34: Boxplots of contribution from extremely wet days as % of PRCPTOT (R99pTOT) for NSW state planning regions (years 2060-2079). Red line indicates ensemble mean, box extends from the 25th to the 75th percentile, whiskers extend to the ensemble range. Red dots indicate individual RCMs, black squares indicate the AWAP estimate.

Chapter 7

Conclusions and Recommendations for Further Work

The NARCliM ensemble is able to simulate the precipitation indices well with few significant biases for most variables. Exceptions include: Rx1day and Rx5day have significant low winter biases over much of NSW; SDII has significant low biases along the Eastern Seaboard and parts of north-western NSW; and CDD and CWD also have significant low biases over much of the state.

Overall NARCliM projects increases in the (moderately) extreme precipitation indices across NSW and the ACT. While these increases in the ensemble mean are consistent with the trends in past observations, the full range of future change projected often includes zero change. The result is that most projected changes are not statistically significant at the 5% level when compared to the inter-annual variability.

The Simple Daily Intensity Index (SDII) is the only index to have significant increases over large parts of NSW. This is likely due to the SDII having a better signal to noise ratio than the other extreme indices. That is trends in extreme indices are often harder to detect due to their larger inherent variability.

It is interesting to note that very little change in the maximum wet spell is projected but an increase (though not significant) in the maximum dry spell (CDD) is projected over most of NSW. This increase in CDD is a reverse of the decreasing trend found in the AWAP observations and warrants further investigation.

7.1 Recommendations for Further Work

Precipitation extremes occur across a wide range of time and space scales. The NARCliM dataset allows us to investigate changes over durations from hours to years and space scales from 100 km^2 to all of south-east Australia.

ETCCDI indices

This report summarizes the changes projected for the extreme preciptation indices. A number of open questions and opportunities for future work remain.

- The work presented here is focused on the ensemble mean changes and the spread of the ensemble. This initial look at the results assumed the indices are normally distributed and applied significance tests accordingly. For some of these indices this assumption is fine but for some (such as Rx1day) this is not true and the application of more sophistcated statistical techniques is required to properly assess the significance of the results.

- Most of these indices are defined on an annual basis and thus do not allow investigation of the seasonal changes that are occurring. Further adaptation of the indices to allow investigation of the seasonal cycle and projected changes seasonally should be done.
- The statistics used here are applied on a grid point basis however there are a number of statistical approaches including max-stable models [4] and field significance approaches [33] that could be applied. These techniques enable stronger statements to be made on domain-averaged trends.
- To make the analysis more relevant for flood risk, a better understanding of how trends in extreme rainfall behave at different levels of spatial aggregation is needed. Floods are dependent on the total volume of rainfall falling over a catchment area, so performing the analysis over catchments that span a range of sizes would be useful from a flood impact perspective.
- The reversal of trends in the maximum consecutive dry spell (CDD) from a decrease over the last century to an increase in the next century warrants further investigation. The decreasing length of dry and wet spells (CDD and CWD) in the AWAP observations suggest that the climate has been progressively displaying less persistence over the last century. The future increases in CDD (and perhaps CWD) suggest the climate will display more persitence in the future. These changes may have real implications for both human and natural systems. A study aimed at unraveling the causes of these changes should be performed.
- The currently implemented Gamma distribution based bias correction for precipitation does not do a good job at correcting the tails of the distribution (extremes). The bias correction could be imporved to specifically correct the extremes through the use of second theoretical distribution just for the extremes.

Sub-daily precipitation extremes

The NARCliM dataset allows us to examine changes in precipitation down to the hourly duration. This level of detail for projections of sub-daily precipitation has not existed before and allows a number of aspects of precipitation extremes to be explored.

- Evaluate the NARCliM ensemble at hourly time scales. The first step toward investigating changes in sub-daily precipitation extremes is to evaluate the ensemble against appropriate observations. No gridded observational product with sub-daily resolution exists so such an evaluation will necessarily involve station data directly. The Bureau of Meteorology (BoM) has collected a large set of stations recording climate information at sub-daily time-scales which brings together the BoM automated station network and a wide range of third party climate stations. With careful consideration of station-gridcell mismatch, an evaluation of RCM performance at these time scales needs to be performed.

- Intensity-Duration-Frequency (IFD) curves can be calculated from annual maxima precipitation time series for durations from hourly up to multiple days. When dealing with observations it is common practice to fit a Generalized Extreme Value (GEV) distribution to the time series, perform a regionalization using nearby stations, and use the resulting GEV to estimate rainfall depths across all durations. How best to perform similar analysis with RCM data is a relatively new area of research. Complications include accounting for the gridcell-station spatial mismatch by adjusting areal reduction factors, using statistical methods to specifically bias-correct the extremes, performing a regionalization on a model grid, and addressing the non-stationarity of the GEV itself. Relatively new statistical methods such as a Bayesian Hierarchical Model applied to IFD curves with the scale parameter relationship of Koutsoyiannis et al. [23], or max-stable models [4], could be applied to this problem.

- Within storm temporal distribution of rainfall may also be changing. Very recent work [31] has shown that the within storm peak rain rate increases with temperature in recent observations. This implies that with global warming we will see further increases in within storm peak rate rates. This has implications for flooding and should be investigated with the NARCliM data.

- Spatial characteristics of short-lived thunderstorms are becoming better understood largely through the analysis of new more comprehensive precipitation radar datasets such as Rainfields developed by the BoM. Analyzing the spatial characteristics of rainfall produced by the RCMs in comparison to the radar data could provide new insights into precipitation mechanisms and areas for model improvement.

Large scale precipitation extremes

Much is known about the large-scale climate modes that influence Australian rainfall (ENSO, etc), so far little work has been done looking at this connection in the NARCliM ensemble. Synoptic systems such as tropical cyclones and East Coast Lows also have a strong influence on the production of precipitation extremes.

- An examination of the large-scale climate mode influence on rainfall over all of Australia using domain 1 has been performed. A similar exercise examining the NARCliM domain needs to be performed. Connecting the changes in these climate modes modelled by the NARCliM GCMs with those found in the CMIP5 ensemble remains to be done. From this one could infer changes in the NARCliM climate based on CMIP5 projected changes in large-scale climate modes.

- Work examining East Coast Lows and their future changes has been ongoing within the ESCCI-ECL project which will soon be coming to an end. While we have learned a great deal about future changes in ECLs, a number of areas remain unexplored including: connecting future ECL changes with on-land impacts in terms of wind, rain and floods; connecting future ECL changes with wave production and coastal erosion; examining the climatological impact on ECLs of actually resolving the East Australian Current by implementing a coupled regional ocean model with WRF; differentiating ECLs by origin and tracks and explaining the changes projected separately for the north (with increasing tropical influences) and the south (Tasman Sea warming).

- The reanalysis driven simulations are not able to capture the very wet years in the 1950s and 1970s that was probably the wettest period in the instrumental region for the Sydney region. It is hypothesised that unusually frequent ECLs may have been responsible but no data that could confirm this currently exists. An effort to manually examine past sea level pressure charts to identify ECLs and compare this with reanalysis and NARCliM simulations could shed light on the model performance during this period.
- The production, intensification and movement of tropical cyclones (TCs) particularly in domain 1, is yet to be examined. While recent studies suggest that the frequency of south Pacific TCs will decrease in the future [30], a number of factors such as the widening of the Hadely cell may encourage TC tracks to move further south and perhaps to impact northern NSW.

Process studies

Some further studies are suggested to improve our overall understanding of relevant precipitation processes.

- The future climate of the Australian Alps remains highly uncertain. The Alps are a major source of water for several agriculturally productive river basins and hence future changes in precipitation over these mountains are of major economic interest for Australia. The NARCliM projections should be analyzed with a specific focus on the Alps. Here the representation of solid precipitation and the transition between solid and liquid become very important. The NARCliM ensemble would allow us to explore the relationships with the atmospheric environment, convection and cloud microphysics in terms of producing changes in the precipitation phase as climate change occurs.
- Relatively little is known about the source regions of the water vapour that produces precipitation over NSW. Does it come from the Tasman Sea? Pacific Ocean? Timor Sea? land evaporation? or further afield? If a significant proportion comes from land evaporation (other parts of the world have been shown to get more than 25% of the precipitated water vapour from relatively local land evaporation [8]) then land-use changes in these areas could have significant impact on our precipitation. By combining the detailed atmospheric fields from NARCliM with a back-trajectory and moisture accounting model these water vapour source regions could be quantified.
- Explicitly understanding the land-atmosphere coupling including its impact on precipitation is required to understand our influence on the regional climate through land cover modifications. Quantifying this coupling and its effect on climate extremes in Australia remains to be done.

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