NSW | ACT Regional Climate Modelling project

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Heatwaves affecting NSW and the ACT - recent trends, future projections and associated impacts on human health

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Chapter 1

Introduction

This report presents heatwave characteristics derived from the CAWCR Excess Heat Factor [65, 64] metric, their biases, and projected future changes for the State of New South Wales, and the Australian Capital Territory. These results are based on simulations performed as part of the NARCliM (New South Wales / Australian Capital Territory Regional Climate Modelling) project [29, 68]. 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 describes the heatwave index and characteristic metrics, chapter 3 presents climatologies and trends from observations, chapter 4 compares the NARCliM modelled results with the AWAP observations for the present period (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. These are followed by a short review of heat-health relationships and the health implications of the NARCliM heatwave projections, then a short discussion of the urban heat island effect. The report concludes with some short conclusions and recommendations for future work. 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 making [29]. 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 physics). All RCM simulations were performed at 10-km resolution over NSW/ACT (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 [47] 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 the production of 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 RCMs ability to simulate both these very wet periods and the recent dry period known as the Millennium Drought [95]. This phase provides an estimate of the RCM quality including any systematic RCM biases.

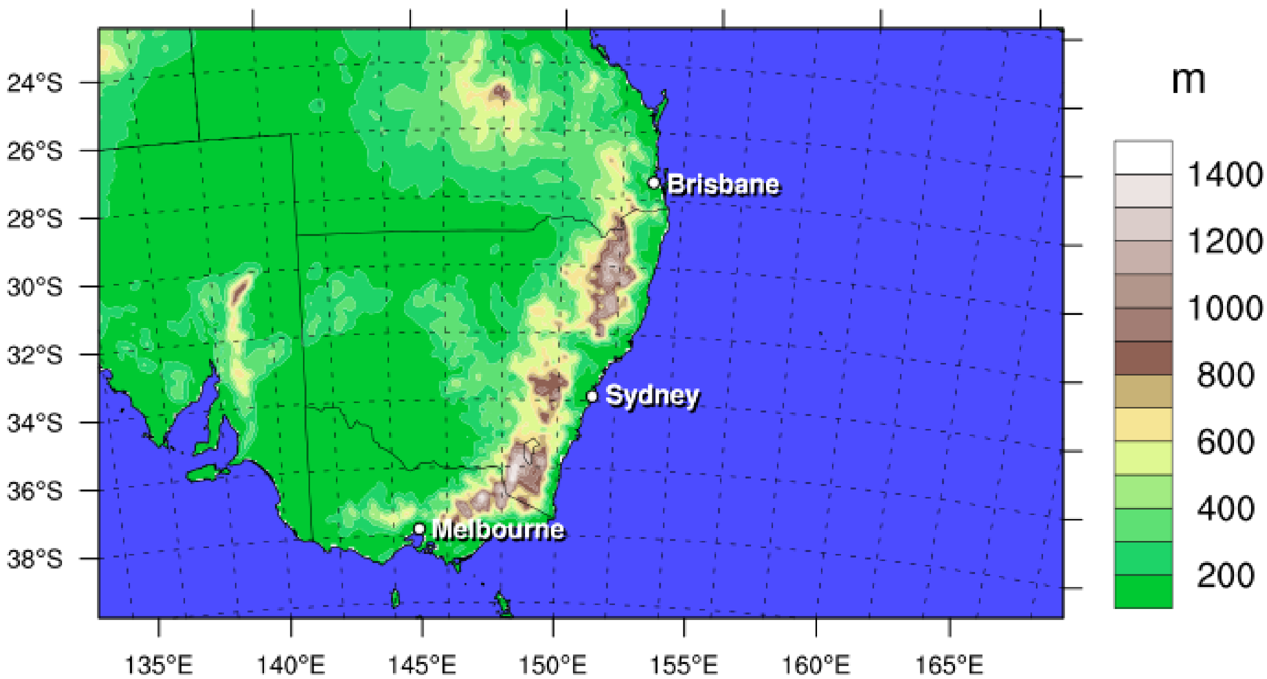

Figure 1.1: Map of the NARCliM domain

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 [39] is used. This scenario assumed 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 [28, 27]. 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, microphysics, 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 [41] with Eta similarity surface layer; YSU / MM5 similarity: Yonsei University PBL scheme [38] with the MM5 similarity theory surface layer [72, 25, 101]; KF: Kain-Fritsch cumulus scheme [45, 46, 44]; BMJ: Betts-Miller-Janjic cumulus scheme [15, 14, 41, 42]; WDM5: WRF Double Moment 5-class microphysics scheme [55]; Dudhia: Dudhia shortwave radiation scheme [24], RRTM: Rapid Radiative Transfer Model longwave radiation scheme [62]; CAM: NCAR Community Atmosphere Model version 3.0 shortwave and longwave radiation schemes [19].

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 [43] 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 [26] while plots of the bias corrected climatology can be found in [79].

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.

1.2 Review of the literature on heatwaves

This section provides a review of the existing literature on heatwave trends and indices applied to define heatwaves of relevance to NSW, including indices being applied or proposed for use by the Bureau of Meteorology.

Heatwaves represent a significant hazard in Australia on both humans and the environment and have been responsible for more deaths than any other natural hazard, including bushfires, storms, tropical cyclones and floods [66]. While human and natural systems have adapted to function best within an expected climatic range or thermal coping range (e.g., [3, 86]), heatwaves represent events outside this range which can push a system into a state of vulnerability beyond its coping range, leading to unexpected impacts. In physical systems, the presence of extreme heat can change the probability of occurrence of other extreme events (such as fire weather leading to bushfires). In addition, the functioning of living creatures can be stressed by increased temperatures leading to unfavourable health outcomes and even death. For example, extreme temperatures above $42°C$ in 2002 led to the death of over 3500 flying foxes in New South Wales [104] while in early 2009, an exceptional and devastating heatwave [71] and one of the worst bushfires on record

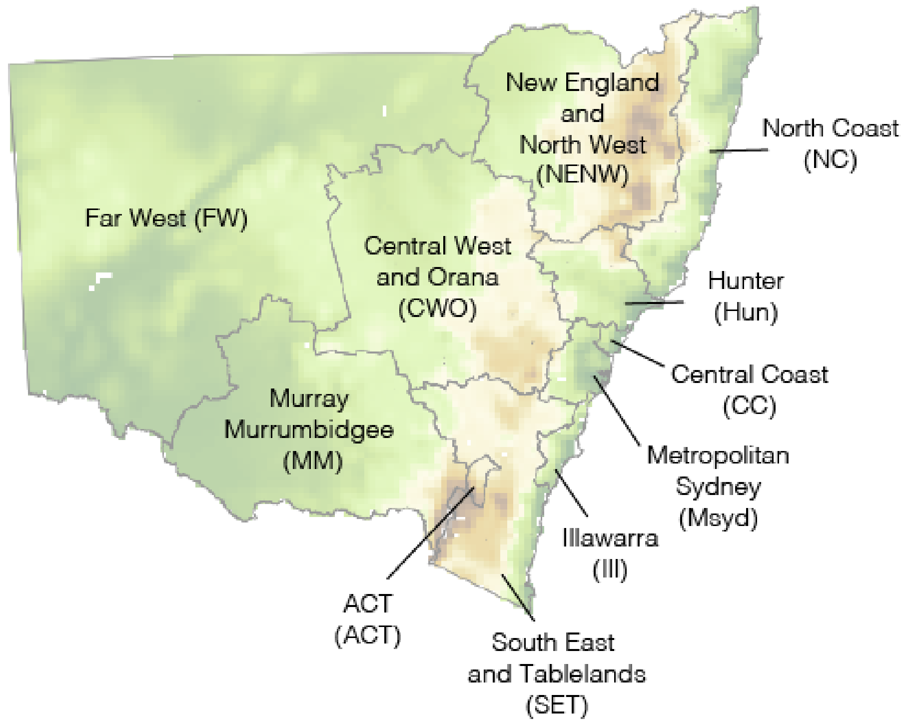

Figure 1.2: Name of state planning regions and abbreviations in NSW and ACT

struck southeast Australia, costing 173 lives as a direct result of the fires, with many more lives lost in the preceding heatwave [4, 66]. While these are immediate direct impacts from excessive heat, there may also be indirect repercussions from heatwaves, such as increases in the national health burden or insurance losses. In terms of the health burden, it is estimated that extreme temperatures contribute to the deaths of over 1,000 people aged over 65 each year across Australia [61] with Coates et al. [18] suggesting that 85% of fatalities in Australia due to natural hazards since 1900 are extreme heat-related. As far as human physiology is concerned, excessive heat leads to hyperthermia, a condition where the body produces or absorbs more heat than it dissipates [53]. When this thermoregulation breaks down it can lead to heat stroke and more serious conditions (for example as experienced by some tennis players during the Australian Open in 2014). Recent research has identified several features of the heat-health relationship relevant to Australia and New South Wales, such as temperature thresholds [12], heat sensitive conditions [50], lag effects [111], risk factors [103], and distinctiveness in regional responses [57, 97].

Excess heat can also affect crops and food security [60] and this has serious consequences for the Murray-Darling Basin - Australia's breadbasket - being the source of 40% of the nation's agricultural income, a third of the wheat harvest, 95% of the rice crop and other products such as fruit, wine and cotton. For example, during the 2014 heat event wheat, barley and canola yields likely dropped by 14%, 22% and 12% respectively [99]. In terms of insurance, the economic cost of the 2009 heatwave and bushfire disaster alone in southeast Australia was estimated to be US$1.3 billion [63]. Despite the obvious importance of understanding heatwave characteristics, although broadly defined as a period of unusually or exceptionally hot weather, there is currently no universal definition to classify heatwaves [76]. This has led to a plethora of studies using different metrics which cannot easily be compared. For example, some studies of heatwave (and extreme temperature) trends define heatwaves according to the number of days above a temperature threshold (i.e. percentile-based or absolute, such as a warm spell index) with a differing number of days contributing to a heatwave. Others focus on heatwave duration or frequency, some on intensity. Similarly, some studies analyse only temperature, using either daily or monthly averaged temperature extremes as a proxy for heatwaves in Australia [16, 17, 93], while others include other variables such as humidity. However a wide range of studies have assessed various aspects of historical trends in relation to heatwaves, either for Australia [94, 5, 77, 76, 74] or globally incorporating the Australian region [75, 22, 23] generally finding increasing trends particularly in frequency or duration.

To provide a more consistent analysis, Perkins and Alexander [76] recommended a framework that defines heatwaves based on aspects of their duration, frequency and intensity introduced in Nairn and Fawcett [64]. Perkins and Alexander [76] show that the frequency, intensity and duration of heatwaves have each increased over Australia since the 1950s but particularly since the 1970s. Different characteristics of heatwaves have increased across many regions of Australia since the middle of the 20th century [5], with trends for some characteristics accelerating in the most recent decades [76]. Each heatwave characteristic, however, shows different rates and patterns of change across Australia [85]. Over the period 1971-2008, larger observed trends in the hottest part of a heatwave suggest that heatwave intensity is increasing faster than the mean heatwave magnitude, with both the duration and frequency of heatwaves also increasing [76]. Using a warm spell duration metric, Donat et al. [23] show that heatwave frequency in Australia has been increasing since the early 20th Century, while a different heatwave duration index also shows a significant increase in heatwave frequency since the mid 20th century [5]. The Bureau of Meteorology employs the Excess Heat Factor or EHF definition for a heatwave [64, 66]. The EHF is a measure of heatwave intensity, incorporating two measures of excess heat. In this way EHF takes into account the expectation that people acclimatise to their local, recent climate (at least to some extent), with respect to its temperature variation across latitude and throughout the year, but may not be prepared for a sudden rise in temperature above that of the recent past [66]. The EHF has previously been used to study the impacts on human health from extreme heat events [54, 78]. Langlois et al. [54] examined the 2009 south-east Australian heatwave event using the EHF, concluding that peak morbidity and mortality rates in the region were experienced immediately after the highest EHF value. The EHF can provide a universal definition for heatwaves, and could be a powerful metric in projecting heat-related morbidity and mortality [54, 75]. It is also incorporated into the framework recommended by Perkins and Alexander [76]. For this reason, it is one of the metrics that we present in this report and a full description is outlined in chapter 2.

In New South Wales specifically, trends in the intensity of EHF-positive events, annual maxima EHF and the severity rate of EHF events have increased between 1958-2011 [66] although interestingly with a slight decrease in all of these metrics east of the Great Dividing Range. Over a similar period, trends tend to show up more strongly and statistically significantly in EHF measures across New South Wales compared to other heatwave measures (such as days when maximum temperature is above the 90th percentile) using the Perkins and Alexander [76] framework and broadly speaking duration/frequency measures tend to show stronger trends that amplitude measures.

These observed heatwave trends are analogous with the annual number of record hot days more than doubling across Australia since 1950 [2] coupled with a mean temperature increase of about 0.9 $^{\circ}C$ for the same period [1]. Notably, the frequency of record hot days has been more than three times the frequency of record cold days over the past decade [92]. The observed heatwave trends are consistent with trends for other regions globally [85]. What all studies therefore have in common —irrespective of the heatwave characteristic studied or the metric used —is that records show that trends in the frequency, intensity and duration of heatwaves have all increased since the mid to late 20th century across most of Australia including New South Wales.

In the context of this report we will extend some of these measures to look at trends over the period from 1911 to 2013. In the next chapter we describe the methodology adopted to identify and measure different heatwave characteristics based on our literature review.

Chapter 2

Methodology

In this section, we describe the methodology adopted to identify and measure different heatwave characteristics. Broadly speaking, heatwaves are defined as particularly hot conditions sustained over a number of consecutive days. However, heatwaves are complex extreme events to measure because multiple factors need to be accounted for in their definition. Therefore, a number of indices have been proposed to define heatwaves, although not all of them are equally suitable to study the phenomenon in its full complexity [76]. In this report, we have chosen the CAWCR Excess Heat Factor (EHF) metric [65, 64] because it incorporates most of the factors that need to be considered and provides a measure of different heatwave features. It is also the index chosen by the Bureau of Meteorology to operationally define and monitor heatwaves.

The underlying idea of EHF is to estimate the excess of heat accumulated over three consecutive days through two indices. The first index is a measure of acclimatisation (EHIaccl) and compares the 3-day average temperature with the previous 30-day average temperature:

$$EHI_{accl} = (T_i + T_{i-1} + T_{i-2})/3 - (T_{i-3} + \cdots + T_{i-32})/30 \quad (2.1)$$

where T_i is the daily mean temperature of day i, calculated as the mean between daily maximum (tmax) and minimum (tmin) temperature on a daily 9am to 9am cycle, such that tmin occurs after tmax for day i. The second index is denoted as "significance" (EHIsig) and determines how extreme temperature conditions are by comparing the 3-day average temperature with the 95th percentile of the daily mean temperature calculated over the period of reference (base period) and is denoted by T_{95}:

$$EHI_{sig} = (T_i + T_{i-1} + T_{i-2})/3 - T_{95} \quad (2.2)$$

The original definition used the period 1961-1990 to calculate the percentile, but in this report we use the 1990-2009 period. The reason for this change is that we need to match the NARCliM present climate period and thus make the results comparable across datasets. Further discussion on the impact of the base period choice is provided in the next section.

It is important to note that future climate heatwaves are obtained using the same reference period (1990-2009) to calculate the percentiles and thus future changes can be directly interpreted with respect to current climate conditions.

These two indices are combined to compute the final EHF in the following equation:

$$EHF = max(1, EHI_{accl}) \times EHI_{sig} \tag{2.3}$$

EHF has $^{\circ}C^2$ units because it is the product of two temperature anomalies. A heatwave is identified when EHF takes values larger than 1 over three or more consecutive days. This ensures that the conditions are extreme and that they persist long enough for the event to be considered a heatwave. Once heatwave events are identified, EHF provides us information to quantify multiple heatwave characteristics, such as their intensity, frequency and duration. In this report we will analyse the following metrics:

- **HWA**: amplitude of the hottest day in the hottest heatwave event in a year. Maximum EHF of the heatwave with the highest average EHF in a year ($^{\circ}C^2$)
- **HWM**: average magnitude across all heatwaves in a year. Mean EHF across all heatwave days in a year ($^{\circ}C^2$)
- **HWN**: number of heatwave events in a year
- **HWF**: number of heatwave days expressed as the percentage of days in a year.
- **HWD**: duration of the longest heatwave in a year (days)

The 95^{th} percentile at each location is calculated over the entire year, thus virtually all heatwaves estimated using this EHF definition occur during summer months. Years are then assumed to begin the 1st of July, so that heatwave indices for a given summer are assigned to a single year, instead of being split into two years. In this report, we have decided to denote years by the corresponding December. That is, heatwave indices for year 1990 correspond to indices calculated using the period from July 1990 to June 1991. It should also be noted that according to this convention, 20-year simulations spanning natural years (e.g., NARCliM simulations) have an incomplete year at the end, which needs to be discarded from the analysis leading to 19 years (summers) being considered.

HWA and HWM are difficult to interpret in their original units and thus an alternative measure is also presented here. The 3-day mean temperature is extracted for all days contributing to HWM and the average is calculated. Similarly, the 3-day mean temperature corresponding to the day when HWA occurs is also extracted. As such, we obtain two new indices (HWMt and HWAt) that are actual temperatures ($^{\circ}C$) and therefore easier to interpret.

Finally, in addition to EHF related metrics, the number of days in a year when maximum temperature is above 40$^{\circ}C$ is also calculated. The resulting index (TX40) is an indicator of the occurrence of particularly hot conditions regardless of their persistence in time. Despite not being strictly heatwaves, changes in the frequency of particularly hot days are of relevance for many sectors, such as health, energy and transport.

Both EHF indices and TX40 are calculated using bias-corrected model outputs. In the case of EHF indices this has only moderate impact on the results because they are based on percentiles, but it is of substantial importance in the case of threshold-based indices such as TX40. Further discussion on this decision is provided in section 4.

Chapter 3

AWAP Observed Climatologies

In this chapter we present an analysis of observed heatwave characteristics as obtained using temperature from the Australian Water Availability Project (AWAP), produced by the Bureau of Meteorology and CSIRO [43]. AWAP is a daily gridded dataset at a spatial resolution of 0.05° by 0.05° (approximately 5 km by 5 km) covering Australia. It was constructed using an anomaly-based approach to interpolate information from meteorological stations onto a regular grid for a range of variables including daily maximum and minimum temperature. AWAP temperature records start in 1910 and extend up to the present, being constantly updated with the latest observations. Since years are considered to start the 1st of July in order to preserve continuity of the summer season (see Chapter 2), the AWAP record extends from 1911 to 2013 for our purposes.

The number of temperature stations used to generate AWAP varies through time, but during most of the NARCliM reanalysis period (1950-2009) it ranges from ∼300 to 800 stations. Substantially fewer stations were available for the years before 1956 and in some cases the number of stations used decreases to ∼100. A more detailed description of the methodology is provided in [43].

The calculation of EHF requires the selection of a reference period to calculate the climatological percentiles. While the original definition used the period 1961-1990 as the base period, in this report we have selected 1990-2009 because it is the NARCliM present climate period shared by all runs. Therefore, it is the most suitable period to make indices comparable across datasets. Indices calculated over the period 1990-2009 from AWAP using both reference periods are examined here.

The observed climatology of TX40 over the present climate period (1990-2009) from AWAP maximum temperature is also presented here.

3.1 Present-Day (1990-2009) AWAP Observations

This section contains present-day (1990-2009) heatwave indices from AWAP observations using the reference period 1990-2009. Present-climate indices from AWAP calculated using the original definition reference period 1961-1990 are also presented for comparison.

Figure 3.1 shows the present (1990-2009) climatologies for all indices using the 1990-2009 reference period. Both heatwave amplitude (HWA) and mean magnitude (HWM) show a similar spatial pattern with higher values towards the southwest of NSW and lower values along the coast, particularly to the north. The heatwave peak reaches on average annual values in the range 40-

48°C^2 in Murray Murrumbidgee region, and remains in the interval 8-16°C^2 along the coast. The mean magnitude climatology is 15 to 17.5°C^2 in areas of the southwest and only 2.5 to 5°C^2 in the south and north coast. The amplitude and magnitude expressed in temperature-equivalent indices (HWAt and HWMt) have a substantially different spatial pattern, similar to maximum temperature spatial distribution [79] in that they are strongly linked to topography and distance to the ocean. On average, highest HWAt and HWMt are recorded in the northwest corner (34-37°C and 31-34°C, respectively), whereas the lowest values occur along the mountains, particularly to the south (16-19°C for HWAt and 13-16°C for HWMt).

The average number of heatwave (HWN) events is relatively homogeneous across NSW and ACT and takes values between 1.6 and 2.8 heatwaves each year. In terms of the percentage of heatwave days (HWF), they are below 6% (less than 21 days) over the entire region and the spatial distribution is also quite uniform.

On average, heatwaves tend to be longer (HWD) in the centre of the state, where the longest heatwave in a year typically lasts 7 to 8 days. This contrasts with values in south and central coast, which stay below 5 days. Longest heatwaves in a year are in the 5-7 days range over most of the state.

Finally, the index measuring number of days with maximum temperature above 40°C has a clear pattern similar to HWAt and HWMt, with the highest values (up to 30 days/year) concentrated in the north west (Far West region) and the lowest values in the mountainous areas to the south east ($<$1 day/year).

Figure 3.2 shows the present climatologies for all indices, but using the 1961-1990 reference period following the original definition of EHF. In this report we have chosen to use the 1990-2009 period to make all datasets comparable because GCM-driven present-climate simulations span those years. Differences between present climatologies (1990-2009) from AWAP for all indices using both periods are shown in Figure 3.3.

Metrics measuring heatwave amplitude and mean magnitude are relatively similar using both reference periods. Over most of NSW and ACT differences in HWA are below 6°C^2, with the exception of a few areas in the interior where the disagreement is larger. The mean magnitude is very similar using both periods and differences are within -3 to 3°C^2, with most areas showing absolute differences smaller than 1°C^2. The temperature equivalent amplitude and magnitude show decreases of less than 1 °C across the state.

Differences in the frequency of heatwave days (up to 3%, or 10 days) and heatwave events ($<$2 events) are larger, and so is the mean duration of the longest heatwave (up to 3 days). Using a different base period has an effect on the percentiles (Fig. 3.4), which in turn affects the number of days flagged as heatwave days. A slight shift in the percentile threshold may substantially change the number of days considered as heatwaves.

Overall, using the 1961-1990 reference period results in more frequent and longer heatwaves, but the intensity of heatwaves remains comparable with that calculated using the 1990-2009 reference period. It should be noted that the impact of these differences on projected changes is very limited because the base period is simply used as a baseline to represent present climate conditions and refer future projections to them.

The number of days with maximum temperature above 40°C is the same in both cases because no reference period is required for its calculation.

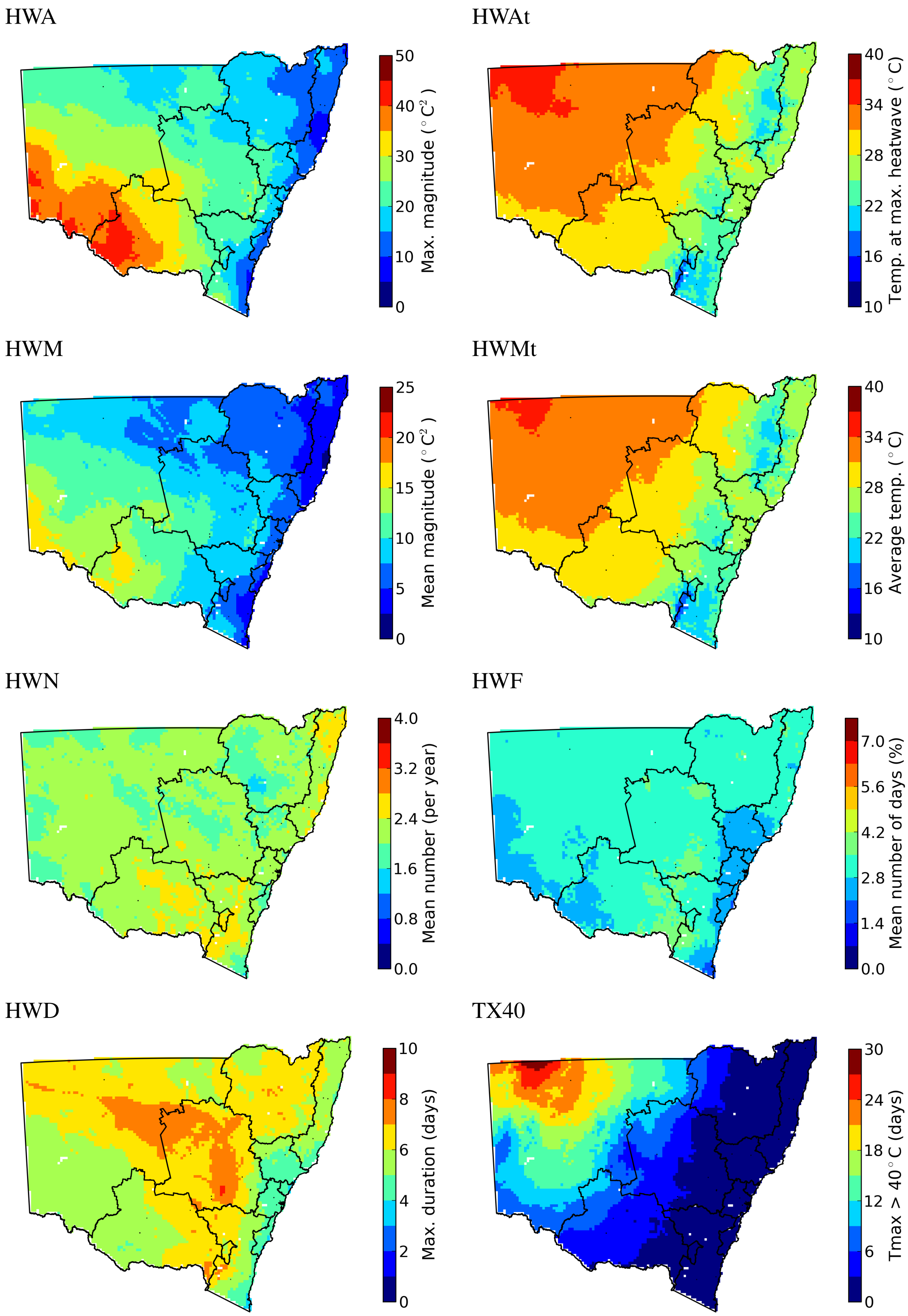

Figure 3.1: Present-climate (1990-2009) heatwave indices from AWAP observations using the 1990-2009 reference period.

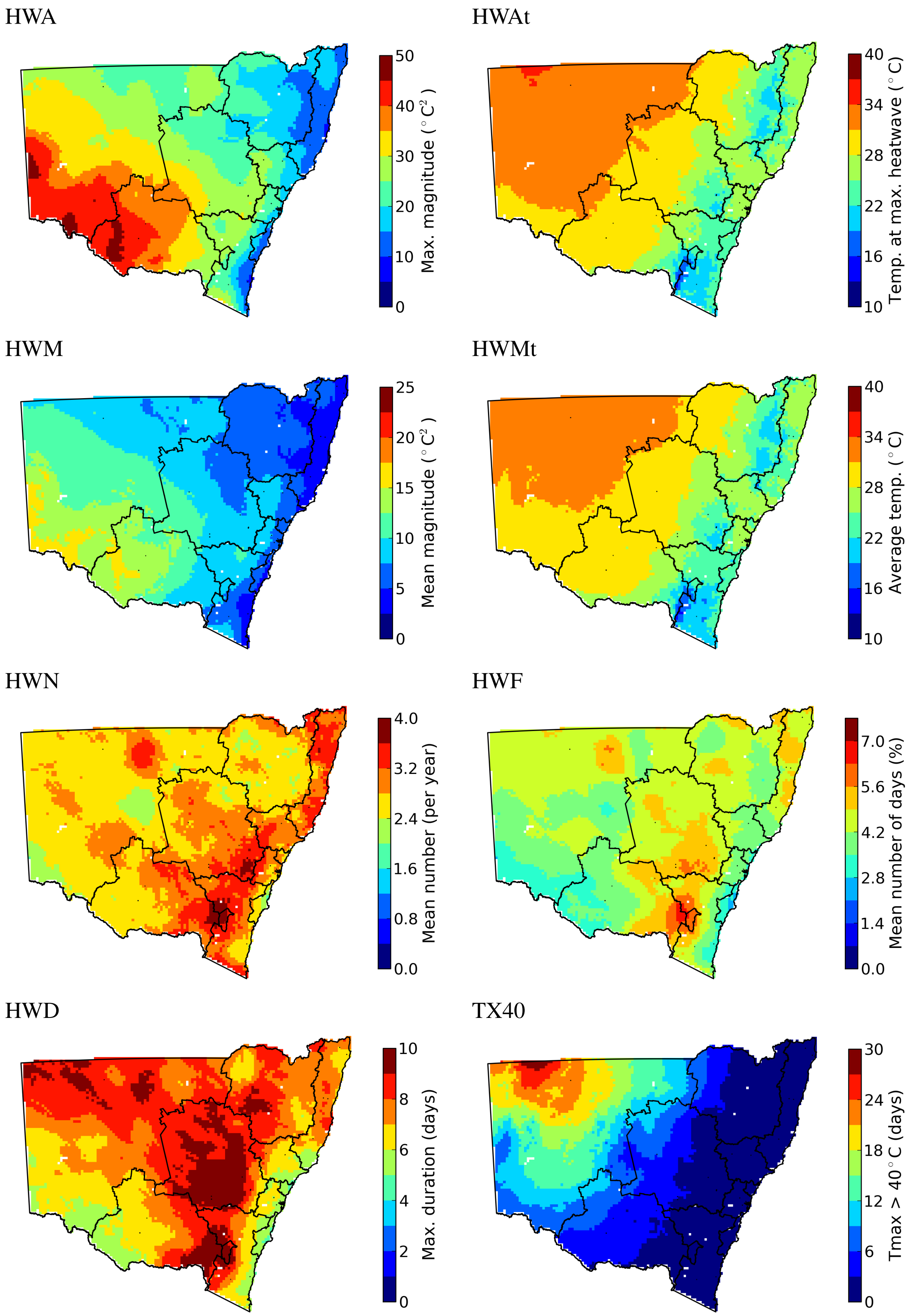

Figure 3.2: Present-climate (1990-2009) heatwave indices from AWAP observations using the 1961-1990 reference period.

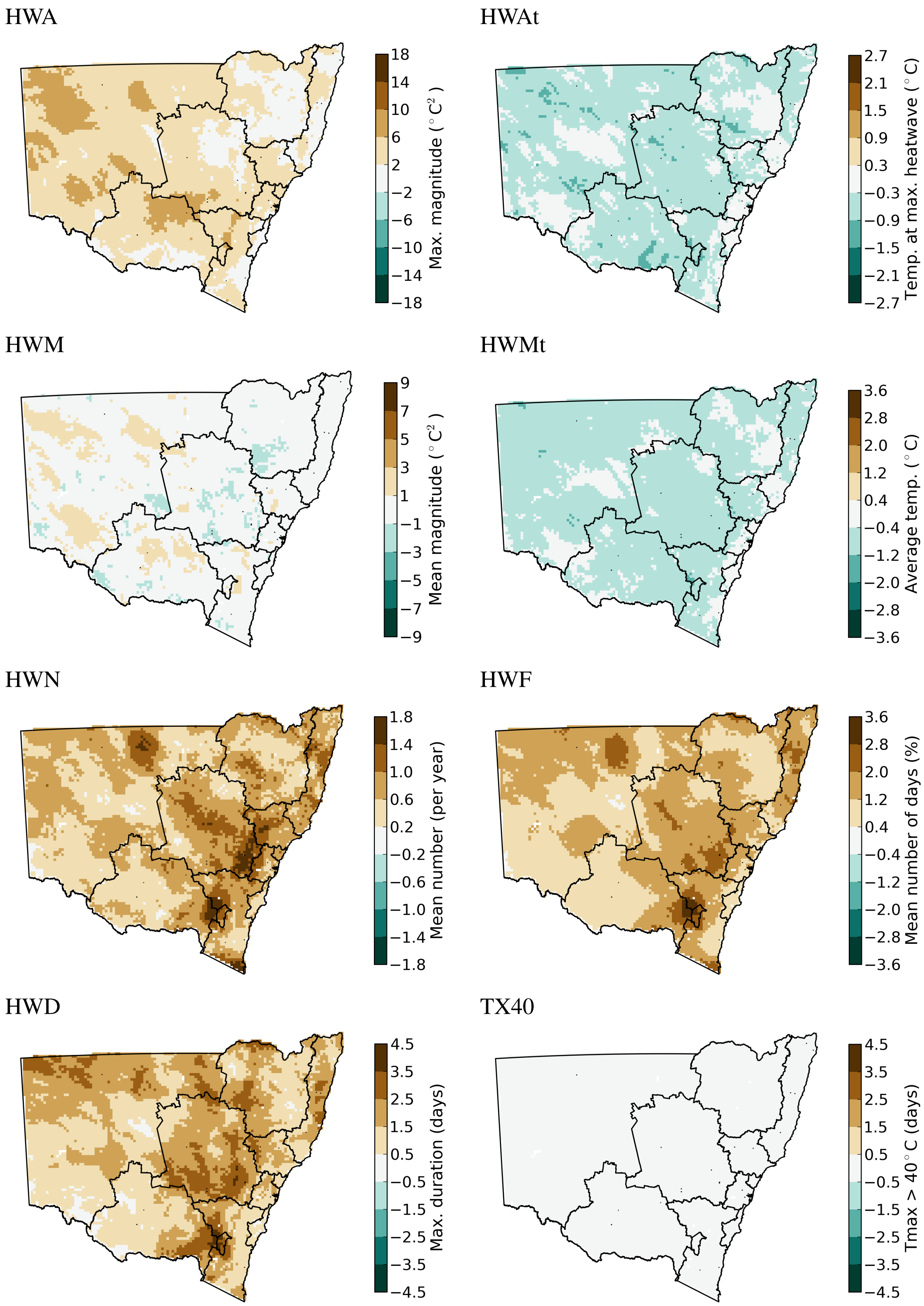

Figure 3.3: Differences in present-climate (1990-2009) heatwave metrics between indices calculated with using the 1961-1990 reference period minus indices using the 1990-2009 reference period.

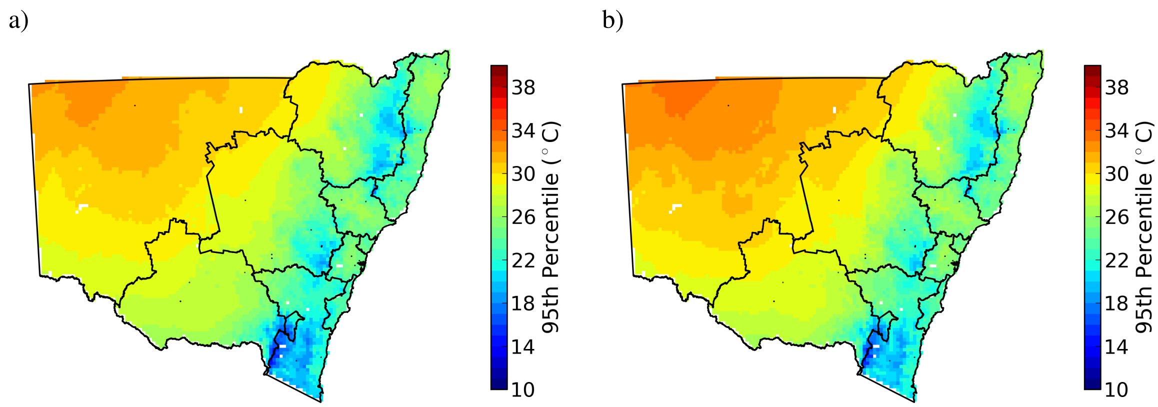

Figure 3.4: 95th percentile of mean temperature using 1961-1990 (a) and 1990-2009 (b) base periods.

3.2 Entire observational period (1911-2013) AWAP Observations

This section provides a description of how the duration, frequency and intensity of heatwaves across NSW/ACT varied over the full observational record and recent past according to AWAP dataset.

In the resulting maps, trends are estimated using a linear trend model employed in the Intergovernmental Panel on Climate Change Fifth assessment Report [40]. 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.[21] (Supp. Mat. pp 10-13).

Figure 3.5 shows the decadal trends in each of the EHF heatwave characteristics (described in Chapter 2) over the period 1911 to 2013 relative to the period 1990 to 2009 using the relevant units for each characteristic. All heatwave characteristics indicate increasing trends over most of NSW. Trends are statistically significantly increasing along the eastern seaboard for the duration/frequency characteristics and in some western parts of NSW and are up to 0.5% per decade in the south-east of the state in heatwave frequency (HWF - equivalent to about 18 additional heatwave days over the record in that region). Where trends are increasing results suggest that there are about 4-11 more heatwave days in a year now than there were at the beginning of the 20th century. For intensity characteristics (e.g. HWA, HWM) most of the statistically significant increasing trends occur along the Great Dividing Range. Increases of up to about 25$^\circ C^2$ over the whole 1911 to 2013 period are seen in HWA over parts of the Hunter Valley or looking at it another way about a 1.4$^\circ C$ rise in the hottest part of the heatwave on average (see HWAt trend in Fig 3.5). There are almost no statistically significant decreases in heatwave characteristics except for a small region in central northern New South Wales when considering average heatwave magnitude (HWM). Figure 3.5 also shows that in this region there is also a significant decreasing trend in the number of days above 40$^\circ C$ (TX40). However caution needs to be applied when interpreting this result (see below).

Figure 3.6 shows similar plots but now trends in EHF are calculated over the period 1911 to 2013 relative to the period 1961 to 1990. The spatial patterns of trends are very similar to Figure

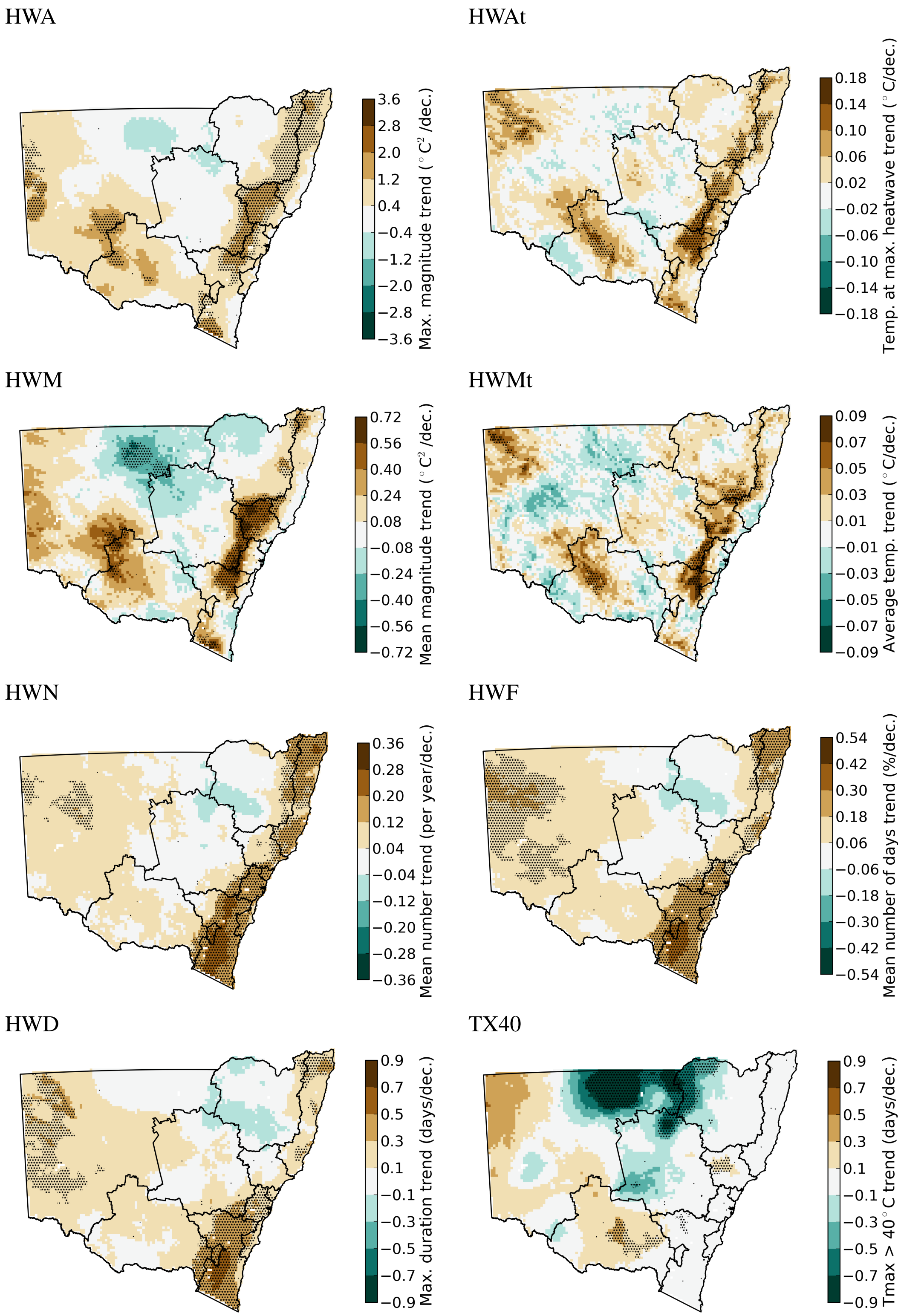

Figure 3.5: Trends in heatwave metrics over the full AWAP record with using the 1990-2009 reference period. Stipling indicates that the trends are significant at the 5% level using a Mann-Kendal test.

3.5 and broadly speaking of similar magnitude. There are a few exceptions. Heatwave frequency (HWF) has larger and more statistically significant trends relative to this period than to the 1990 to 2009 period along the South Coast, the Snowy Mountains region and the ACT. The statistically significant decline in average heatwave magnitude (HWM) that we saw in Fig. 3.5 is no longer seen in Fig. 3.6.

It should be noted that caveats need to be added to the interpretation of the trends shown in Figs 3.5 and 3.6. For a start the meteorological data used in AWAP are derived from the Bureau of Meteorologys database ADAM (Australian Data Archive for Meteorology) which exhibits an abrupt increase in data availability in the mid-1950s [43]. What this means is that the AWAP data are more reliable after this time and by extension (due to the abrupt data increase introducing likely inconsistencies into the daily temperature records in AWAP), this will adversely affect trends that are calculated over the whole 1911-2013 period. This will likely have a greater impact in regions where data are sparse or regions where data were sparse prior to the mid-1950s but are now plentiful. In addition, even the introduction of an individual site in a data sparse region can introduce a substantial inhomogeneity (i.e. an artificial change in the temperature record that is not due to a change in climate) into the resulting daily AWAP timeseries (e.g. see King et al.[51]). For this reason we also apply caution to the results which indicate that heatwave intensity characteristics have increased significantly along the Great Dividing Range over the period 1911 to 2013 since this is a data sparse region with steep topography.

Because of this issue, we also calculated trends over the 1958 to 2013 period for each of the heatwave characteristics and TX40 (not shown) in order to examine a period where we have more confidence in the robustness of the underlying AWAP data. These agreed well with the results shown in Figure 11 of Nairn and Fawcett [66] (which showed a similar metric to HWM) even though in that study EHF was relative to a 1971-2000 climatology and they used a slightly different trend calculation method. That is, across most of NSW and ACT, mean heatwave magnitude increased (mostly up to a maximum of $0.5°C^2$ per decade) while there was a decline in HWM of around the same magnitude east of the Great Dividing Range. This region on the Eastern Seaboard has been found to operate as a separate climate entity where climate variability is not majorly influenced by ENSO unlike the rest of the state and territory [87]. A similar spatial pattern was seen in the trends in HWA over this shorter period too with large statistically significant trends across much of the state and territory in the frequency/duration characteristics (HWN, HWD, HWF) which agrees well with the results from Perkins and Alexander [76]. In addition, TX40, which saw a significant decline over the period 1911 to 2013, indicates a significant increase in days above $40°C$ in the same region over the period 1958 to 2013.

So to conclude, heatwave characteristics have increased across much of NSW and ACT with only a few exceptions since 1911 with the most significant increases occurring in the east and far west of the state. A small region where there have been significant declines is found in the northern central part of NSW in TX40 and mean heatwave magnitude (HWM) but note that this is only when EHF is calculated relative to the 1990-2009 reference climatology. More robust increases have been noted since 1958 across most of the state when data are more reliable, except in a region on the eastern seaboard which is separated physically and climatologically from the rest of the region by the Great Dividing Range and has experienced a decline in heatwave intensity characteristics since the mid-20th century. Results over this later period agree well with other published literature.

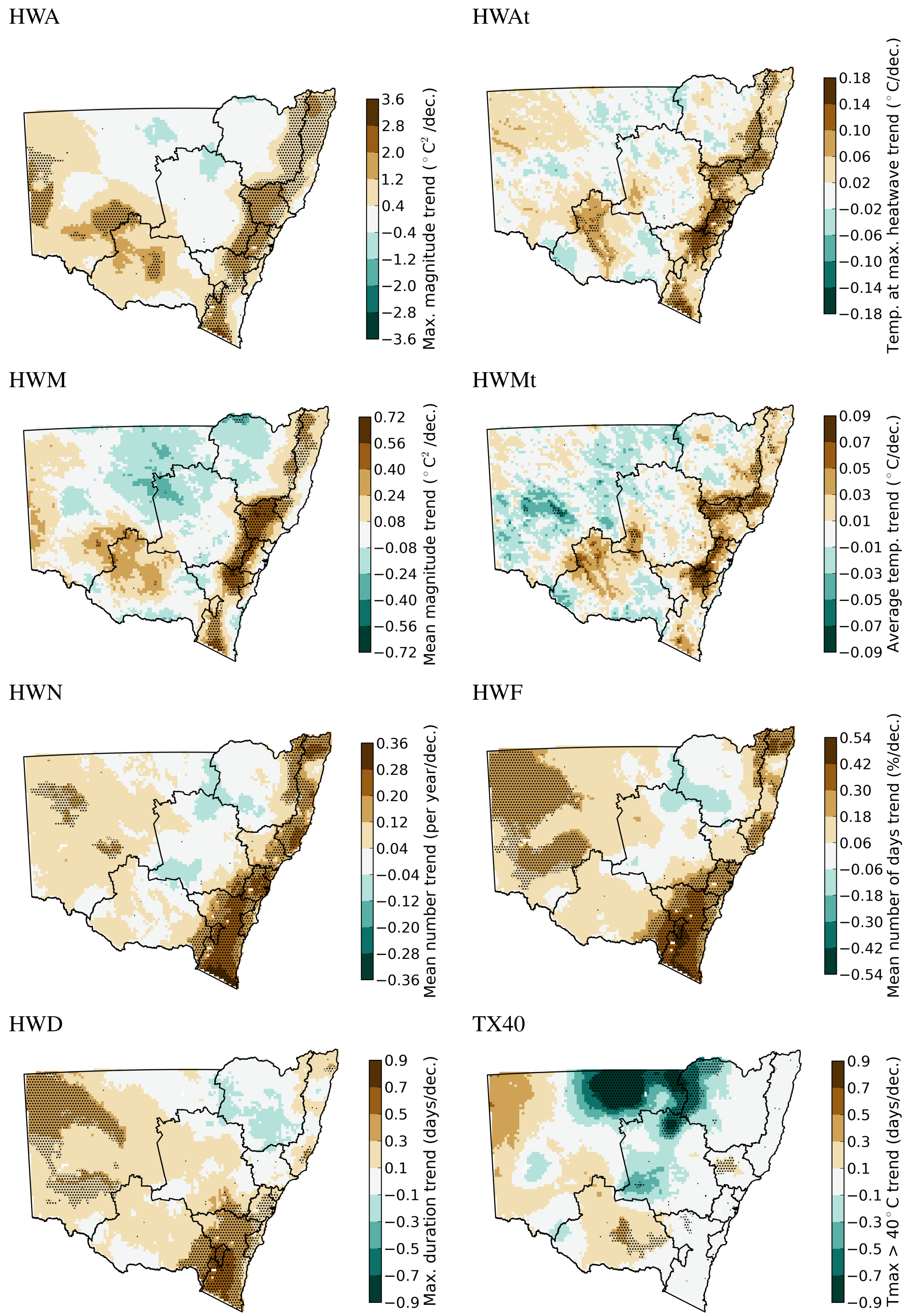

Figure 3.6: Trends in heatwave metrics over the full AWAP record with using the 1961-1990 reference period. Stipling indicates that the trends are significant at the 5% level using a Mann-Kendal test.

Chapter 4

Present climate heatwaves from NARCliM

This chapter presents heatwave index climatologies from the bias-corrected NARCliM ensemble mean for present climate (1990-2009). It also provides a comparison of NARCliM outputs with AWAP to determine the ability of the NARCliM ensemble to reproduce observed heatwave characteristics. Only results obtained from the bias-corrected model outputs are shown here. Model outputs were corrected using a quantile mapping approach through a gaussian fitting of the cumulative probability functions (see [26] for a full description of the bias-correction methodology). Heatwave climatologies as derived from the original and the bias-corrected outputs are very similar because the algorithm used to measure the heatwaves is based on a percentile approach that implicitly removes most of the biases. As a consequence, the choice of the original or the bias-corrected data does not affect the conclusions of this report. The exception is the climatology of the TX40 index because it is based on an absolute threshold (i.e., 40$^\circ C$) and thus even minor biases would have a major impact on the values of this index.

4.1 Regional Model Output: present climate (1990-2009)

This section is devoted to the analysis of present-climate heatwave indices as simulated by the NARCliM ensemble.

Figure 4.1 shows the NARCliM ensemble mean of all heatwave indices for present climate (1990-2009). The average heatwave peak (HWA) from the NARCliM ensemble ranges from 16 to 24$^\circ C^2$ in the north of NSW to 32 to 40$^\circ C^2$ in the south. A similar spatial distribution is obtained for the mean magnitude of heatwaves (HWM) with the highest values located in the southern part of South East and Tablelands region (up to 20$^\circ C^2$) and the lower mean magnitude in New England and North West and areas of the North Coast. The overall latitudinal gradient is explained by the largest variability in temperature at higher latitudes compared to areas near the tropics, which produces longer tails in temperature probability distribution functions. Mean temperature for the peak (HWAt) and for the mean magnitude of heatwaves (HWMt) have a pattern that is consistent with the spatial distribution of the maximum temperature [79] with larger values in the northern Far West (34-37$^\circ C$ for both HWAt and HWMt) and lower in the high-elevation areas in the south (16-19$^\circ C$ for both indices).

According to NARCliM outputs, the northern interior of NSW is where heatwaves events (HWN) and the percent of heatwave days (HWF) are more frequent (2.0-2.4 heatwaves/year and

$\sim$3% of days), while the south coast and pockets in the southwest show the lowest number of heatwaves per year ($<$1.6 heatwaves/year). A similar spatial structure is obtained for the average duration of the longest heatwave in a year, with longer heatwaves over much of the north (5-6 days) and shorter ones along the south coast (2-3 days).

The index that measures the number of extremely hot days (TX40) is distributed very similar to HWAt and HWMt, and therefore to maximum temperature. In the northern Far West, maximum temperature exceeds the 40$^{\circ}C$ threshold as many as 30 days/year, whereas in eastern third of NSW and ACT temperatures over 40$^{\circ}C$ are recorded less than 5 days/year on average. Indeed there are regions along the coast without days experiencing temperatures above 40$^{\circ}C$.

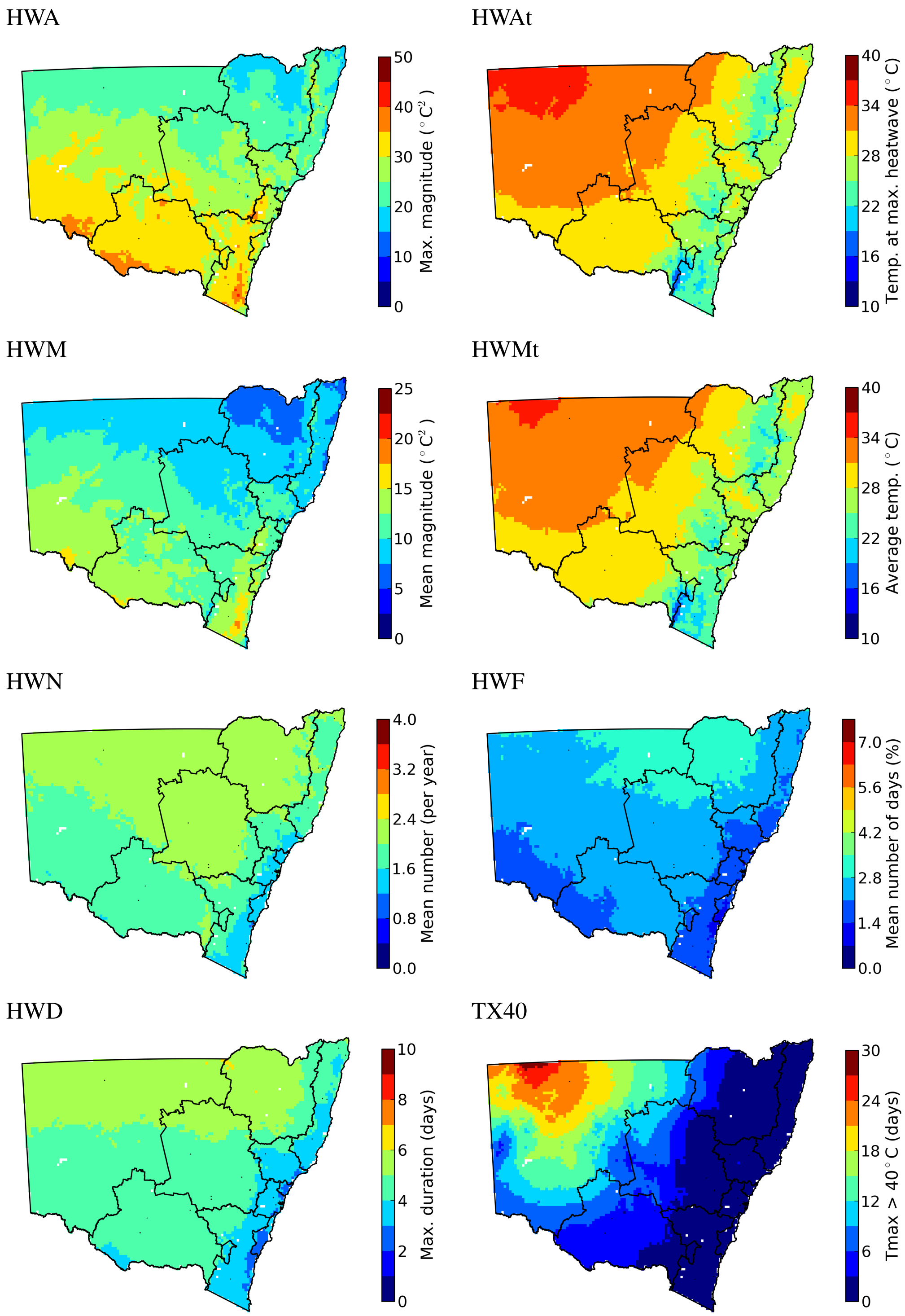

Figure 4.1: Present-climate (1990-2009) heatwave indices from the NARCliM ensemble using the bias-corrected outputs. NARCliM ensemble means of heatwave indices.

4.2 Biases: 1990-2009 Regional Model Output - Observations

This section contains a comparison between climatological heatwave indices from the NARCliM ensemble and AWAP observations. Biases in the climatologies of all indices are examined. Biases are defined as the difference between the climatological average from the NARCliM ensemble and the AWAP observations for the period 1990-2009, both calculated using the reference period 1990-2009.

Figure 4.2 shows the difference between simulated heatwave indices from the NARCliM ensemble and AWAP observations. The coloured contours provide information on differences between the NARCliM ensemble mean and the AWAP data, while the stippling indicates the level of model agreement. The NARCliM ensemble-mean biases are separated into three categories (a) less than half of the models show a significant bias (insignificant areas, ensemble-mean bias 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 sign of the bias (significant agreeing areas, stippled with an asterisk ("*") symbol), and (c) at least half of the models show a significant bias and less than 80% of significant models agree on the sign of the bias (significant disagreeing areas, stippled with a forward slash ("/") symbol). Non-stippled areas thus indicate that biases are within the interannual variability and is the preferred outcome. For each index, the significance of biases of individual models was estimated with respect to the interannual variability using a Student's t-test at the 5% significance level.

The NARCliM ensemble mean produces heatwaves that are too intense along the coast, especially in the north and south, in terms of both the amplitude (HWA, 14-18$^\circ C^2$) and the mean magnitude (HWM, 7-9$^\circ C^2$). It also simulates less extreme heatwaves peaks (HWA) and, to a lesser extent, milder mean heatwave magnitude in the southwestern corner. However, most of these differences are not statistically significant compared to the observed variability. Biases in the mean magnitude of heatwaves are significant only over very isolated areas in the northern and southern parts of the Great Dividing Range.

The temperature-equivalent of heatwave amplitude (HWAt) shows a similar spatial distribution of biases: HWAt is also slightly overestimated along the coast (0.5-2.5$^\circ C$) and underestimated over limited areas in the southwest (-0.5 to -1.5$^\circ C$). However, similar to HWA, biases are overall within the expected range of variability with very few exceptions. Mean temperature during heatwave days (HWMt) in the NARCliM ensemble agrees with AWAP in most regions and only small overestimations are produced along the coast (1-3$^\circ C$). Very small biases (between -1 and 1$^\circ C$) in New England, the North West, and Murray Murrumbidgee regions are statistically significant despite their magnitude.

The comparison between the NARCliM ensemble and AWAP suggest that simulations are producing less frequent heatwaves (HWN) in the south and along the coast (up to 1.0-1.4 less heatwaves/year). New England and North West, and Central West and Orana regions, are exposed to slightly more heatwaves in NARCliM simulations than AWAP (0.2-0.6 heatwaves/year). Only small pockets in the southeastern corner are subjected to statistically significant biases. In terms of the number of heatwave days, NARCliM simulates slightly lower values over most of the state (between 0.4 and 1.2% less heatwave days per year), but once again the significant biases are confined to areas in the south where biases are moderately larger (1.2 to 2.0% less heatwave days per year).

Similarly to the frequency of heatwaves days, NARCliM tends to produce shorter heatwaves over most of the state. Longest yearly heatwaves in NARCliM lasts on average 0.5 to 2.5 less days than in AWAP over large areas of NSW and ACT. Sectors in the interior and the southern mountains show larger biases and such heatwaves are between 2.5 and 3.5 days shorter in NARCliM than AWAP. Except for those areas prone to larger biases, differences are generally not significant compared to interannual variability.

Differences between the NARCliM ensemble and AWAP in the number of extremely hot days (TX40) are very small across the domain, which is not surprising considering that NARCliM outputs were bias-corrected toward AWAP. Nonetheless, there are residual biases in the north west (3-5 days per year) that are not significant and thus explained within the range of observed variability. It should be remembered that AWAP is less reliable towards the northwest due to the scarcer number of stations available.

4.3 Regional analysis: Regional Model Output and observations

The heatwave index climatologies from the NARCliM ensemble and AWAP for each of the regions (see Fig. 1.2) are shown in Figure 4.3. This region-based representation also shows the variability across NARCliM ensemble members for each index (i.e., box plots) across the various regions. Values from AWAP serve as observational reference and are also included (black squares).

In consistence with previous figures, the NARCliM ensemble tends to underestimate the intensity of heatwaves (HWA and HWM) in most regions. Such deviations in the intensity are particularly noticeable in regions along or near the coast (SET, Ill, NC, CC and MSyd), where the AWAP mean values lies outside of the range of the NARCliM ensemble members. On the other hand, the NARCliM ensemble is very close to observations in regions to the interior (FW, MM and CWO), which are also the largest regions. There is a substantial spread across NARCliM members, particularly in areas over the southeast, which makes some of these regions climatologically indistinguishable in NARCliM while significantly different in the observations (e.g., Ill and CWO for the HMA index). The spread is partly due to the definition of indices, where the percentiles are calculated for each location and thus differences between regions mostly reflect their temperature variability, and not the relative difference in temperature magnitude.

The temperature-equivalent indices for heatwave peak (HWAt) and magnitude (HWMt) show a much better agreement of the NARCliM ensemble with observations and among NARCliM members themselves, although this is likely conditioned by the bias-correction. Despite correction, simulations still show a tendency to overestimate these metrics, but according to Figure 4.2 the remaining biases are within the interannual variability and thus statistically non-significant. Differences between regions are more apparent in this case because the metrics are related to absolute temperature values. Both observations and the NARCliM ensemble produce higher values of both HWAt and HWMt in the interior (FW, MM and CWO), with HWAt reaching up to 33$^{\circ}C$ (3-day temperature mean), while the lowest values take place in elevated regions (ACT, HWAt$\sim$23$^{\circ}C$) or regions to the southeast (SET and Ill, HWAt$\sim$24-25$^{\circ}C$).

The number of heatwaves (HWN) and heatwave days (HWF) is very similar across regions. According to AWAP, all regions experience $\sim$2-2.5 heatwaves/year on average, whereas the NARCliM ensemble mean is slightly lower, with frequencies as low as 1.5 heatwaves/year in Illawarra (Ill) region, where the spread across model is also quite large. Once again, NARCliM members seem to perform better in inland regions (FW, CWO, and NENW), although for most regions the

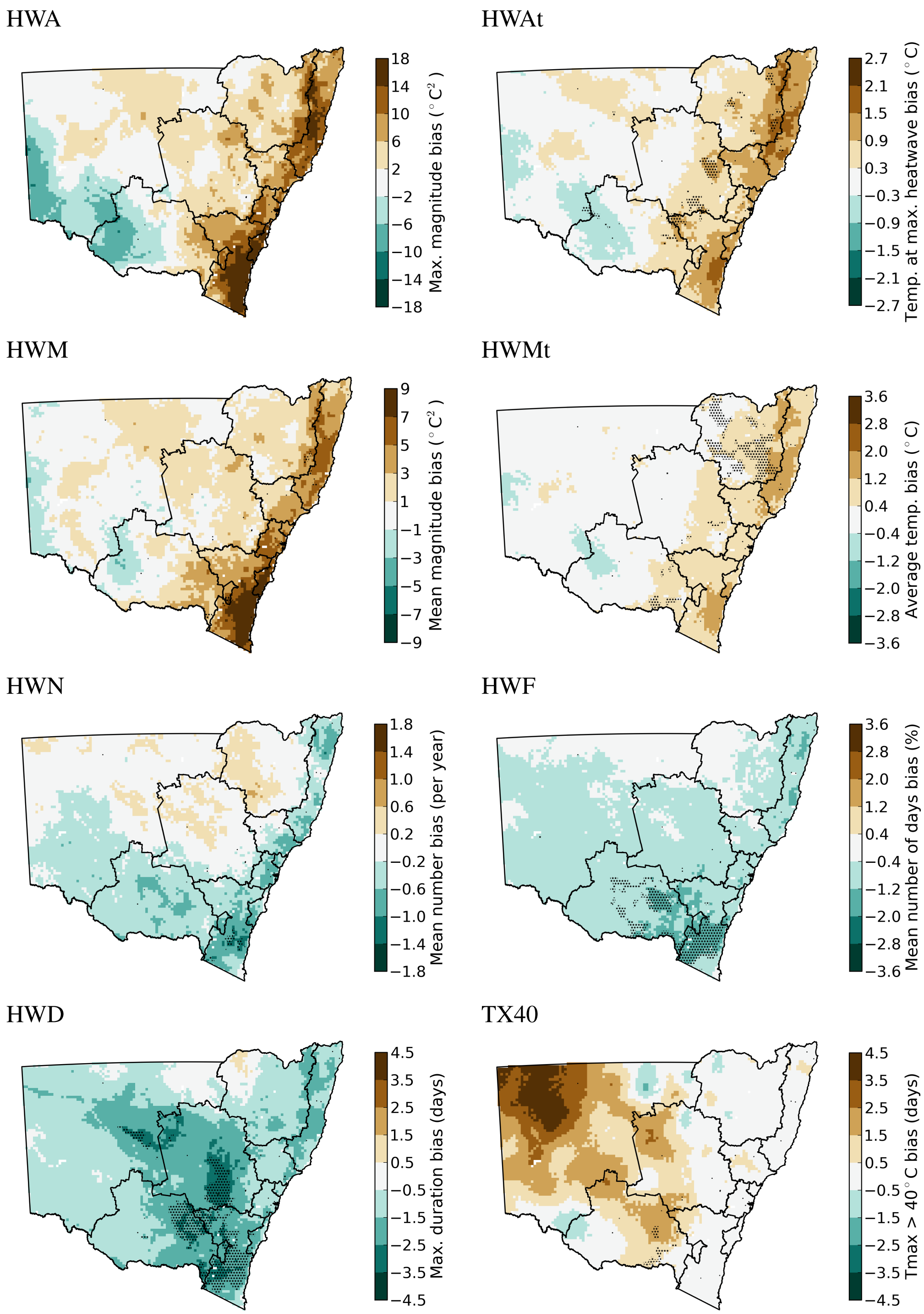

Figure 4.2: Bias of each heatwave index between the NARCliM ensemble mean and AWAP observations for present climate (1990-2009) using the 1990-2009 reference period. Stippling indicates areas where the biases are significant for at least half of the models and at least 80% of them agree on the sign of the bias (see Section 4.2 for details).

observations are within the NARCliM range. NARCliM simulations show better agreement in these regions too, while spread across members tends to be larger in regions over the southern half of the coast. The frequency of heatwave days (HWF) presents a similar variaiblity across regions to HWN, although differences in the NARCliM spread are not as marked between regions. NARCliM also tends to underestimate the heatwave day frequency, especially in southeastern regions. Both NARCliM members and observations show lower number of heatwave days in regions along the southern half of the coast (Ill, CC, Msyd), but they disagree in the southernmost region (SET) because observations rank it among the regions with highest frequency (above 3% of days) by contrast with NARCliM mean. However, the NARCliM ensemble still produces a good estimate of heatwaves frequency as evidenced the non-significance (Fig. 4.2) of most biases when compared to observed variability.

The duration of the longest heatwave in a year (HWD) is also underestimated in all regions by the NARCliM ensemble. This is directly related to the underestimation of heatwave days. Nonetheless, the differences among regions observed in AWAP are well reproduced by the NARCliM ensemble, with the longest heatwaves concentrated in FW, CWO and NENW. The exception is ACT, a region that AWAP places among those with the longest heatwaves on average ($\sim$6 days), while the NARCliM ensemble does not ($<$4 days). The spread across NARCliM is generally small in all regions, with the inter-quartile range being 1 day for all regions except for the Far West, where the range is slightly larger.

Finally, the number of days when maximum temperature exceed $40°C$ (TX40) is very well captured by the NARCliM ensemble. Similar to HWAt and HWMt, such accuracy is partly obtained through the bias correction. In most regions, temperature exceeds $40°C$ less than once a year. Only regions away from the coast (FW, MM, CWO, NENW and Hun) experience a larger number of very hot days, according to both AWAP and the NARCliM ensemble. The Far West region experience on average as many as 15 days per year with temperature above $40°C$. Temperature reaches this threshold between 4 and 5 days a year in MM and CWO. The spread of the NARCliM models seems to be related to the magnitude of the index itself and they show the largest disagreement in FW. For most of the other regions all models produce similar values of TX40 and are in agreement with AWAP observations.

4.4 Summary

The comparison between the NARCliM ensemble and observations indicates that differences between both datasets exist, but on the whole they are statistically non-significant and therefore can be considered to be within the range of natural variability. Some exceptions were found over the mountains and areas immediately to the west of the Great Dividing Range, but they were limited to a few indices only. Differences also exist in the spatial patterns of heatwave attributes with NARCliM producing too intense but shorter heatwaves along the coast. The southwest to northeast gradient observed in AWAP for HWA and HWM is weaker in the NARCliM ensemble. In terms of frequency, NARCliM members produce fewer heatwaves in general but differences among regions are captured adequately and again these differences are overall within the bounds of observed variability according to the statistical test performed. The NARCliM ensemble also tends to produce shorter heatwaves in general particularly in the southeast regions.

Indices that rely on absolute temperature values (HWAt, HWMt and TX40) are very well re-

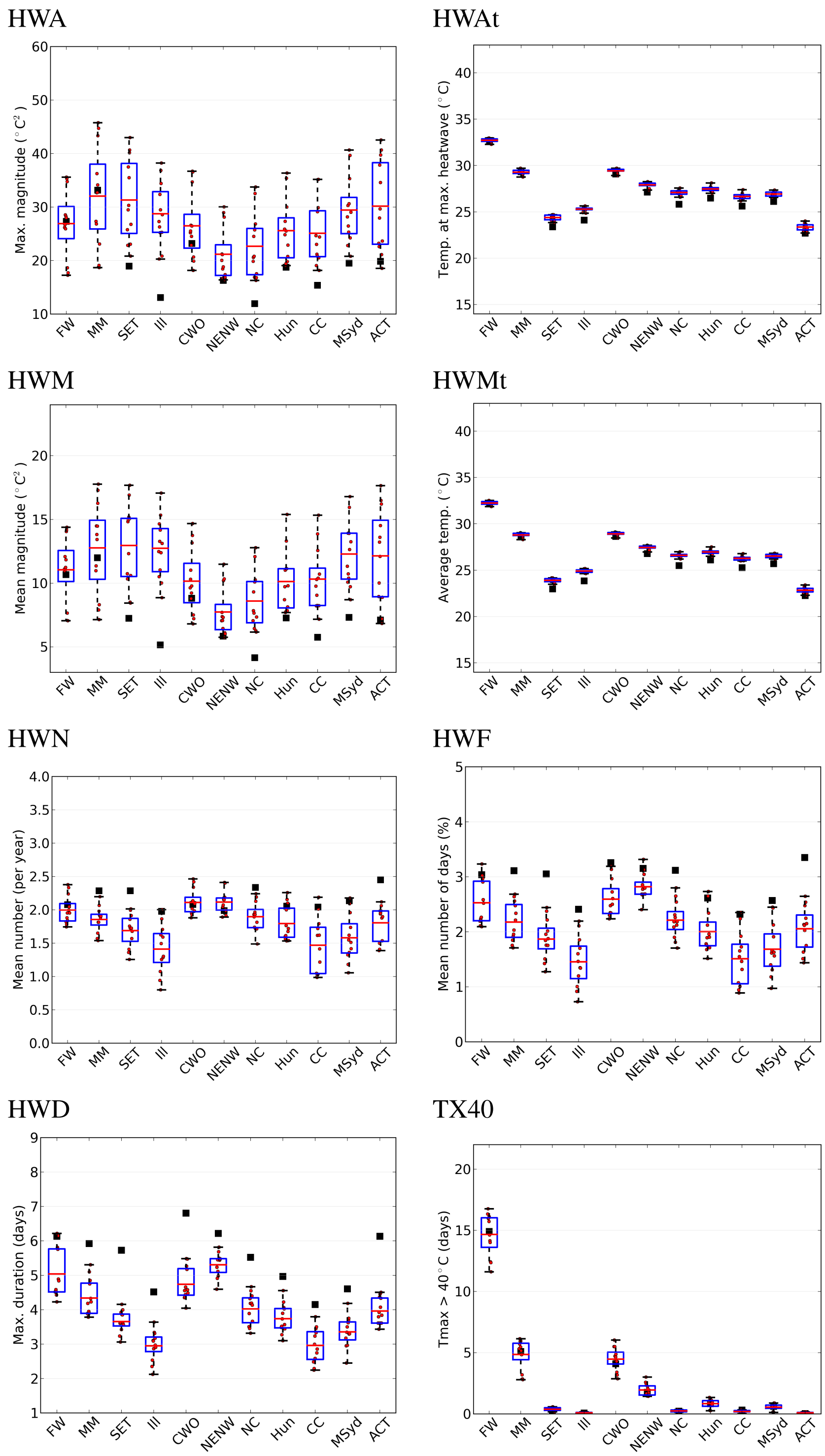

Figure 4.3: Present-climate (1990-2009) heatwave indices from the NARCliM ensemble using the bias-corrected outputs. The NARCliM ensemble model mean (red line), inter-quartile range (blue box) and range (whisker) are represented for each heatwave index and region. Red circles represent values from individual models and black square represent AWAP observations.

produced by the NARCliM ensemble and by individual members (i.e., very small range). This is partly due to the bias correction applied to the NARCliM ensemble.

Chapter 5

Near Future Modelled Changes Compared to the Present Period

This chapter contains projected climatologies and changes in heatwave characteristics between near-future (2020-2039) and present (1990-2009) climates from the NARCliM ensemble. Future climate heatwave features were quantified using the present climate percentiles calculated over the reference period (1990-2009).

5.1 Regional Model Output: near-future climatologies (2020-2039)

In this section, near-future (2020-2039) projected climatologies of heatwave indices are presented. Figure 5.1 shows the NARCliM ensemble mean of all heatwave indices for the near-future climate (2020-2039). The average heatwave peak (HWA) from the NARCliM ensemble ranges from 20 to 30$°C^2$ in the north of NSW to 35 to 45$°C^2$ in the south. A similar spatial distribution is obtained for the mean magnitude of heatwaves (HWM) with the highest values located in the southern part of South East and Tablelands region (up to 20$°C^2$) and the lowest in New England and North West and areas of the North Coast. The overall latitudinal gradient is explained by the largest variability in temperature at higher latitudes compared to areas near the tropics, which produces longer tails in temperature probability distribution functions. Mean temperature for the peak (HWAt) and for the mean magnitude of heatwaves (HWMt) have a pattern that is consistent with the spatial distribution of the maximum temperature [79] with larger values in the northern Far West (34-37$°C$ for both HWAt and HWMt) and lower in the high-elevation areas in the south of NSW (16-19$°C$ for both indices).

According to NARCliM outputs, the northern interior of NSW is where heatwaves events (HWN) and heatwave days (HWF) are more frequent (about 3.2 heatwaves/year and $\sim$5% of days), while the south coast and the south west show the lowest number of heatwaves per year ($<$2.6 heatwaves/year). A similar spatial structure is obtained for the average duration of the longest heatwave in a year, with longer heatwaves over much of the north (8-9 days) and shorter ones along the south coast (5-6 days).

The index that measures the number of extremely hot days (TX40) is distributed very similar to HWAt and HWMt, and therefore to maximum temperature. In the northern Far West, maximum temperature exceeds 40$°C$ as many as 30 days per year, whereas in eastern third of NSW and ACT temperatures over 40$^\circ C$ are recorded less than 5 days per year on average. Some regions along the coast do not experience days with temperatures above 40$^\circ C$.

5.2 Regional Model Output: near-future changes (2020-2039) with respect to present climate (1990-2009)

Figure 5.2 illustrates the NARCliM ensemble mean changes for all heatwave indices as obtained from the difference between climatologies for the periods 2020-2039 and 1990-2009. The coloured contours provide information on near-future changes in the NARCliM ensemble mean, while the stippling indicates the level of model agreement. The NARCliM ensemble-mean changes are separated into three categories (a) less than half of the models show a significant change (insignificant areas, ensemble-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 sign of the change (significant agreeing areas, stippled with an asterisk ("*") symbol), 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, stippled with a forward slash ("/") symbol). For each index, the significance of biases of individual models was estimated with respect to the interannual variability using a Student's t-test at the 5% significance level.

Figure 5.2 shows that indices characterising amplitude and mean magnitude will experience non-significant changes in both their original (HWA and HWM) and their temperature-equivalent (HWAt and HWMt) versions. Actually, almost the entire region will be exposed to changes in HWAt and HWMt that will not exceed 0.5$^\circ C$, with very minor exceptions for HWAt around Sydney and in the interior. It is worth noting that HWM will see decreases in some regions, particularly over the southeast. This is a consequence of how the index is built. The mean magnitude of heatwaves may decrease despite the number of heatwaves increasing considerably. This is due to the mild heatwaves increasing much more than the severe heatwaves. A detailed explanation of this feature with a practical example is provided in Section 6.4.

On the other hand, indices measuring frequency and duration of heatwaves will undergo statistically significant changes with respect to 1990-2009 over most of NSW and ACT even for this 30-year time horizon. HWN will increase between 0.9 and 1.5 heatwaves per year almost everywhere in NSW with the exception of the southern interior and the northern coast. In terms of the number of heatwave days, all regions except the NC and parts of NENW will be exposed to statistically significant changes, although the northern interior will see the largest changes (increase of 2.1-2.7% of days, equivalent to $\sim$7.5-10 more heatwave days per year). Similarly, the longest heatwave in a year (HWD) will be 1.5-3.5 days longer on average over most regions, with exceptions along the coast and in the southwestern corner. Such changes in the duration of heatwaves are statistically significant over most areas.

The number of days with temperature above 40$^\circ C$ will significantly increase by 2020-2039 over the interior half of NSW, where changes are projected to be in the range 1.5-7.5 days/year on average. In the very northwest corner, changes may be larger, reaching 7.5-10.5 days/year. In the eastern half of NSW and in ACT, changes are not statistically significant and are smaller than 1.5 days/year.

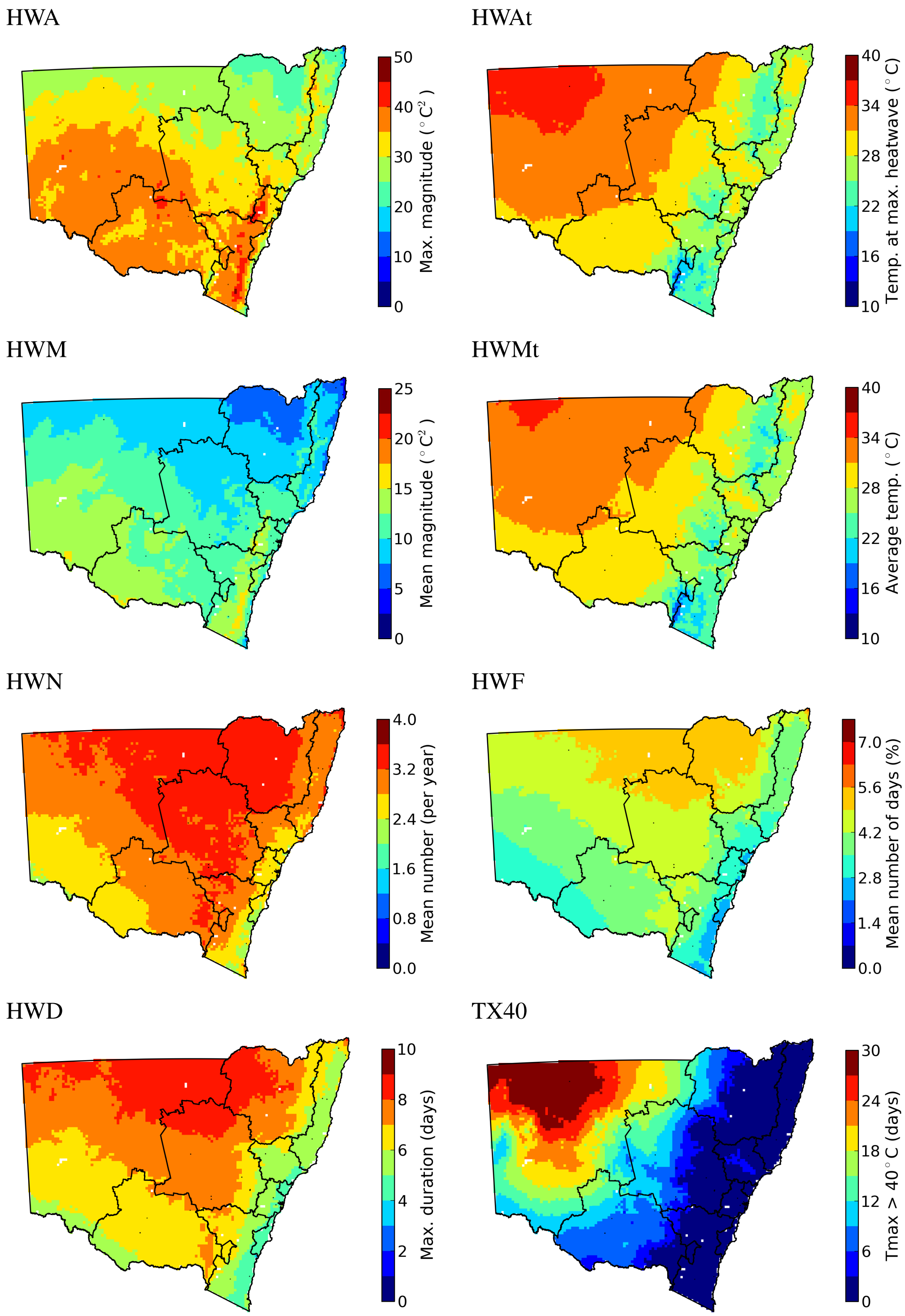

Figure 5.1: Near-future (2020-2039) projected climatologies for heatwave indices from the NARCliM ensemble using the bias-corrected outputs.

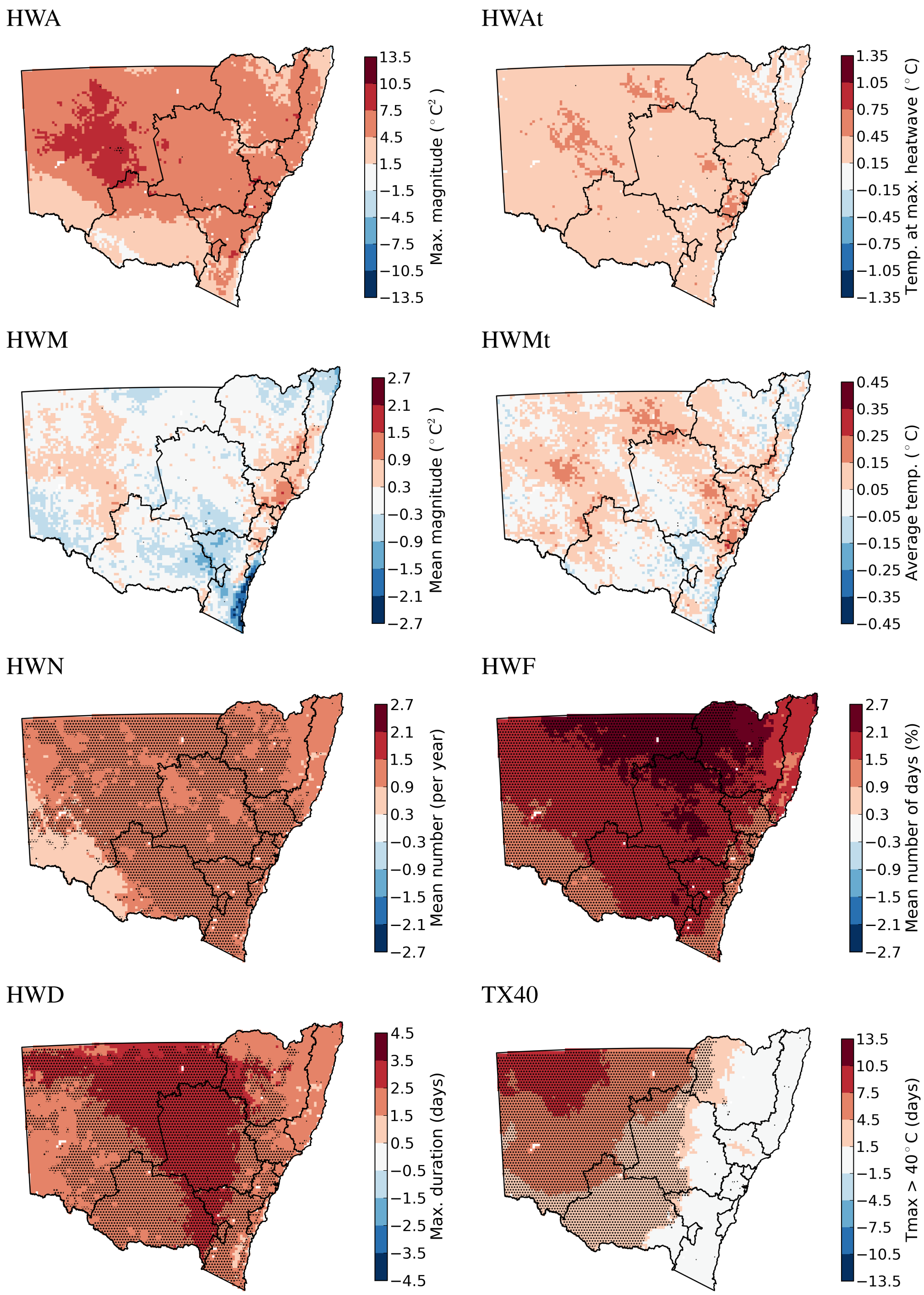

Figure 5.2: Near-future (2020-2039) projected changes for heatwave indices from the NARCliM ensemble using the bias-corrected outputs with respect to present climate (1990-2009). Stippling indicates areas where future changes are significant for at least half of the models and at least 80% of them agree on the direction of the change (see Section 5.2 for details).

5.3 Regional analysis: near-future changes (2020-2039) with respect to present climate (1990-2009)

This section presents an analysis of the near-future changes for each individual region in NSW (see Fig. 1.2). Figure 5.3 shows near-future projected changes (2020-2039 minus 1990-2009) of heatwave indices for each of the regions, including the spread across NARCliM ensemble members.

The NARCliM ensemble mean projects similar changes in the yearly maximum intensity of heatwaves (HWA) for all regions ($\sim 5°C^2$), although there is a substantial spread across individual members, with a few of them even projecting slight decreases of HWA. There does not seem to be a clear pattern that explains the differences in spread between regions, with FW and MSyd showing the smallest inter-quartile ranges ($\sim 5°C^2$) and MM, SET and NENW the largest ($> 10°C^2$).

Patterns are clearer when looking at the temperature-equivalent index (HWAt). All regions show a similar increase in HWAt between 0 and $0.5°C$ according to the NARCliM ensemble mean. Regions in the the centre and near the coast (Hun, CC, and MSyd) together with ACT, show the largest changes according to the NARCliM ensemble (0.4-0.5$°C$). In these regions and NC, NARCliM members show the largest disagreement in projections, whereas NARCliM simulations show a reduced spread in the western and southern regions.

As for the mean magnitude of heatwaves (HWM), the NARCliM mean projects both decreases (SET, Ill and ACT) and increases (rest of the regions), although this is largely explained by the way the HWM index is defined in present and future climates (see section 6.4 for further details). NARCliM mean changes, however, appear to be quite uncertain with the NARCliM ensemble showing a large spread in all regions with individual members suggesting different directions of change. In this case, models seem to agree better in the northeastern quarter (NENW, NC, Hun, CC and Msyd) and they are more discordant in the south (MM) and southeast (SET, Ill and ACT). Near-future changes in HWMt are almost $0°C$ in most regions, and only some show slightly larger increases (Hun, CC and MSyd). In all cases, the spread of models spans the zero-change line.

Overall, changes in heatwave maximum and mean intensity are not statistically significant as evidence by Figure 5.2 and thus may well be due to natural climate variability.

On the other hand, frequency and duration of heatwaves is expected to increase in all NARCliM models and regions. All regions are projected to experience increases of slightly more than one additional heatwave per year on average according to the NARCliM mean, except for NC. Individual models indicate that larger uncertainty of these changes are located in NC, along with NENW and Hun, where the inter-quartile ranges are the largest. Similar results are obtained for the frequency of heatwave days, projected to increase from $\sim 1.4\%$ of days in Ill and NC to over 2% of days in CWO and NENW. However, some models project increases as large as 4% of days in NENW and NC, supporting the uncertainty over these two regions mentioned before. In most of the regions, the inter-quartile range is below 1% of days and in some cases models tend to agree even better with the inter-quartile range being $\sim 0.5\%$ of days (FW, MM, Ill and CWO).

The duration of the longest heatwave in a year is projected to increase in all regions. The largest increases in CWO (just below 3 days longer) followed by FW and NENW ($\sim$ 2.5 days longer). The northern coast shows the lowest values, with changes hardly exceeding 1 day, although once again NC is among the regions with largest spread. According to [79], NARCliM models showed large disagreement over this region in terms of temperature and precipitation changes during summer, when most heatwaves occur.

Finally, the number of extremely hot days (TX40) is projected to increase in the near future in all regions of NSW and ACT according to the NARCliM ensemble mean. Few exceptions are obtained for individual models that project slight decreases in most regions. Nonetheless, the inter-quartile range projects positive changes for all regions. Regions with the largest present-climate values will also be prone to the largest increases in TX40. For instance, the NARCliM mean projects increases above 5 days in FW and about 3 days in MM and CWO. The rest of regions remain in the range 0-2 more days above $40°C$, with ACT and Ill experiencing almost no changes. NARCliM ensemble members display substantial spread in some regions, especially over the western half of NSW, while they agree in projecting little to no changes over eastern regions.

5.4 Summary

Near-future (2020-2039) changes of heatwave characteristics from the NARCliM ensemble were described in this chapter. Differences between near-future and present climate are not strong enough to translate into statistically significant changes in heatwave intensity and therefore, the projected changes cannot be discerned from natural variability. Despite the fact that most models project increases in the peak magnitude of heatwaves, there are some individual models that indicate a decrease in HWA in the near future. As for the mean magnitude, there are both increases and decreases projected for NSW and ACT, although they should be interpreted carefully due to HWM definition (see section 6.4 for further details).

The frequency and duration of heatwaves are projected to experience statistically-significant increases over large areas in NSW and ACT. The most remarkable exception is the NC, where none of these indices are projected to change significantly, although NARCliM models showed large spread in HWN, HWF and HWD and thus there is a considerable uncertainty in this region. Projections for other regions seem to be more consistent across simulations and near-future heatwaves are expected to be about 50% more frequent (HWN and HWF) and longer (HWD) than present climate heatwaves (Fig 4.3).

Extreme hot days measured by TX40 will increase in most regions, although significance of such changes is limited to the western half of NSW, where the NARCliM ensemble projects up to 6 more days/year with temperature above $40°C$ on average. Most of the eastern regions will continue to see very similar values of TX40, with increases below 1 day/year.

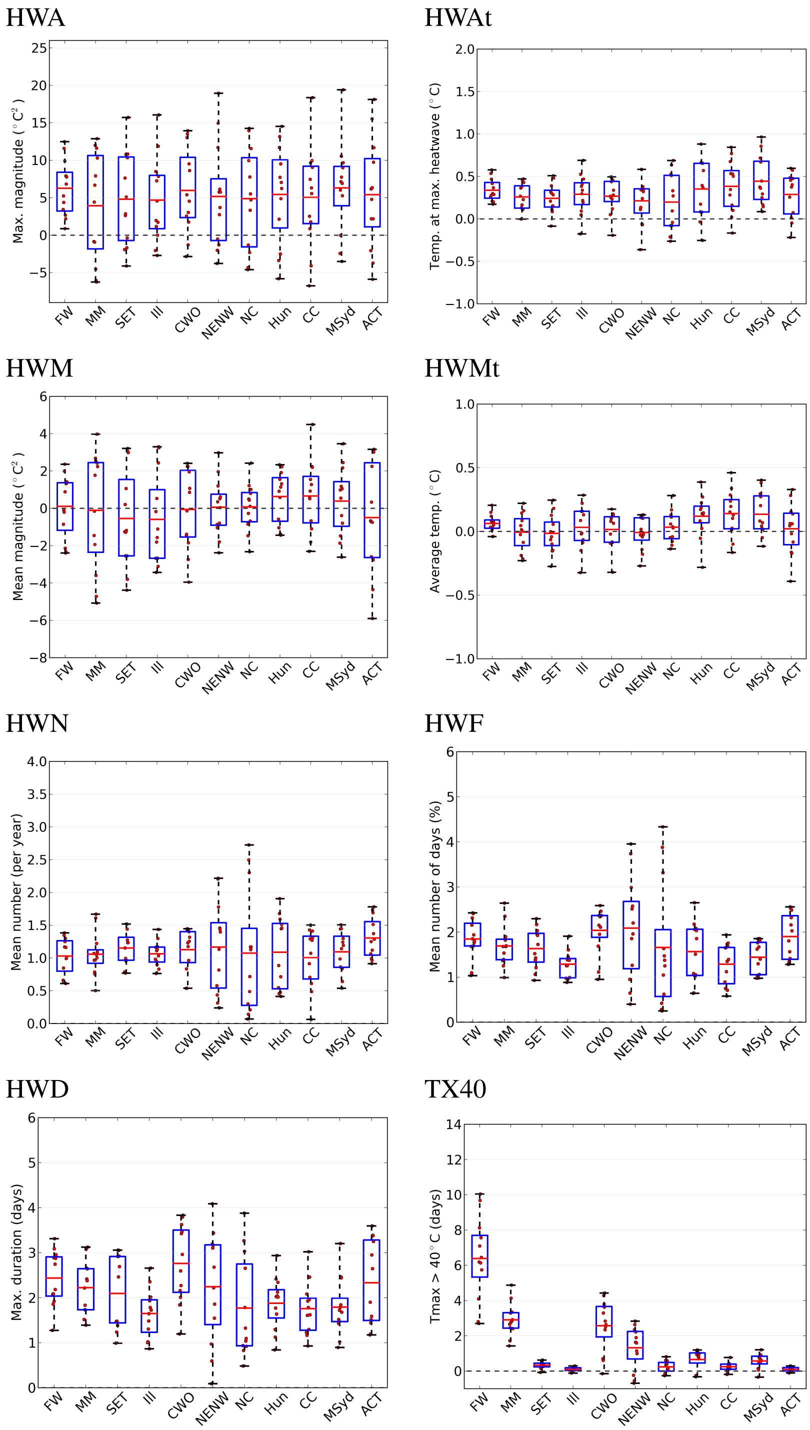

Figure 5.3: Near-future (2020-2039) projected changes for heatwave indices from the NARCliM ensemble using the bias-corrected outputs with respect to present climate (1990-2009). The NARCliM ensemble mean change (red line), inter-quartile of changes (blue box) and range (whisker) of changes are represented for each heatwave index and region (see Fig. 1.2). Red circles represent values from individual members.

Chapter 6

Far Future Modelled Changes Compared to the Present Period

This chapter contains projected changes in heatwave characteristics between far-future (2060-2079) and present (1990-2009) climates from the NARCliM ensemble. Future climate heatwave features were quantified using the present climate percentiles calculated over the reference period (1990-2009).

6.1 Regional Model Output: far-future climatologies (2060-2079)

In this section, far-future (2060-2079) projected climatologies of heatwave indices are presented. Figure 6.1 shows the NARCliM ensemble mean of all heatwave indices for the far-future climate (2060-2079). The NARCliM ensemble mean heatwave peak (HWA) ranges from 24 to 32$°C^2$ in the northeast of NSW to about 50$°C^2$ in the southwest. A similar spatial distribution is obtained for the mean magnitude of heatwaves (HWM) with the highest values located in the southern part of South East and Tablelands and Far West regions (up to 20$°C^2$) and the lowest values in New England and North West and areas of the North Coast. As for the present climate, the overall north/south gradient is explained by the larger temperature variability at higher latitudes compared to areas to the north of NSW. Mean temperature for the peak (HWAt) and for the mean magnitude of heatwaves (HWMt) have a pattern that is consistent with the spatial distribution of the maximum temperature with largest values in the northern Far West ($\sim$34-37$°C$) and lowest values in the high-elevation areas in the south ($\sim$16-19$°C$).

The number of heatwave events (HWN) and the percent of heatwave days (HWF) are largest in the northern interior of NSW with about 6 heatwaves per year and around 10% of days, while the south west of NSW and pockets in the south coast show the lowest number of heatwaves per year ($<$5 heatwaves/year). A similar spatial structure is obtained for the average duration of the longest heatwave in a year, with longer heatwaves over much of the north (12-18 days) and shorter ones along the south coast and the south west (6-8 days).

As for the present climate, the index that measures the number of extremely hot days (TX40) is distributed very similar to HWAt and HWMt, and therefore to maximum temperature. In the northern Far West, maximum temperature exceeds the 40$°C$ threshold as many as 50 days per year, whereas along the NSW coast temperatures over 40$°C$ are recorded generally less than 4 days per year on average.

6.2 Regional Model Output: far-future changes (2060-2079) with respect to present climate (1990-2009)

In this section, far-future (2060-2079) projected changes of heatwave indices are presented. For each index, the significance of biases of individual models was estimated with respect to the inter-annual variability using a Student's t-test at the 5% significance level. The stippling convention is the same as the one described for near-future changes (see Section 5.2).

Figure 6.2 illustrates the NARCliM ensemble mean changes for all heatwave indices as obtained from the difference between climatologies for the periods 2060-2079 and 1990-2009. The yearly heatwave peak (HWA) shows increases over all of NSW although they appear as statistically significant only over western regions. A similar pattern of changes is observed for the temperature-equivalent HWA (HWAt) with changes ranging between 0.5 and 1.5$^{\circ}C$ over all NSW.

The mean magnitude of heatwaves index (HWM) and its temperature equivalent index (HWMt) show increases to the west of NSW and decreases to the east with the largest reductions over the southern coast of NSW. However, none of these changes are statistically significant when compared with the interannual variability. Changes in the HWM index should be interpreted with caution because they are strongly influenced by the way the projected HWM index is calculated. A detailed explanation of this feature with a practical example is provided in Section 6.4.

Indices measuring frequency (HWN and HWF) and duration (HWD) of heatwaves will undergo statistically significant changes over all of NSW and ACT with respect to the present period. The number of heatwaves (HWN) is expected to increase by 2.5 to 4.5 in the far future with somewhat larger increases to the north of NSW according to the NARCliM ensemble mean. A similar pattern of changes is observed for the mean number of heatwave days (HWF) with between 2 and 10% more days of heatwaves per year. The longest heatwave in a year (HWD) is expected to be 2-14 days longer on average depending on the region considered. Regions in the north east (NENW) would experience the largest changes in HWD while the smallest changes are expected to arise in the southern part of NSW.

The number of days with temperature above 40$^{\circ}C$ will significantly increase in 2060-2079 over most of NSW with increases attaining about 30 days in the northwestern corner. In the eastern part of NSW and in ACT, changes are generally smaller than 3 days/year and not statistically significant.

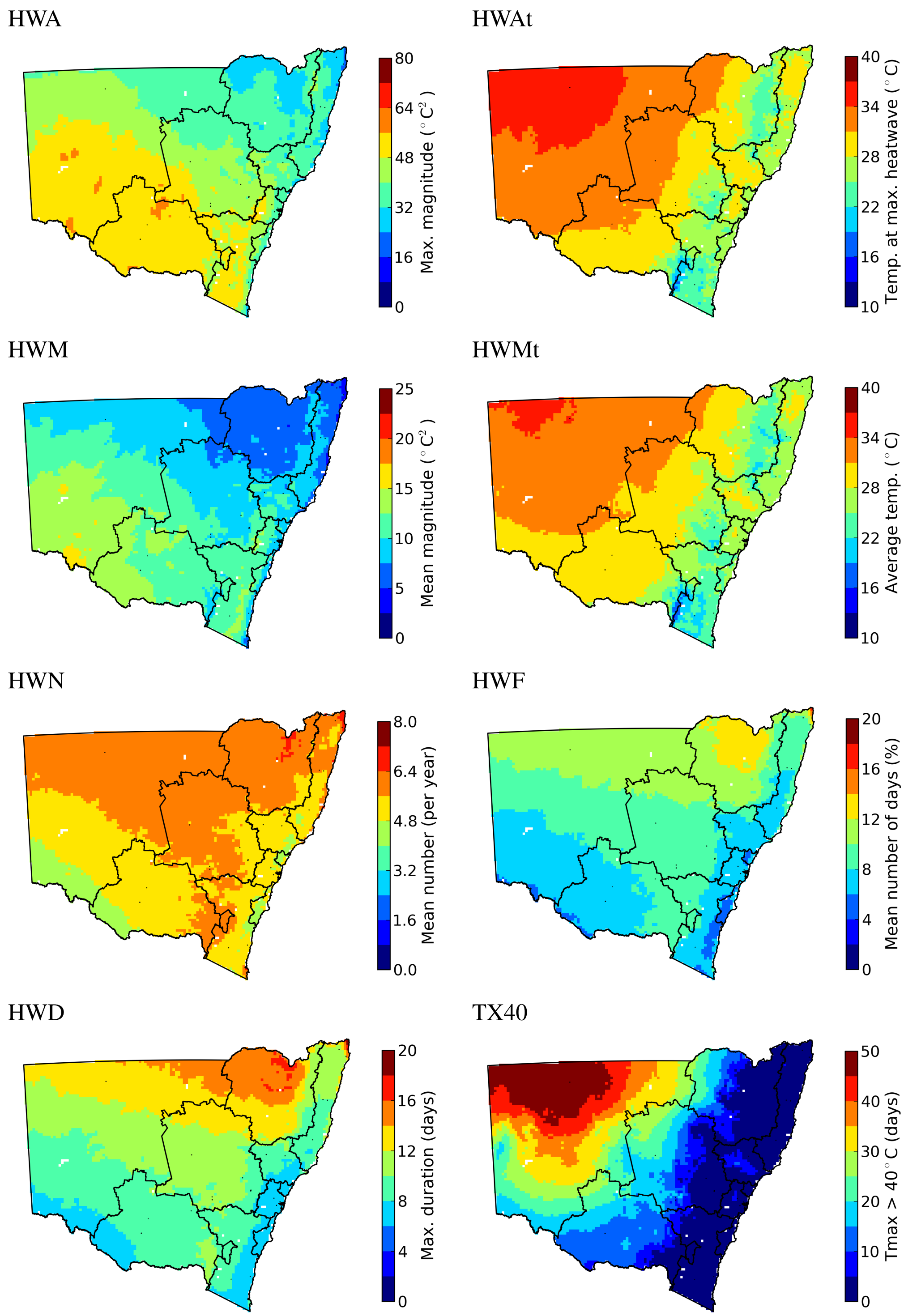

Figure 6.1: Far-future (2060-2079) projected climatologies for heatwave indices from the NARCliM ensemble using the bias-corrected outputs.

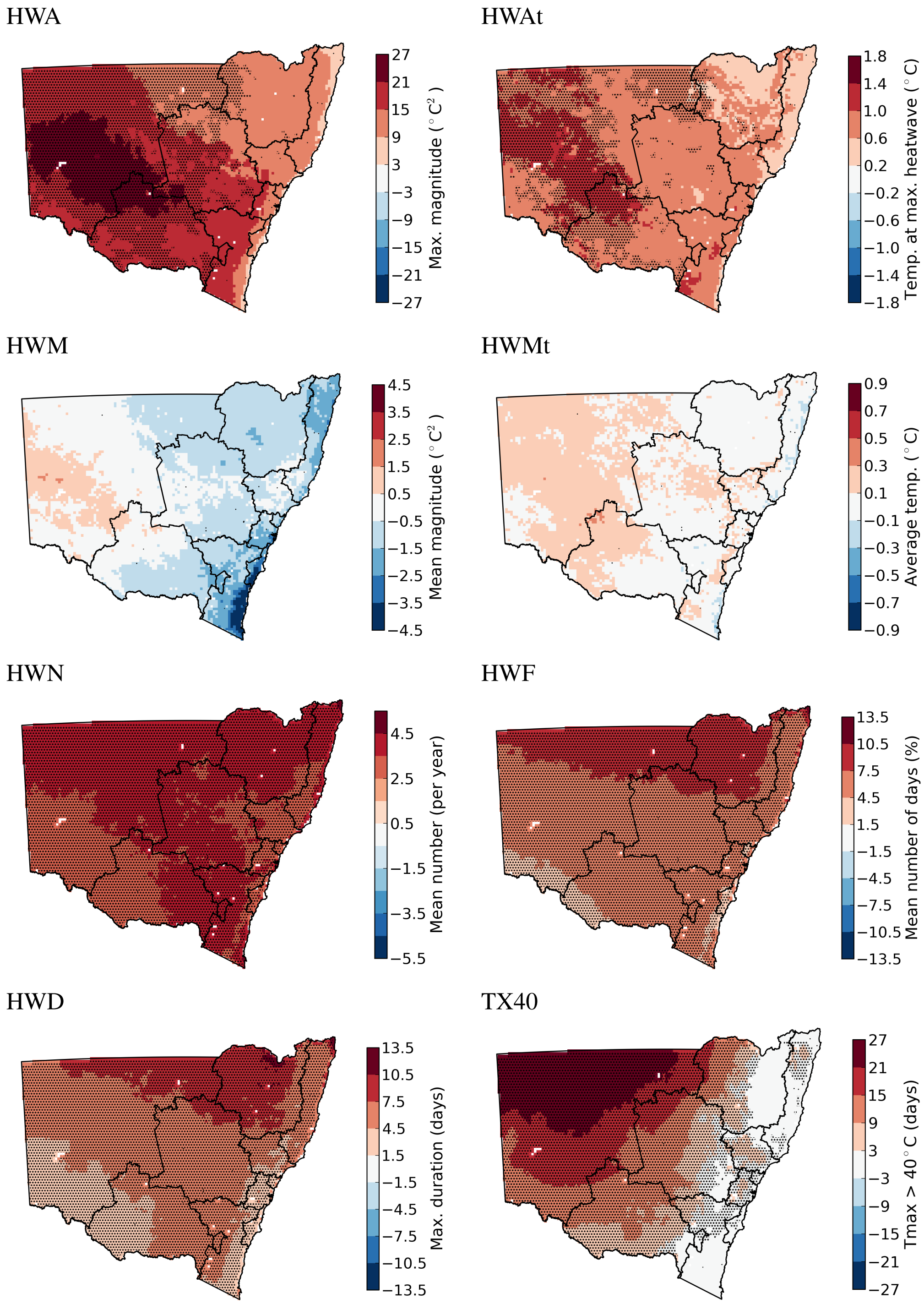

Figure 6.2: Far-future (2060-2079) projected changes for heatwave indices from the NARCliM ensemble using the bias-corrected outputs with respect to present climate (1990-2009). Stippling indicates areas where future changes are significant for at least half of the models and at least 80% of them agree on the direction of the change (see Section 5.2 for details).

6.3 Regional analysis: far-future changes (2060-2079) with respect to present climate (1990-2009)

This section presents an analysis of the far-future changes for each individual region in NSW (see Fig. 1.2). Figure 6.3 shows far-future projected changes (2060-2079 minus 1990-2009) of heatwave indices for each of the regions, including the spread across NARCliM ensemble members.

All NARCliM ensemble members project increasing changes in the yearly maximum intensity of heatwaves (HWA) and its temperature-equivalent (HWAt) for all regions in NSW. The HWA index shows NARCliM ensemble mean values that vary between $\sim$10$°C^2$ and $\sim$20$°C^2$) with the largest values in the FW and MM regions and the lowest in Ill, NENW, NC and CC regions. Most regions show a substantial spread across individual members, that can attain 50% of the ensemble-mean values. The temperature-equivalent index (HWAt) shows NARCliM ensemble mean increases that vary between 0.5 and 1$°C$ with smallest changes arising over northeastern regions of NSW.

As for the mean magnitude of heatwaves (HWM), most individual members and the NARCliM mean project mostly decreases, although this is explained by the much larger number of heatwaves in the future and their relatively weak intensities as discussed in Section 6.4. Far-future changes in HWMt are around zero for the NARCliM mean values and the range spans both increases and decreases. This suggests that the mean heatwave temperature is not projected to change in the future.

Far-future projections about the number (HWN), frequency of days (HWF) and duration (HWD) of heatwaves is expected to increase in all NARCliM members and regions. The number of heatwaves increases between 3 and 4 per year on average with a maximum in ACT and minima in Hun, CC and MSyd. The increase in the number of heatwaves together with changes in the mean duration lead to an increase in the mean number of heatwave days that vary between 4 and 10% of days compared to present values. The largest changes arise in northeastern regions of NSW while the smallest in Hun and CC. The duration of the longest heatwave also increases in far-future projections by about 4 days in regions along the coast and by about 10 days in the NENW region.

Finally, the number of hot days (TX40) is projected to increase in the far future in all regions of NSW and ACT according to the NARCliM ensemble mean. A few regions show no changes simply because they do not record any day with temperatures above 40$°C$ in present nor in far-future periods. Far-future projections suggest that the number of days with mean temperature above 40$°C$ will be more than double the present climate values for most regions. Specifically, the NARCliM ensemble suggests around 35 instead of 15 days with temperatures above 40$°C$ in the far future compared to the present period in the FW region.

6.4 Interpreting changes in the HWM index

In this section, we discuss future changes in the mean magnitude of heatwaves as derived using the current implementation of the CAWCR Excess Heat Factor (EHF).

Figure 6.4a shows an histogram of the EHF index during heatwave days only for present (green) and far-future (pink) periods. This figure is intended to assist the interpretation of HWM changes and thus refers to a single location (near Sydney) and a single ensemble member (ECHAM5 R1).

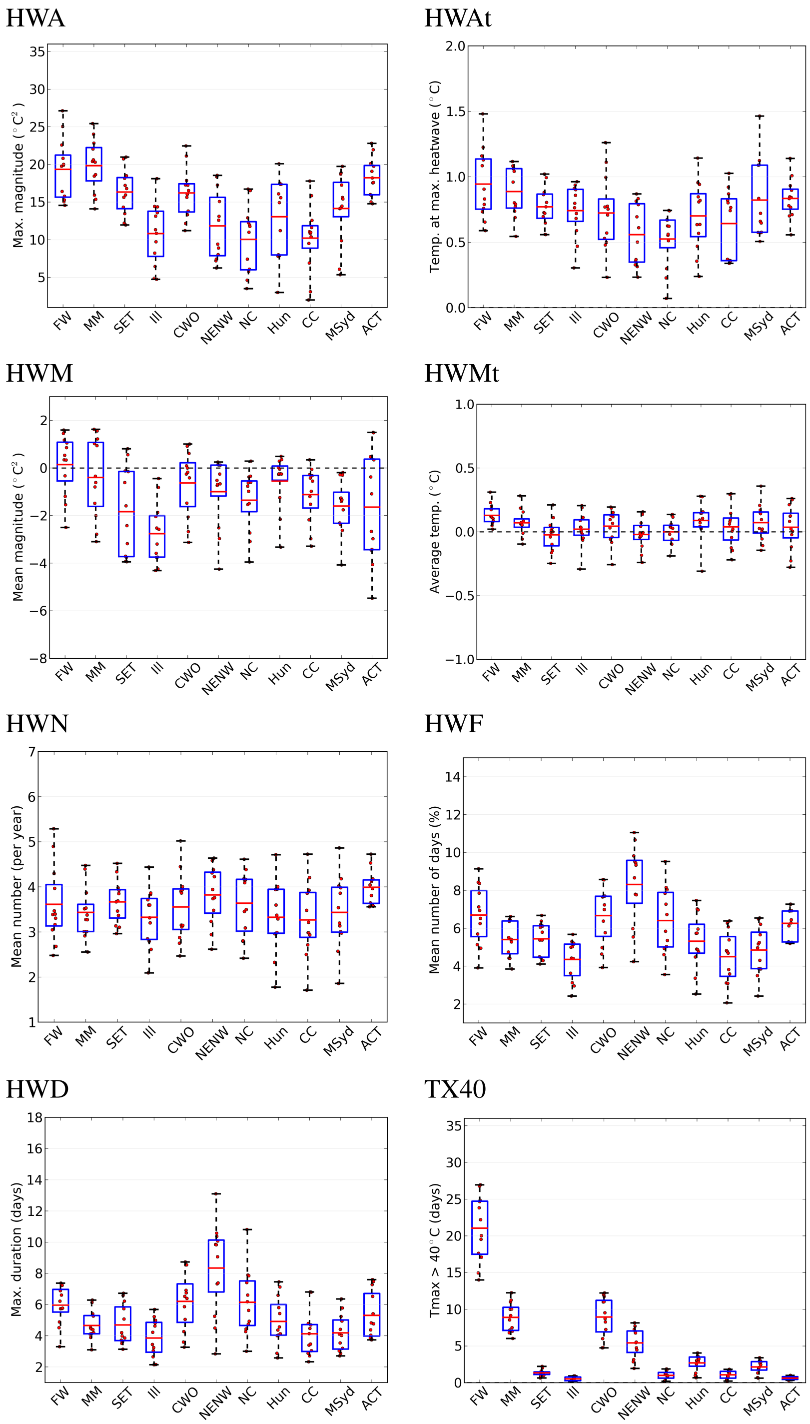

Figure 6.3: Far-future (2060-2079) projected changes for heatwave indices from the NARCliM ensemble using the bias-corrected outputs with respect to present climate (1990-2009). The NARCliM ensemble mean change (red line), inter-quartile span of changes (blue box) and range (whisker) of changes are represented for each heatwave index and region (Fig 1.2). Red circles represent values from individual members.

The number of heatwave days increases in the future no matter the intensity of EHF, but the increase is much larger for relatively weak intensities than for moderate and strong intensities. For example, the number of heatwave days increases from about 1.2 days to 6.6 days (factor 5.5) for EHF values in the range 0-2$°C^2$, while it only increases from approximately 0.6 days to 1.2 days (factor 2) for intensities in the range 20-22$°C^2$. As a consequence, the average of EHF for all heatwave days (vertical lines), which is equivalent to HWM, is smaller in the future (pink) than in the present, although the occurrence is larger for almost all EHF values. The temperature-equivalent index (HWMt) is represented in Figure 6.4b, where temperature for heatwave days is represented in classified in 0.5$°C$ bins. Similar to HWM there are increases at all intensities, however in this case the increases are more evenly spread across intensities (instead of being much larger at lower intensities) and the mean result suggests almost no change (vertical lines).

This sensitivity to the distribution of events in the HWM index means that future changes in this index need to be interpreted with caution.

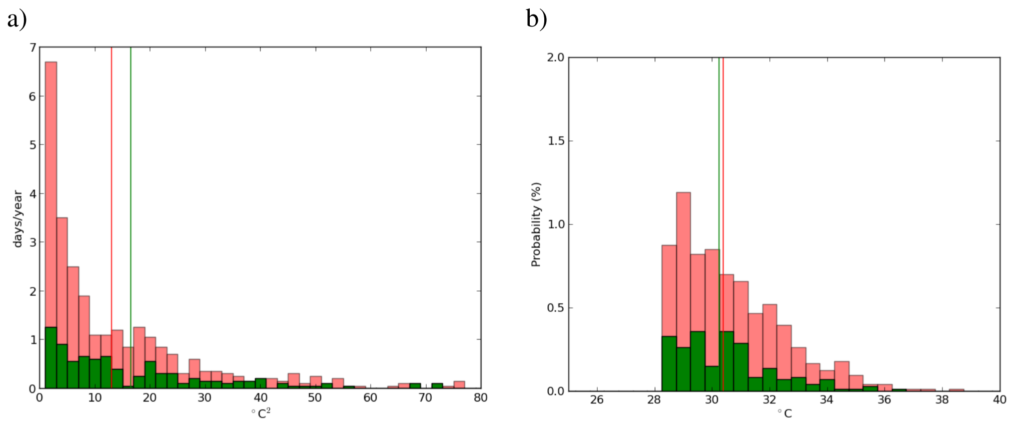

Figure 6.4: Probability distribution functions of EHF (a) and 3-day average temperature (b) for heatwave days (EHF1.) from one NARCliM simulation (ECHAM5 R1) for 1990-2009 (green) and 2060-2079 (red) over Sydney - one grid point located in 33.85$°S$ and 151.12$°E$. Vertical lines represent the mean of all values.

6.5 Summary

Far-future (2060-2079) changes of heatwave characteristics from the NARCliM ensemble were described in this chapter. Differences between far-future and present climate appear to be significant for most of the indices with systematic increases in the number, duration and intensity of the strongest heatwaves. The index characterising the mean magnitude of heatwaves does not show significant changes in the far future although this is related with the specific way in which the future index is constructed and so this result should be interpreted with caution.

All individual members of the NARCliM ensemble agree on the sign of the change for the intensity of the heatwave peak and the number and duration of heatwaves. However, NARCliM members show a large range of changes and suggest relatively large uncertainties around mean changes.

Extreme hot days measured by TX40 will increase in most regions in NSW with the NARCliM ensemble suggesting more than twice the number of days in the far-future compared to present period in some regions (e.g., FW and MM).

Chapter 7

Health effects of heatwaves

7.1 Definitions are important

There is no universal definition of a heatwave. Consequently, international and domestic studies that assess the impacts of heatwaves on human health have employed a range of definitions. Studies tend to use heatwave metrics developed for local climate conditions, frequently leading to a lack of consistency between health effect studies with regard to the temperature metric used, the temperature threshold used, and the number of days defined as heatwave days [7]. For example, some studies have used an absolute temperature threshold [36, 112]; a relative temperature threshold [49, 107]; or compared both [88]. Further, to define a heatwave event, some studies have used mean temperature [89]; maximum temperature [69]; apparent temperature and its variations [107]; or a combination of these metrics [7]. The use of a range of definitions complicates any attempt to make comparisons between the health effects that occur as a result of a heatwave event, and hinders attempts to standardise public health warning systems.

Consequently, the strength of the association between heatwaves and human mortality and morbidity is dependent upon the heatwave definition used [7, 48, 88]. One Australian study that quantifies this relationship confirms that changes in heatwave definition do lead to differences in their associated health risk estimates [88]. This study used ten heatwave definitions to explore increases in mortality and emergency hospital admissions. It found significant increases in admissions and mortality during a heatwave event, however, depending on the heatwave definition used, the adjusted odds ratios of an increase in admissions ranged from 1.03 to 1.18 and the significant adjusted odds ratios of an increase in mortality ranged from 1.10 to1.73 [88].

Despite the obvious benefit of agreeing on one universal definition for heatwaves, it is likely that the debate will not quickly resolve due in part to the fact that for some localities, different metrics are deemed more significant than others in relation to the effects on human health. Some studies have indicated that metrics based on mean temperature might be most appropriate as it incorporates both maximum and minimum temperature [13, 48, 89, 96]. High minimum temperatures are said to be of particular importance during periods of prolonged heat, as the body is unable to obtain its usual relief from cool night time temperatures [7]. In contrast, some authors suggest metrics incorporating humidity, such as apparent temperature, are more appropriate to define heatwaves [11, 32, 20, 81]. This is because such metrics are said to be representative of the overall impact of heat stress on the human body - a feature that cannot be measured by temperature alone [98].

However, to complicate this issue further, heatwave indices derived from daily maximum and minimum temperature arguably imply relative humidity, as high minimum temperatures can be a result of high humidity [67].

The recent development of the Excess Heat Factor (EHF) may resolve some of these problems as it includes daily maximum and minimum temperature in its derivation. EHF is a relative measure which might provide a more universal approach in evaluating the severity of heatwave events relevant to health outcomes [54]. 'Excess heat', a result of the accumulation of high maximum and minimum temperatures, is one of two integral components of EHF, and has been shown to be a significant contributing factor to the adverse health outcomes from a heatwave event [54]. For example, temperatures exceeding 43$^{\circ}C$ during the 2009 south-east Australian heatwave event were linked with substantial increases in mortality in the region [78, 71]. Further, the highest morbidity and mortality rates during the event immediately followed the highest EHF value calculated for the heatwave [54].

The second component of EHF, incorporates acclimatisation factors that can affect health outcomes from heatwave events. The acclimatisation index (see 2) within EHF incorporates the days immediately preceding the heatwave, and so suggests the ability of an individual to adapt to excessively hot temperatures [67]. If individuals can effectively acclimatise to warmer temperatures, relative to their location, there would indeed be a reduction in the mortality rate during extreme heat events.

The EHF has been shown to correlate well with excess mortality [54, 78]. Langlois et al. [54] found that mortality and morbidity rates during the 2009 south-east Australian heatwave were highest immediately following the peak EHF value. This supports the use of EHF as a suitable metric to evaluate the health impacts from heatwave events, while also having potential to be an indicator, and predictor, of heat-related mortality and morbidity.

7.2 Health effects

Heatwaves result in significant short-term increases in human mortality and morbidity [6, 83, 84, 91]. These increases are seen because extreme heat exacerbates pre-existing illnesses, such as cardiovascular, respiratory, and renal diseases, or causes heat-specific illnesses, such as heat-stroke or dehydration. For example, it is reported that the 2003 European heatwave resulted in between 40,000 to 70,000 excess deaths [30, 80], and the 1995 Chicago heatwave resulted in 485 heat-related deaths and 739 excess deaths during its most intense period [105]. In Australia, the 2009 Victorian heatwave resulted in a 62 per cent increase in total all cause-mortality, a 12 per cent increase in emergency department presentations, and a 25 per cent increase in total emergency ambulance call-outs [71]. The 2004 Brisbane heatwave resulted in 75 excess deaths [88].

Longer, more intense heatwaves have considerably larger impacts on human health [6, 7, 48]. There is also evidence of an additional heatwave burden on human heath; that is, the effect of a prolonged period of heat on human health is greater than the sum of the expected effects of single hot days [7, 33]. In general, increases in mortality and morbidity are observed on the day of the extreme temperature event, or one to three days after the exposure; that is, there is an observed lag effect [110].

The impact of heatwaves on human health can be measured in a number of different ways. These include: mortality [88, 91]; hospital admissions [37, 112]; emergency department presentations [70]; and ambulance call-outs [90].

7.2.1 Seasonality

There is some evidence indicating that heatwaves that occur early in the summer season have a greater impact on human health than those that occur later in the season [7]. Two reasons are proposed to explain this finding: (i) individuals acclimatise to the heat as the summer season progresses, and (ii) those individuals who are particularly vulnerable to extreme heat have died earlier in the season, leaving a robust, and less susceptible, pool of individuals. This latter phenomenon is known as mortality displacement or the harvesting effect [7].

7.2.2 Vulnerable sub-populations

Much of the research examining the health impacts of heatwaves has sought to identify sub-populations that are particularly vulnerable during heatwave events. This research has revealed that such populations include: the young [109], the elderly [82, 71, 100]; individuals with pre-existing medical conditions such as cardiovascular, respiratory and renal disease, diabetes, and mental and behavioural disorders [36, 37, 58, 97, 106]; individuals living alone [112]; individuals who have a low socioeconomic status [112]; outdoor and occupational workers [35, 108]; and Indigenous populations [102].

7.3 Health effects resulting from NARCliM simulations

In general, studies of future heat-related mortality using various scenarios and climate models have found an increase in the mortality rate [52, 73]. The health effects that may be coupled with increases in heatwave duration, frequency and intensity depend on a number of factors, including the spatial distribution of the future population, the mean temperatures relative to each region, and the magnitudes of increases for all indices respectively.

Although a quantitative assessment on the projected health outcomes is not made here, future work may benefit in using a similar approach proposed by the Price Waterhouse Coopers (PwC) National Framework on Protecting Human Health and Safety During Severe and Extreme Heat Events [78]. The report suggests a model combining climate and population projections with previous analogues of heat events that were linked with heat-related morbidity and mortality to make a quantitative assessment on future health outcomes. The model includes vulnerable population groups, as well as responses to heat events, such as heat-health warning systems and heat-health policy. Indeed, uncertainties are inherent in this type of model, as is the case with climate model projections. These uncertainties may arise from factors such as the distribution of the future population, future health policy initiatives, as well as socioeconomic and demographic factors that cannot be projected with accuracy.

A qualitative assessment of the health effects from the projected changes in heatwaves from the NARCliM simulations depends on numerous factors such as population growth, acclimatisation, socioeconomic and demographic factors, and the effectiveness of climate-health adaptation plans, such as heat-health warning systems.

7.3.1 Near-future health effects (2020-2039)

The frequency and duration of heatwaves are projected to significantly increase over large areas in NSW and the ACT (see Chapter 5). It could be inferred from this result, based on the current understanding of the health effects from heatwaves, that this would lead to increases in excess mortality and morbidity. However, the small, yet uncertain changes in relation to heatwave amplitude and mean magnitude make it difficult to predict how this would affect health outcomes. Although it is currently known that the intensity of a heatwave affects mortality and morbidity levels, it is unknown how this particular heatwave characteristic would combine with the projected increases in the other characteristics (i.e. frequency and duration) to affect human health.

Some regions of NSW indicate that the number of days above $40°C$ will significantly increase, where over the interior half of NSW, changes are projected to be in the range of 1.5-7.5 days/year, and potentially 7.5-10.5 days/year in the northwest. This projection is particularly important for human health outcomes, as single hot days, not just heatwaves alone, result in significant short-term increases in mortality and morbidity. Indeed, most studies have shown the existence of temperature thresholds; that is, a particular daily temperature (usually maximum temperature) above which there are marked increases in mortality and morbidity [56, 106]. These temperature thresholds vary significantly across regions and climatic zones due to the population's ability to acclimatise. For example, the temperature threshold for Sydney appears to be within the range of 26-27$°C$ for daily maximum temperature [12, 31]. Therefore, increases in the number of hot days exceeding $40°C$ will likely lead to increases in mortality and morbidity.

Using the relationship described in [78] for heat related excess deaths in Sydney, and the 2011 observed excess deaths as a representative year for the recent past, can provide a rough estimate of excess deaths projected by the NARCliM ensemble. Noting many limitations of this approach it estimates an increase in heat related excess deaths of 13 p.a. in the near future.

7.3.2 Far-future health effects (2060-2079)

Increases in heatwave characteristics, including heatwave intensity, duration and frequency, are projected for the entire region of NSW and the ACT, excluding simulations for average heatwave magnitude for reasons described in Chapter 6. The number of days with temperatures exceeding $40°C$ project increases up to 30 days in the northwest. Although substantial, the health outcomes would be dependent on how long these temperatures persist for, and whether there is any alleviation during the night [7].

Overall, the southern parts of the state, particularly in the west, are projected to experience the largest increases in heatwave intensity compared with smaller increases in the east. More frequent and longer duration events are projected for more north-easterly regions of the state. The greatest health impacts would likely occur for regions projected to experience substantial increases across all indices, such as northern parts of the FW region. Health effects would likely arise from increases in heatwave intensity in the region, combined with significant increases in the duration of events. The severity of health impacts, however, would largely depend on the persistence of high night time temperatures during future heatwave events. Further, despite increases being largest in this region for these heatwave aspects, the health burden may not be particularly prominent as the FW is a largely rural and sparsely populated area. This also makes quantitative assessments on the future health outcomes in this area more complex to interpret. This is largely based on assumptions that the population density of the region will remain similar to the present.

It is likely that MSyd and ACT remain the most populated regions, and as such, the highest health burden may occur here largely due to a greater number of vulnerable people, as well as compounding factors such as the Urban Heat Island [34, 59]. Although increases in heatwave intensity, duration and frequency are not as large as more inland regions, such as FW, CWO and NENW, these dense urban regions might expect increases in heat-related mortality and morbidity due to slightly higher intensity, longer and more frequent events.

Using the relationship described in [78] for heat related excess deaths in Sydney, and the 2011 observed excess deaths as a representative year for the recent past, can provide a rough estimate of excess deaths projected by the NARCliM ensemble. Noting many limitations of this approach it estimates an increase in heat related excess deaths of 46 p.a. in the far future.

Chapter 8

Heatwaves in urban areas

Most Australians live in urban centres and it is well known that cities tend to generate environments that are generally warmer and drier than the surroundings [10]. This has implications for the projections of heatwaves in urban areas, which are expected to be more intense and frequent than in rural counterparts.

A quantitative and rigorous estimation of the urban effects on heatwaves would require cities be explicitly represented in the model. NARCliM simulations do not account for most of the urban factors that alter local climate and only consider differences in the surface properties. This is not enough to fully characterise the urban influence on heatwaves. Furthermore, the scale of NARCliM is still too coarse to correctly represent urban centres and only at spatial resolutions of few kilometres cities begin to be resolved.

Although not focused specifically on heatwaves, two recent studies [8, 9] used the same regional modelling system at 2-km spatial resolution to quantify the contribution of Sydney's urban expansion to local changes under climate change conditions. In addition to high-resolution, these two studies used an urban canopy model to represent the three-dimensional nature of the city and investigate the effects of city growth on local variables relevant to heat-stress assessments such as temperature, humidity and wind. Argüeso et al. [8] determined that nighttime temperature changes due to urban expansion are locally comparable to future changes that arise due to the increase of greenhouse gases. In this case a $2°C$ temperature increase due to climate change by 2050 was accompanied by a further $2°C$ increase in temperatures in newly urbanised areas.

However, these experiments were not formal projections in that they were not performed using a range of models. Instead, they were single realisations that shed light on the urban effects assuming a large-scale change. Therefore, there is an urgent need for further studies in this direction that incorporates the methodology adopted in NARCliM to understand and robustly quantify the repercussions of heatwaves for urban population. This would benefit our preparedness to reduce vulnerability of a population sector that will be likely exposed to more intense and frequent heatwaves and accounts for over 90% of Australians.

Chapter 9

Conclusion and future work

This report presents heatwave characteristics derived from the CAWCR Excess Heat Factor [65, 64] metric, their biases, and projected future changes for the State of New South Wales, and the Australian Capital Territory.

The model displays good ability to simulate heatwaves across NSW and the ACT with almost all present day biases being insignificant.

In the near future significant increases in heatwave frequency and duration are found for much of NSW and the ACT. While increases are projected in the peak heatwave amplitude these increases are not significant in the near future.

In the far future robust future increases in heatwave frequency, duration and peak amplitudes are found across NSW and the ACT. Western NSW is projected to have the most significant increases in peak amplitude. In the far future most of NSW is projected to experience 20 more heatwave days per year than the present day. In many locations this is more than doubling the current number of heatwave days.

Many factors influence the relationship between heat and health outcomes and these are not comprehensively explored here. However, a simple relationship with the EHF as defined in [78] suggests that these heatwave increases may produce increases in excess deaths of 13 in the near future and 46 in the far future. These estimates are made using many assumptions and simplifications. More robust estimates would require a much more in-depth study.

9.1 Recommendations for future work

A number of avenues for research in to heat extremes and their impacts remain to be explored.

Health Impacts

A preliminary literature review around heat related health impacts has been performed here. A comprehensive study that connects heatwave characteristics (rather than the bulk heatwave measure EHF) with health outcomes remains to be performed. Such a study would also include consideration of population growth and vulnerability due to various socioeconomic factors.

Urbanization Impacts

The urban heat island is known to exacerbate high temperatures within urban environments. Explicitly capturing urban landscape effects within future climate projections is required to understand the potential change in heatwaves within cities, including the distribution of impacts across the city which can be substantial for coastal cities like Sydney. Achieving this requires modelling at kilometer scales. With 10km resolution NARCliM is not able to properly capture these effects. The NARCliM-Sydney project demonstrated the ability of the regional models to reach the required scales and given enough resources a robust set of projections could be created at these scales for the greater Sydney region.

Long-term acclimatisation

The EHF explicitly includes a factor to account for acclimatisation over a 30-day period. Long-term acclimatisation (over many years to decades) also occurs such that the heat-health relationships currently calculated likely do not reflect actual health outcomes of the future. Exploring ways to include this long-term acclimatisation in future heatwave estimations and heat-health relationships remains to be done.

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