NARCliM

NSW | ACT Regional Climate Modelling project

NARCliM Technical Note 5

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

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Abbreviations

ACT: Australian Capital Territory

ADAM: Australian Data Archive for Meteorology

AWAP: Australian Water Availability Project

CAWCR: Collaboration for Australian Weather and Climate Research

CC: Central Coast

CWO: Central West and Orana

EHF: Excess Heat Factor

FW: Far West

GCM: Global Climate Model

Hun: Hunter

HWA: heat wave amplitude

HWAt: temperature-equivalent index of heat wave amplitude

HWD: heat wave duration

HWF: heat wave frequency

HWM: heat wave mean magnitude

HWMt: temperature-equivalent index of heat wave mean magnitude

HWN: heat wave number

Ill: Illawarra

IPCC: Intergovernmental Panel on Climate Change

MM: Murray Murrumbidgee

MSyd: Metropolitan Sydney

NARCliM: NSW/ACT Regional Climate Modelling

NC: North Coast

NCEP: National Centers for Environmental Prediction

NCAR: National Center for Atmospheric Research

NENW: New England and North West

NSW: New South Wales

RCM: Regional Climate Model

SET: South East and Tablelands

SRES: Special Report on Emissions Scenario

WRF: Weather Research and Forecasting [WRF] model

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Summary

This report presents a study of past and future heatwave characteristics for New South Wales and the Australian Capital Territory. Heatwave characteristics are defined by using a standard Excess Heat Factor metric and by assessing changes in the number of days over 40 °C. Observations are taken from the Bureau of Meteorology's Australian Water Availability Project (AWAP) daily gridded dataset, and simulations were performed as part of the NSW/ACT Regional Climate Modelling (NARCliM) project.

In general, heatwave intensity, duration and frequency are all projected to increase and, in almost all cases, these increases are statistically significant across the entire state and the ACT.

On the basis of the AWAP gridded dataset, how have the duration, frequency, intensity and timing (i.e. timing within the seasonal cycle) of heatwaves varied across NSW and the ACT over the full observational climate record and the recent past?

Over the last century most of NSW has shown no statistically significant trend in heatwave characteristics. Exceptions include an increase in the hottest day of the hottest heatwave (heatwave amplitude) along the Great Dividing Range; an increase in heatwave frequency along the Eastern Seaboard and in the far west of NSW; and an increase in heatwave maximum duration in the south-east and far west of NSW. Over the last 55 years, scattered parts of NSW have seen increases in heatwave amplitude, larger regions have seen increases in heatwave frequency, and much of central and northern NSW has seen increases in heatwave maximum duration. It is worth noting that the ACT has seen increases in all heatwave characteristics in the last 55 years. On average, heatwaves occur mostly in summer, peaking in January. The observed increase in heatwave days since 1958 has occurred largely in January and February.

How do the duration, frequency, intensity and timing of heatwaves based on the NARCliM 10-km climate data for the 1990–2009 period compare to heatwaves based on observations for this period?

Very few biases between the NARCliM ensemble and AWAP heatwave characteristics are statistically significant indicating very good simulations of heatwaves. The NARCliM ensemble does have a tendency to underestimate the frequency and maximum duration of heatwaves, particularly in the southeast of NSW. On average this underestimate occurs in January and February.

How are the duration, frequency, intensity and timing of heatwaves in NSW/ACT projected to change by 2020–2039 and by 2060–2079 on the basis of the NARCliM 10-km climate projections?

In the near future (2020–2039), statistically significant increases in heatwave frequency (~2% of days) and maximum duration (~2 days) are projected for much of NSW. In the far future (2060–2079), significant increases in amplitude (~1 °C), frequency (~6% of days) and maximum duration (~6 days) are projected across the state. In both cases the frequency increases reflect the current seasonal distribution, with larger increases in January and smaller increases toward the transition seasons.

How do NARCliM heatwave performance and past and projected changes in the duration, frequency, intensity and timing of heatwaves vary between NARCliM models and within the NSW/ACT region (e.g. between inland and coastal areas or between different NSW State Planning Regions)?

The spread across the NARCliM ensemble varies by region and heatwave characteristic. Although differences between models exist, every member of the NARCliM ensemble predicts increases in the key heatwave characteristics of intensity, frequency and duration for every state planning region in the far future.

How do past changes and future projections of NSW/ACT heatwaves differ among different heatwave indices?

Examining changes in the number of days with maximum temperatures above 40 °C emphasises temperature increases in the hottest part of the state, where this threshold is broken most often. It provides little information for most of the rest of the state, where this threshold is rarely broken today or will rarely be broken in the future. Heatwave characteristics based on the Excess Heat Factor index provide a much more informative picture of heatwave changes across the state owing to this factor's explicit consideration of heatwaves significance (relative to location) and short-term acclimatisation. Nevertheless, both the number of days above 40 °C and the Excess Heat Factor index indicate an increase in the frequency of very hot days and heatwaves in the future.

To what extent are urban heat island effects accounted for in the NARCliM projections?

The NARCliM simulations use a very simple representation of urban areas. As such, the representation of urban heat island effects is very crude in these simulations. The resolution of the NARCliM simulations (10 km) is not high enough to explicitly capture urban effects on local climates. Further work will be required to fully understand the role of urban changes in heatwaves, although it is expected that the projected increases may be underestimated over urban areas in the NARCliM ensemble.

Based on links between heatwave indices and human health impacts described in the literature, what might the implications of the projected changes in heatwaves for human health (e.g. mortality, morbidity) be?

The literature around the human health impacts of heatwaves indicates a complex relationship between the urban landscape and the vulnerability of the population. Many factors affect population vulnerability, and there are varying regional dependencies. As such, it is difficult to estimate human health impacts without an in-depth study of the region of interest. While acknowledging the many limitations of the approach, we can extend a previously published methodology [77] to estimate future excess deaths for Sydney at 13 per year in the near future and 46 per year in the far future.

1. Introduction

This report presents heatwave characteristics derived from the Collaboration for Australian Weather and Climate Research (CAWCR) Excess Heat Factor (EHF [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 NSW/ACT Regional Climate Modelling (NARCliM) project [28, 67]. We include results from simulations performed using Regional Climate Models (RCMs) and an observational gridded dataset. The report is organized as follows: section 1 introduces the report and the NARCliM project, section 2 describes the heatwave index and characteristic metrics, section 3 presents climatologies and trends from observations, section 4 compares the NARCliM modelled results with the Australian Water Availability Project (AWAP) observations for the present period (1990–2009), and sections 5 and 6 contain the changes from the present to the near (2020–2039) and far (2060–2079) future periods, respectively. These are followed in section 7 by a short review of heat–health relationships and the health implications of the NARCliM heatwave projections, and then in section 8 by a short discussion of the urban heat island effect. The report concludes in section 9 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).

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 policymaking [28]. Details on NARCliM can be found on The University of New South Wales (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 usability of model outputs by the end-users (e.g. adaptation community). Other benefits of early end-user involvement are improved understanding by 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 the Weather Research and Forecasting [WRF] model using different parameterisations of sub-grid physics). All RCM simulations were performed at a 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 National Centres for Environmental Prediction and National Centre for Atmospheric Research (NCEP/NCAR) reanalysis [47] from 1950–2009. The reanalysis is a numerical ‘reproduction’ of global climate and weather patterns over the years 1950–2009 and is constructed by combining weather observations and climate models. This particular reanalysis was chosen because of its relatively long-term coverage, allowing the production of a 60-year long historical simulation. South-east Australia experienced strong decadal variability in precipitation over the second half of the 20th century, with particularly wet decades in the 1950s and 1970s. These reanalysis-driven simulations provide a strong test of the RCM’s ability to simulate both these very wet periods and the recent dry period known as the Millennium Drought [94]. This phase provides an estimate of the RCM quality, including any systematic RCM biases.

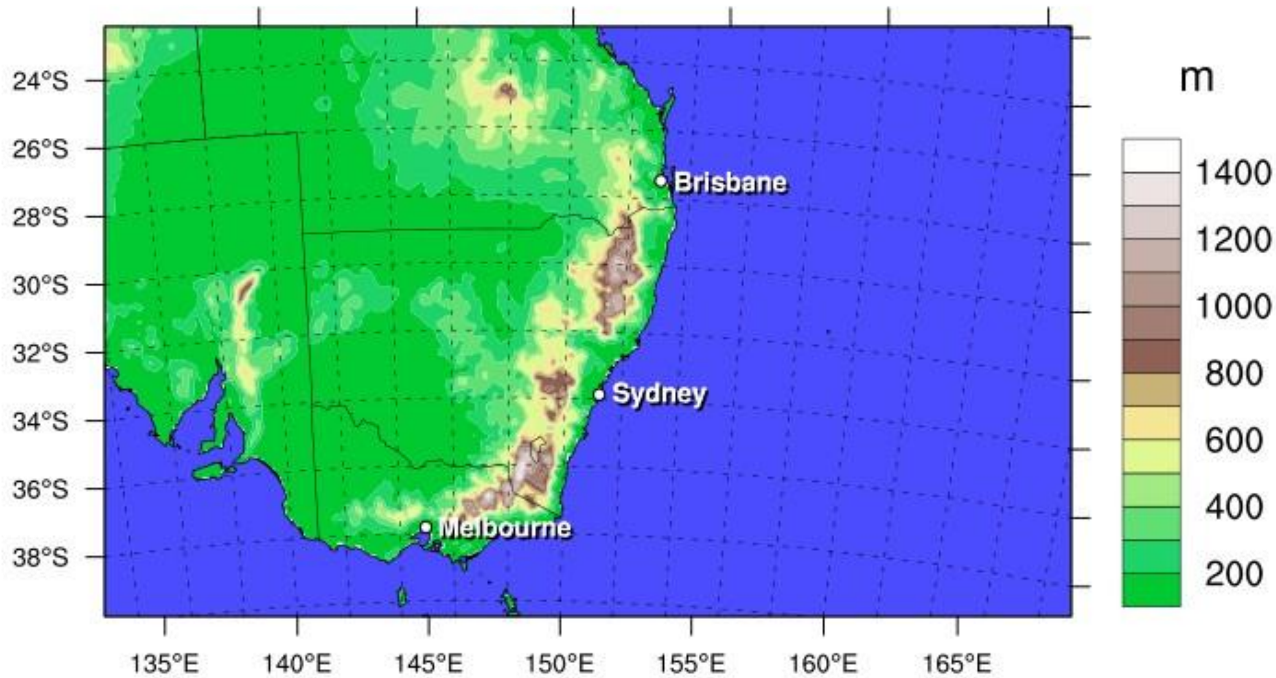


Figure 1.1: Map of the NARCliM domain

In phase two, the three RCMs are used to downscale four GCMs in three 20-year time slices (1990–2009 or 'present'; 2020–2039 or 'near future'; and 2060–2079 or 'far future'). For future projections, the Special Report on Emissions Scenario (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 [27, 26]. The GCMs chosen are the MIROC3.2, ECHAM5, CCCMA3.1 and CSIRO-MK3.0. The chosen RCMs, and the parameterisations used in them, are given in Table 1.1 below. These are versions of the WRF model for different parameterisations of planetary boundary layer, surface layer, cumulus physics, microphysics and radiation.

Table 1.1: The three RCMs selected from a 30-model ensemble

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

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 [71, 24, 100]; KF: Kain-Fritsch cumulus scheme [45, 46, 44]; BMJ: Betts-Miller-Janjic cumulus scheme [15, 14, 41, 42]; WDM 5: WRF Double Moment 5-class microphysics scheme [55]; Dudhia: Dudhia shortwave radiation scheme [23]; 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 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 the daily observations. For the present, near-future, and far-future periods, we use AWAP observations [43] for the period 1990–2009 to calculate corrections. For reanalysis runs, we use AWAP data for the climatological period 1961–1990 to calculate the corrections. An in-depth description of the bias-correction methodology and guidance on when to use the bias-corrected versus the original output are given in report [25]; plots of the bias-corrected climatology can be found in [78].

Results are also presented for individual state planning regions in NSW and the ACT. State region names and their location in NSW are shown in Figure 1.2.

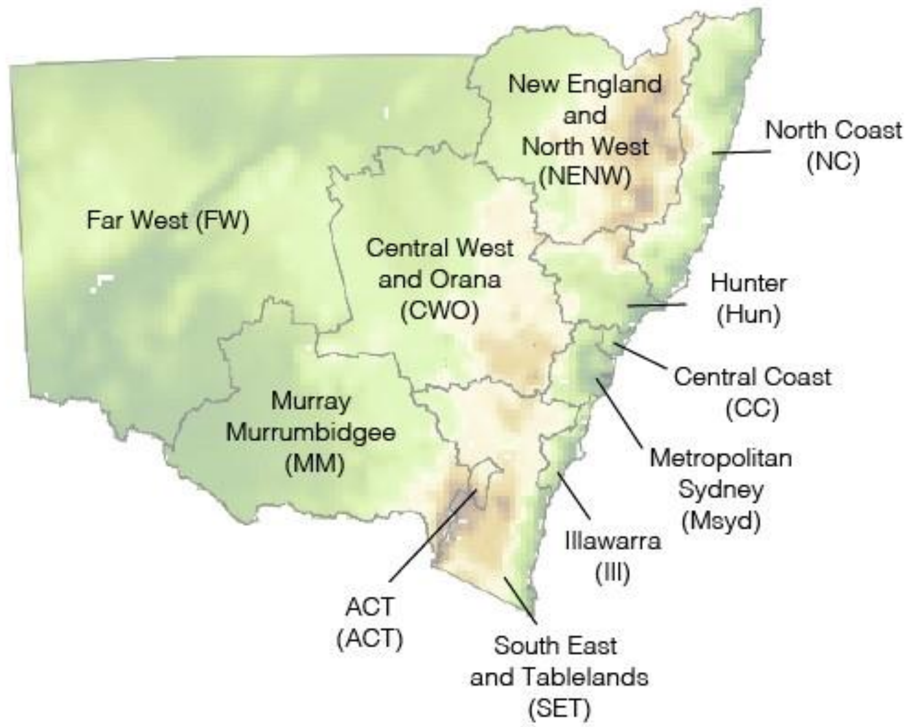


Figure 1.2: Names of state planning regions and abbreviations in NSW and the ACT

1.2 Review of the literature on heatwaves

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

Heatwaves represent a significant hazard in Australia for 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]. Although human and natural systems have adapted to function best within an expected climatic range or ‘thermal coping range’ (e.g. insects [3] and ectotherms [85]), heatwaves represent events outside this range that 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, increased temperatures can lead to unfavourable health outcomes and even death for humans. For example, in early 2009, an exceptional and devastating heatwave [70] and one of the worst bushfires on record struck south-east Australia, costing 173 lives as a direct result of the fires, with many more lost (374 excess deaths in Victoria in 3 days) in the preceding heatwave [4, 66]. These tolls are also seen in other living creatures: for example, extreme temperatures (above 42 °C) in 2002 led to the deaths of over 3500 flying foxes in NSW [102]. Although these are immediate direct impacts from excessive heat, there may also be indirect repercussions from heatwaves, such as increases in the national health burden and insurance losses. In terms of the health burden, it is estimated that extreme temperatures contribute to the deaths of over 1000 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 have been extreme-heat related. As far as human physiology is concerned, excessive heat leads to hyperthermia, a condition in which 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 (e.g. 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 NSW, such as temperature thresholds [12], heat-sensitive conditions [50], lag effects [109], risk factors [101], and distinctiveness in regional responses [57, 96].

Excess heat can also affect crops and food security [60] and this has serious consequences for the Murray–Darling Basin, which is 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 [98]. In terms of insurance, the economic cost of the 2009 heatwave and bushfire disaster alone in south-east Australia was estimated to be US$1.3 billion [63]. Despite the obvious importance of understanding heatwave characteristics, although a heatwave is broadly defined as a period of unusually or exceptionally hot weather, there is currently no universal definition [75]. This has led to a plethora of studies using different metrics that 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 differing numbers of days contributing to a heatwave. Others focus on heatwave duration or frequency, and some on intensity. Similarly, some studies analyse only temperature, using either daily or monthly averaged temperature extremes as proxies for heatwaves in Australia [16, 17, 92], whereas 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 [93, 5, 76, 75, 73] or globally incorporating the Australian region [74, 21, 22], generally finding increasing trends, particularly in frequency or duration.

To provide a more consistent analysis, Perkins and Alexander [75] recommended a framework that defines heatwaves on the basis of aspects of their duration, frequency and intensity, as introduced by Nairn and Fawcett [64]. Perkins and Alexander [75] 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 [75]. Each heatwave characteristic, however, shows different rates and patterns of change across Australia [84]. 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 [75].

By using a warm spell duration metric, Donat et al. [22] showed that heatwave frequency in Australia has been increasing since the early 20th century, whereas 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 EHF definition for a heatwave [64, 66]. The EHF is a measure of heatwave intensity that incorporates two measures of excess heat. In this way, the 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 of extreme heat events on human health [54, 77]. Langlois et al. [54] examined the 2009 south-east Australian heatwave event by 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 it could be a powerful metric for projecting heat-related morbidity and mortality [54, 74]. It is also incorporated into the framework recommended by Perkins and Alexander [75]. For this reason, it is one of the metrics that we present in this report' and a full description is given in section 2.

In NSW specifically, trends in the intensity of EHF-positive events, annual maxima EHF and the severity of EHF events have increased between 1958 and 2011 [66], although, interestingly, there has been a slight decrease in all of these metrics east of the Great Dividing Range. Over a similar period, across NSW and the ACT trends tend to show up more strongly and statistically significantly in EHF measures compared with other heatwave measures (such as days when maximum temperature is above the 90th percentile) using the Perkins and Alexander [75] framework; broadly speaking duration or frequency measures tend to show stronger trends that amplitude measures.

These observed heatwave trends are analogous to the more than doubling of the annual number of record hot days across Australia since 1950 [2], coupled with a mean temperature increase of about 0.9 °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 [91]. The observed heatwave trends are consistent with trends for other regions globally [84]. 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 in NSW and the ACT.

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

2. Methodology

In this section, we describe the methodology used 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 for studying the phenomenon in its full complexity [75]. In this report, we have chosen the EHF metric [64, 65] 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 3 consecutive days through two indices. The first index is a measure of acclimatisation (EHI_{accl}) and compares the 3-day average temperature with the previous 30-day average temperature:

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

where T_i is the daily mean temperature of day i, calculated as the mean between the daily maximum (t_{max}) and minimum (t_{min}) temperatures on a daily 9 am to 9 am cycle, such that t_{min} occurs after t_{max} for day i. The second index is denoted as 'significance' (EHI_{sig}) and determines how extreme the 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 by 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:

$$EHF = max(1, EH\,I_{accl}) \times EH\,I_{sig} \quad (2.3)$$

EHF has $°C^2$ units because it is the product of two temperature anomalies. A heatwave is identified when EHF takes values larger than 1 over 3 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 with information to quantify multiple heatwave characteristics, such as their intensity, frequency and duration ([64, 65]). In this report we will analyse the following metrics (as recommended by [74, 75]):

- **HWA (heatwave amplitude):** amplitude of the hottest day in the hottest heatwave event in a year; the maximum EHF of the heatwave with the highest average EHF in a year ($°C^2$)
- **HWM (heatwave mean magnitude):** average magnitude across all heatwaves in a year; the mean EHF across all heatwave days in a year ($°C^2$)
- **HWN (heatwave number):** number of heatwave events in a year

- **HWF (heatwave frequency):** number of heatwave days expressed as the percentage of days in a year
- **HWD (heatwave duration):** duration of the longest heatwave in a year (days).

The 95th percentile at each location is calculated over the entire year; therefore, virtually all heatwaves estimated by using this EHF definition occur during warm months (November to March). Years are then assumed to begin on 1 July, so that heatwave indices for a given warm season are assigned to a single year, instead of being split into 2 years. In this report, we have decided to denote years by the corresponding December. That is, heatwave indices for 1990 correspond to indices calculated by 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 being considered.

Because HWA and HWM are difficult to interpret in their original units, 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. We thus obtain two new indices (**HWMt** and **HWAt**) that are actual temperatures (°C) and therefore easier to interpret.

Finally, in addition to EHF-related metrics, the number of days in a year when the maximum temperature is above 40 °C is calculated. The resulting index (**TX40**) is an indicator of the occurrence of particularly hot conditions, regardless of their persistence in time. Although hot days are not 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 by using bias-corrected model output. In the case of EHF indices this has only a 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.

3. Heatwaves from AWAP observations

In this section we present an analysis of the heatwave characteristics observed by using temperature from the 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 by 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. Because years are considered to start on 1 July in order to preserve the continuity of the summer season (see section 2), the AWAP record extends from 1911–2013 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].

Calculation of EHF requires the selection of a reference period to calculate the climatological percentiles. Whereas 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 period most suitable for making indices comparable across datasets. Indices calculated over the period 1990–2009 from AWAP by using both reference periods are examined here.

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

3.1 Present-day (1990–2009) heatwaves

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

Figure 3.1 shows the present-day (1990–2009) climatologies for all indices, obtained by using the 1990–2009 reference period. Both heatwave amplitude (HWA) and mean magnitude (HWM) show a similar spatial pattern, with higher values towards the south-west of NSW and lower values along the coast, particularly to the north. The heatwave peak reaches average annual values in the range of 40 to 48 °C^2 in the Murray Murrumbidgee region, and it remains in the interval 8 from 16 °C^2 along the coast. The mean magnitude climatology is 15 to 17.5 °C^2 in areas of the south-west and only 2.5 to 5 °C^2 in the south and on the North Coast. The amplitude and magnitude expressed in temperature-equivalent indices (HWAt and HWMt) show spatial patterns with substantial variation that is similar to the maximum temperature spatial distribution [78] in that they are strongly linked to topography and distance to the ocean. On average, the highest values of HWAt and HWMt are recorded in the north-west corner (34 to 37 °C and 31 to 34 °C, respectively), whereas the lowest values occur along the mountains, particularly to the south (16 to 19 °C for HWAt and 13 to 16 °C for HWMt).

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

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

Finally, TX40, the index measuring the number of days with maximum temperatures above 40 °C has a clear pattern similar to those of 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).

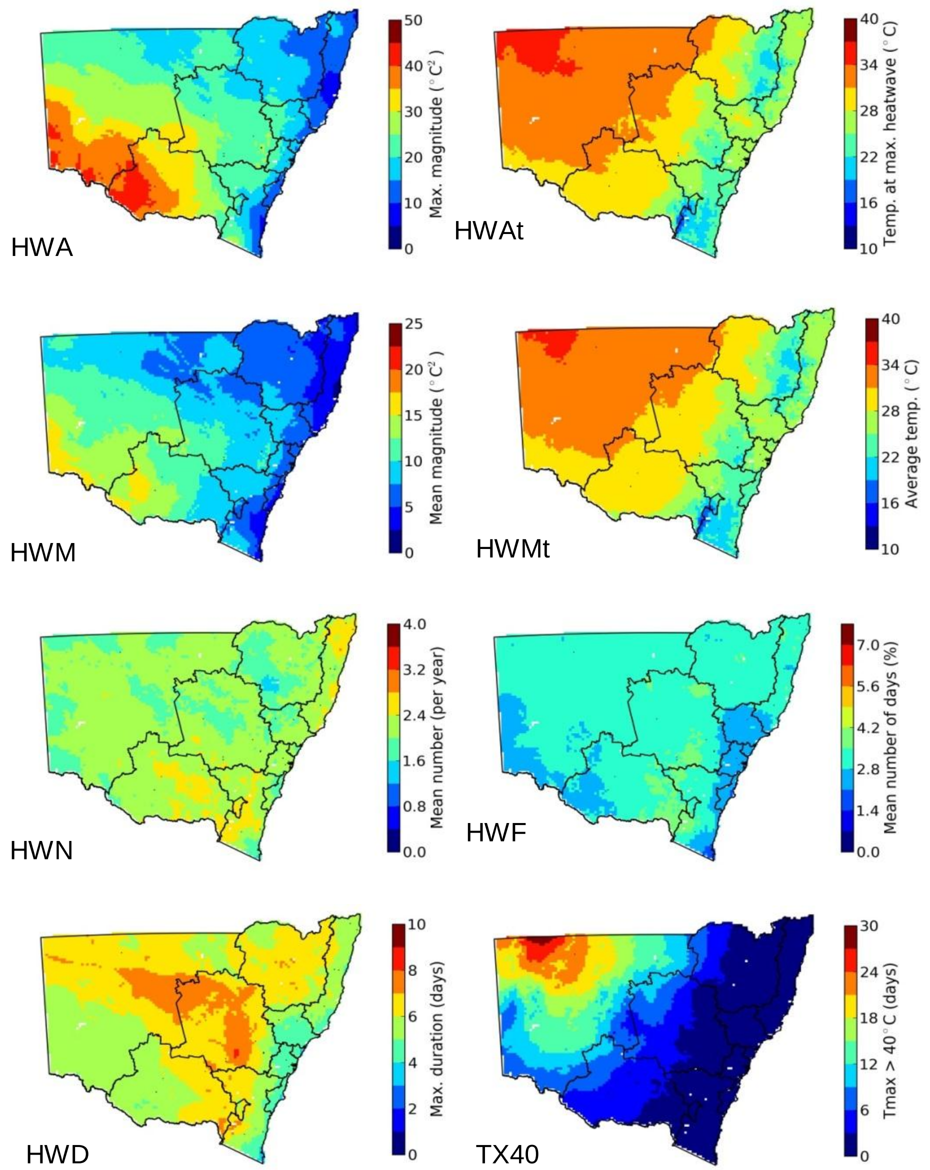


Figure 3.1: Present-day climate (1990–2009) heatwave indices obtained from AWAP observations by using the 1990–2009 reference period

Figure 3.2 shows the monthly number of heatwave days from AWAP observations for the present-day climate (1990–2009). Heatwaves occur exclusively in the warmest months (from November to March), with about 90% of heatwaves during the austral summer. The maximum number of heatwave days occurs in January, with about 5 heatwave days per year.

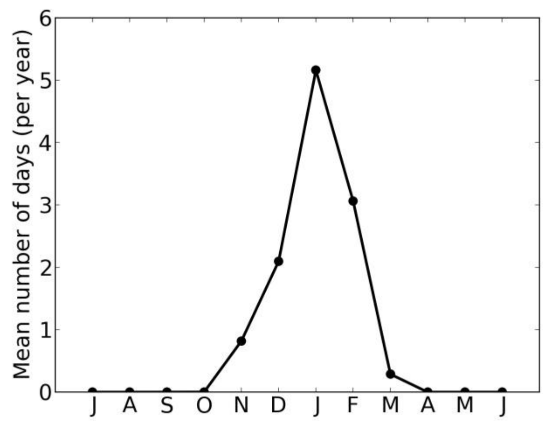


Figure 3.2: Monthly number of heatwave days from AWAP observations for the present-day climate (1990–2009). Results were calculated by using the 1990–2009 reference period and represent the average over NSW and the ACT.

Figure 3.3 shows the present-day 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-day climate simulations span those years. Differences in present-day climatologies (1990–2009) obtained from AWAP between indices calculated by using the 1961–1990 reference period minus indices using the 1990–2009 reference period are shown in Figure 3.4.

Indices quantifying the heatwave amplitude and the mean magnitude show similar results no matter the reference period considered. The heatwave amplitude index shows systematic increases when considering the 1961–1990 reference period, although over most of NSW and the ACT the 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: 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 (HWAt and HWMt) show decreases of less than 1 °C across the state.

Differences in the frequency of heatwave days (HWF) (up to 3% or ~10 days) and the number of heatwave events (HWN) (<2 events) are larger, and so is the mean duration of the longest heatwave (HWD) (up to 3 days). Use of the 1961–1990 reference period tends to produce lower percentile values (Figure 3.5), thus leading to a larger number of days flagged as heatwave days. Although percentile differences are relatively small, a slight shift in the percentile threshold may substantially change the number of days considered as heatwaves.

The number of days with maximum temperature above 40 °C (TX40) is the same in both cases because no reference period is required for its calculation.

Overall, using the 1961–1990 reference period results in more frequent and longer heatwaves, but the intensity of the heatwaves remains comparable with that calculated by using the 1990–2009 reference period. Note 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-day climate conditions with reference to future projections.

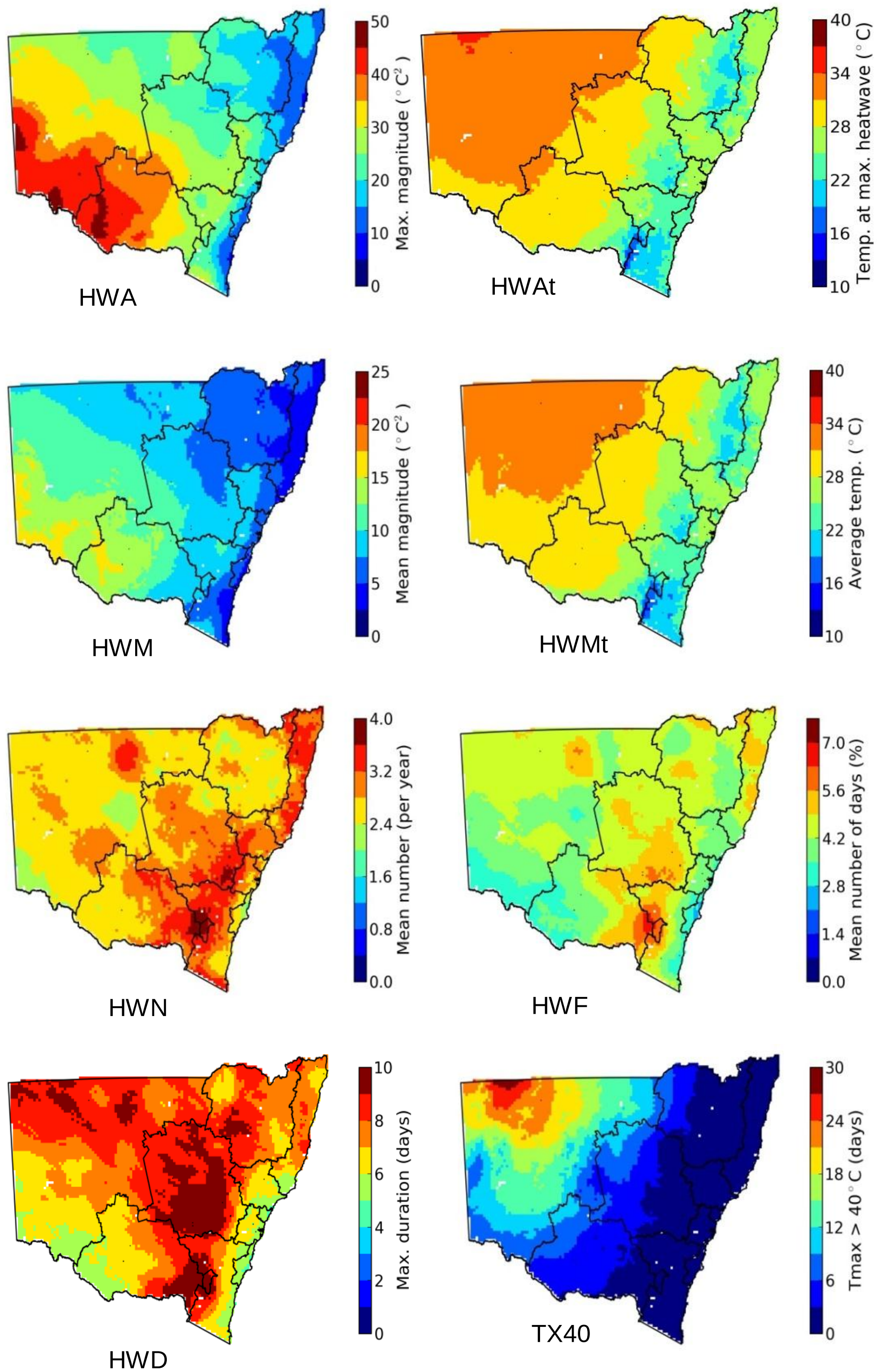


Figure 3.3: Present-day climate (1990–2009) heatwave indices obtained from AWAP observations by using the 1961–1990 reference period

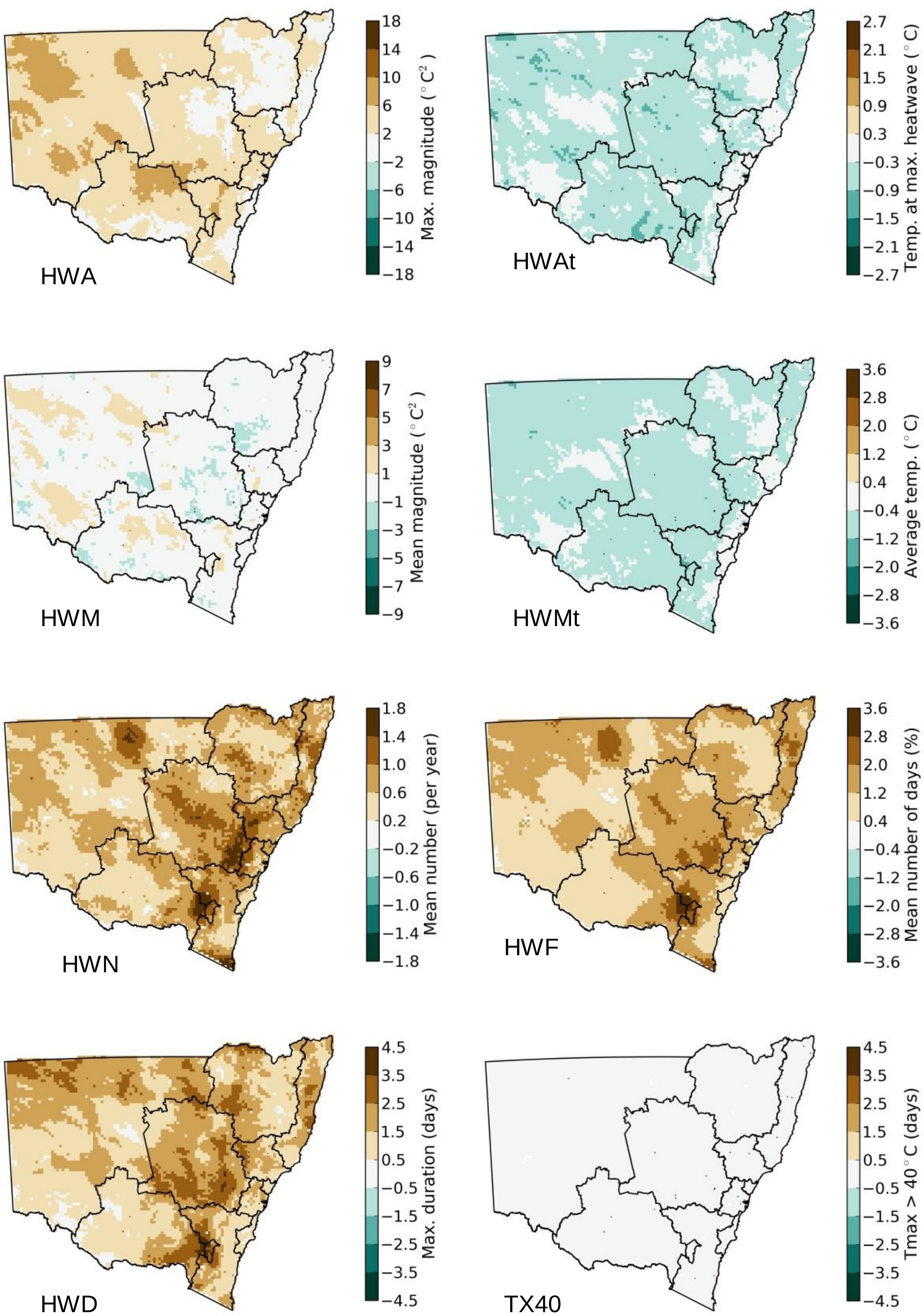


Figure 3.4: Differences in present-day climate (1990–2009) heatwave metrics between indices calculated by using the 1961–1990 reference period minus indices using the 1990–2009 reference period

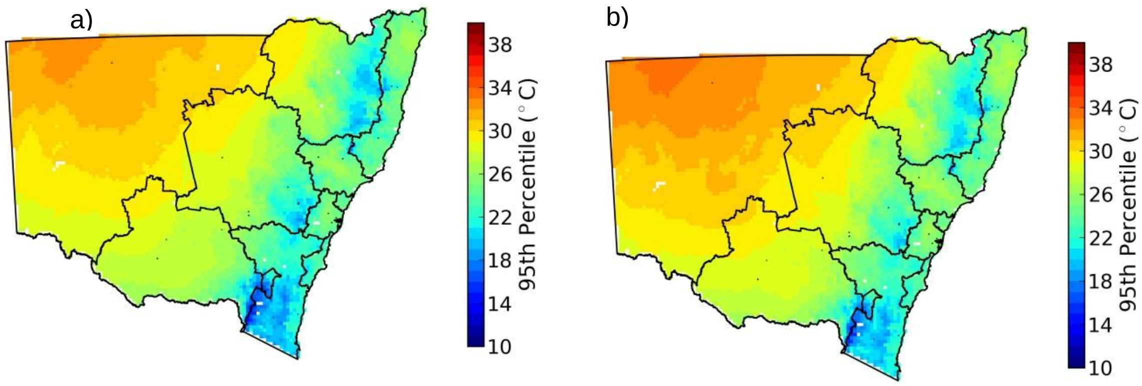


Figure 3.5: Maps of 95th percentile of mean temperature using the 1961–1990 (a) and 1990–2009 (b) base periods

3.2 Past trends in heatwaves (1911–2013)

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

In the resulting maps, trends are estimated by using a linear trend model employed in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC AR5 [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 ($P < 0.05$), also with the IPCC AR5 method. A full description of the method can be obtained from Hartmann et al. [37] (Supp. Mat. Pp. 10–13).

Figure 3.6 shows the decadal trends in each of the EHF heatwave characteristics (described in section 2) over the period 1911–2013 relative to the period 1990–2009, using the relevant units for each characteristic. Stippling indicates that the trends are significant at the 5% level using the IPCC AR5 method. All heatwave characteristics indicate increasing trends over most of NSW. Trends are statistically significantly increasing along the eastern seaboard for the duration and 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 terms of heatwave frequency (HWF - equivalent to about 18 additional heatwave days over the record in that region). Where trends are increasing, the results suggest that there are between about 4 and 11 more heatwave days in a year now than there were at the beginning of the 20th century. In the case of intensity characteristics (e.g. HWA and HWM), most of the statistically significant increasing trends occur along the Great Dividing Range. Increases of up to about 25 $°C^2$ over the whole 1911–2013 period are seen in HWA over parts of the Hunter Valley or, looking at it another way, there is about a 1.4 °C rise in the hottest part of the heatwave on average (see the HWAt trend in Fig. 3.6). There are almost no statistically significant decreases in heatwave characteristics, except in a small region in central northern NSW when considering average heatwave magnitude (HWM). Figure 3.6 also shows that in this region there is also a significant decreasing trend in the number of days above 40 °C (TX40). However, caution needs to be applied when interpreting this result (see section 3.3 Recent-past trends in heatwaves (1958–2013) Recent-past trends in heatwaves (1958-2013).

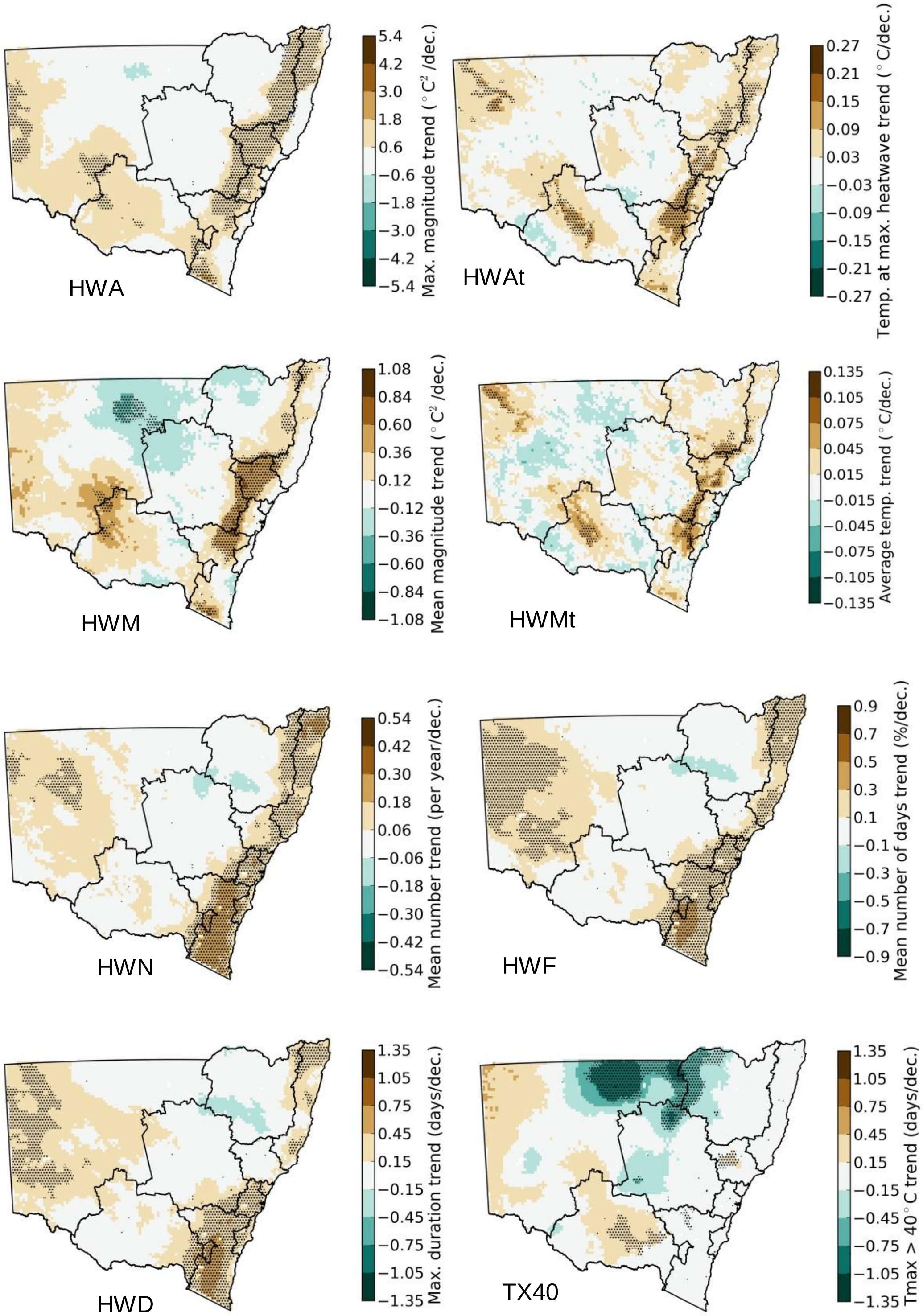


Figure 3.6: Trends in heatwave metrics over the full AWAP record using the 1990–2009 reference period. Stippling indicates that the trends are significant at the 5% level. Trends and significance are calculated by using the method described by Hartmann et al. [37].

Figure 3.7 shows similar plots, but in this case trends in EHF are calculated over the period 1911–2013 relative to the period 1961–1990. The spatial patterns of trends are very similar to those in Figure 3.6 and broadly speaking are 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 1990–2009 period along the South Coast, in the Snowy Mountains region and in the ACT. The statistically significant decline in average heatwave magnitude (HWM) that we saw in Figure 3.6 is no longer seen in Figure 3.7.

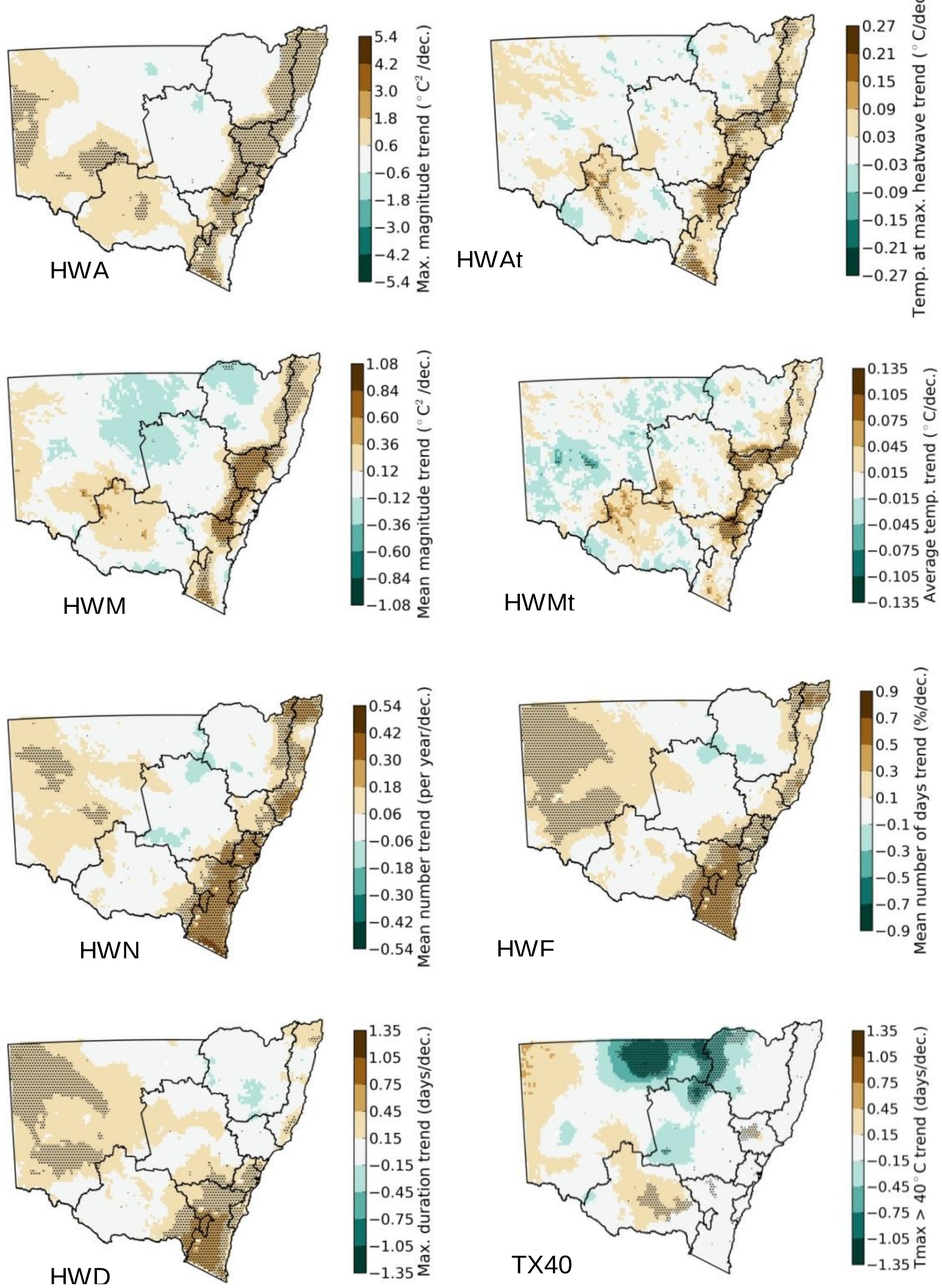


Figure 3.7: Trends in heatwave metrics over the full AWAP record using the 1961–1990 reference period. Stippling indicates that the trends are significant at the 5% level. Trends and significance are calculated by using the method described by Hartmann et al. [37].

Figure 3.8a shows the monthly number of heatwave days from AWAP observations for two past periods: 1911–1957 and 1958–2013. Differences across the two periods (Figure 3.8b) show a general increase in the number of heatwave days in almost every month when heatwaves occur. The largest difference occurs in January: the period 1958–2013 shows about 25% more heatwave days than the period 1911–1957.

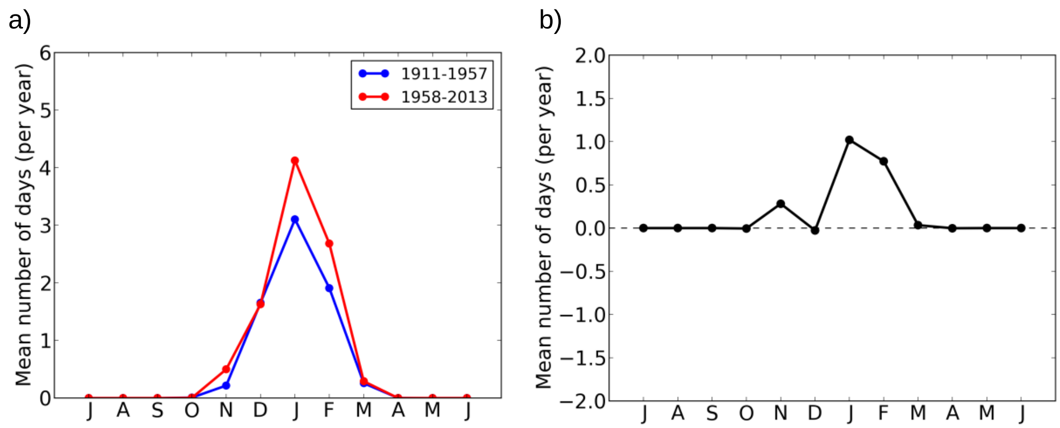


Figure 3.8: Monthly number of heatwave days from AWAP observations for a) two different periods (1911–1957 and 1958–2013) and b) their difference (1958–2013 minus 1911–1957). Results were calculated by using the 1990–2009 reference period and represent the average over NSW and the ACT.

3.3 Recent-past trends in heatwaves (1958–2013)

Note that caveats need to be added to the interpretation of the trends shown in Figures 3.6 and 3.7. For a start, the meteorological data used in AWAP are derived from the Bureau of Meteorology's ADAM (Australian Data Archive for Meteorology) database, 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 that, by extension (owing 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 before 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 time series (e.g. see King et al. [51]). For this reason, we also apply caution to the results that indicate that heatwave intensity characteristics have increased significantly along the Great Dividing Range over the period 1911–2013, because this is a data-sparse region with steep topography.

Because of this issue, we also calculated trends over the 1958–2013 period for each of the heatwave characteristics and for TX40 (Figure 3.9) in order to examine a period where we had more confidence in the robustness of the underlying AWAP data. The results agreed well with those shown in Figure 11 of the work of Nairn and Fawcett [66] (which showed a metric similar to HWM), even though in that study EHF was relative to a 1971–2000 climatology and they used a slightly different trend-calculation method. Across most of NSW and the ACT, mean heatwave magnitude increased (mostly up to a maximum of 0.5 $^{\circ}C^2$ per decade), whereas 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 the El Niño Southern Oscillation, unlike the rest of the state and territory [86]. A similar spatial pattern was seen in the trends in HWA over this shorter period (Figure 3.9), with large statistically significant trends across much of the state and territory in terms of frequency and duration characteristics (HWN, HWD, HWF); this agrees well with the results from Perkins and Alexander [75]. 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.

To conclude, heatwave characteristics have increased across much of NSW and the ACT with only a few exceptions since 1911, with the most significant increases occurring in the east (from the South East and Tablelands region up to the North Coast region) and Far West of the state (see regions in Figure 1.2). A small region where there have been significant declines in TX40 and mean heatwave magnitude (HWM) is found in the northern central part of NSW, 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 (when data became more reliable) across most of the state, except in a region on the eastern seaboard that 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 those in other published literature.

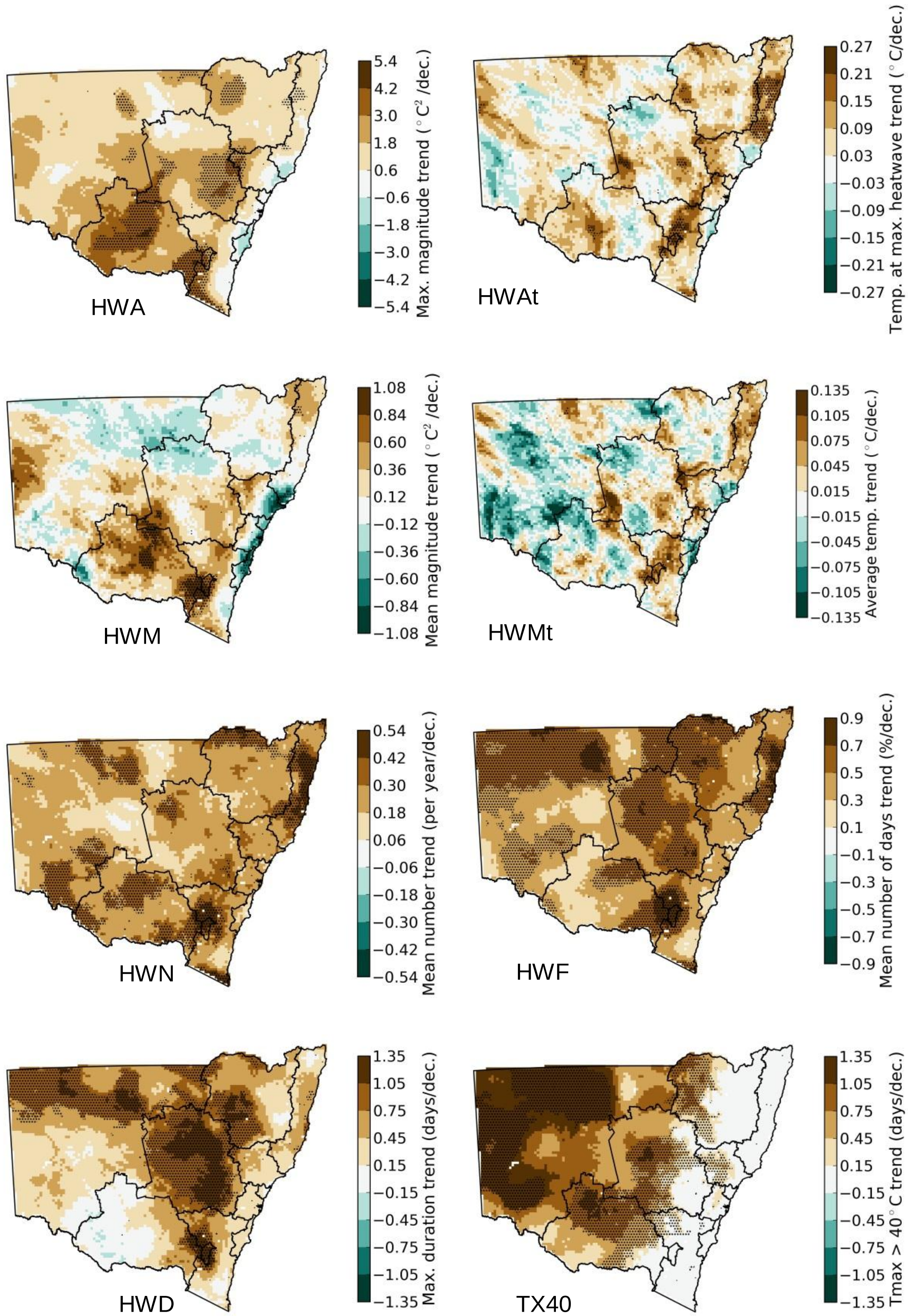


Figure 3.9: Trends in AWAP heatwave metrics over the shorter 1958–2013 period using the 1961–1990 reference period. Stippling indicates that the trends are significant at the 5% level. Trends and significance are calculated by using the method described by Hartmann et al. [37].

4. Present-day heatwave data from NARCliM

This section presents heatwave index climatologies derived from the bias-corrected NARCliM ensemble mean for present-day climate (1990–2009). It also provides a comparison of NARCliM output with AWAP to determine the ability of the NARCliM ensemble to reproduce observed heatwave characteristics. Only results obtained from the bias-corrected model output are shown here. Model output was corrected by using a quantile mapping approach through a Gaussian fitting of the cumulative probability functions (see [25] for a full description of the bias-correction methodology). The heatwave climatologies as derived from the original and the bias-corrected output 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 °C); thus even minor biases would have a major impact on the values of this index.

4.1 Regional model output: present-day climate (1990–2009)

This section analyses present-day climate heatwave indices as simulated by the NARCliM ensemble.

Figure 4.1 shows the NARCliM ensemble means of all heatwave indices for the present-day climate (1990–2009). The average heatwave peak (HWA) from the NARCliM ensemble ranges from 16 to 24 $°C^2$ in the north of NSW to 32 to 40 $°C^2$ 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 the South East and Tablelands regions (up to 20 $°C^2$) 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 larger variability in temperature at higher latitudes than in areas near the tropics; this produces longer tails in temperature probability distribution functions. The mean temperature for the peak (HWAt) and for the mean magnitude of heatwaves (HWMt) both have patterns that are consistent with the spatial distribution of the maximum temperature [78], with larger values in the northern Far West (34 to 37 °C for both HWAt and HWMt) and lower values in high-elevation areas in the south (16 to 19 °C for both indices).

According to the NARCliM output, the northern interior of NSW is where heatwave events (HWN) are more frequent (2.0 to 2.4 heatwaves/year) and the percentage of heatwave days (HWF) is higher (~3% of days), whereas the South Coast and pockets in the south-west have the lowest number 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 or 6 days) and shorter ones along the South Coast (2 or 3 days).

The index that measures the number of extremely hot days (TX40) is distributed similarly to HWAt and HWMt, and therefore similarly to the maximum temperature. In the northern Far West, the maximum temperature exceeds the 40 °C threshold on as many as 30 days/year, whereas in the eastern third of NSW and the ACT temperatures over 40 °C are recorded on fewer than 5 days/year on average. There are regions along the coast that have no days with temperatures above 40 °C.

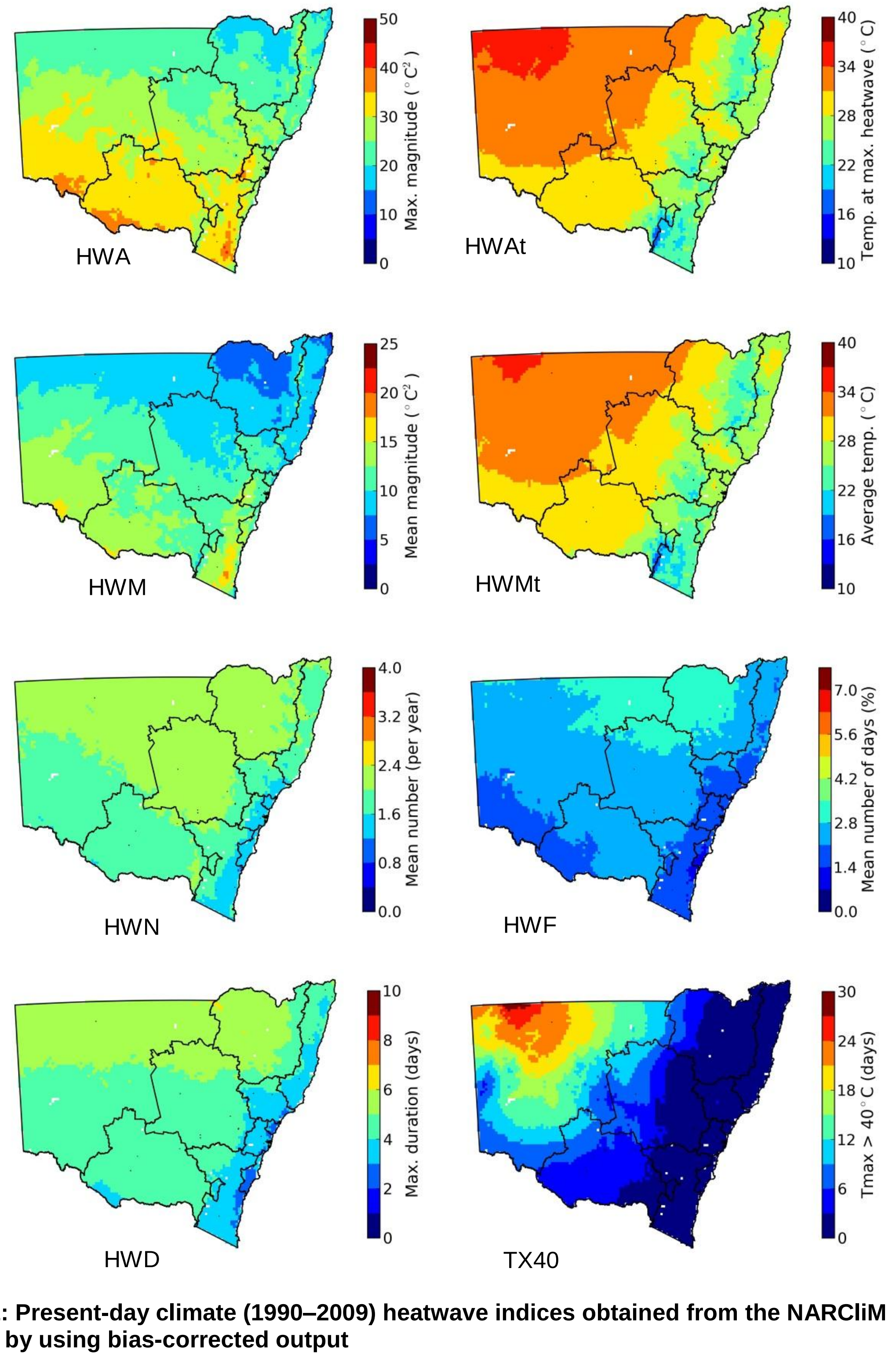


Figure 4.1: Present-day climate (1990–2009) heatwave indices obtained from the NARCliM ensemble by using bias-corrected output

Figure 4.2 shows the monthly number of heatwave days from the NARCliM ensemble for the present-day climate (1990–2009). As with the AWAP dataset, heatwaves occur exclusively in the warmest months (from November to March), with almost 90% of heatwaves during the austral summer. The spread among different members of the ensemble varies strongly throughout the year, being largest in spring and early summer and smallest in late summer and early autumn.

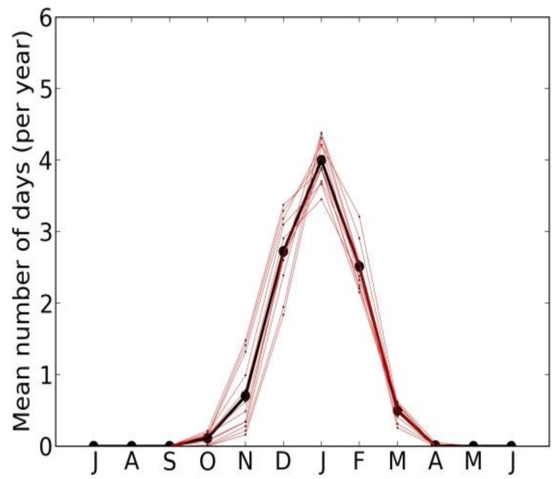


Figure 4.2: Monthly number of heatwave days from the NARCliM ensemble for the present-day climate (1990–2009). Black thick line shows the ensemble mean results and red thin lines show the individual members of the ensemble.

4.2 Biases: 1990–2009 regional model output observations

This section compares the 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 by using the reference period 1990–2009.

Figure 4.3 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, whereas the stippling indicates the level of model agreement. The NARCliM ensemble-mean biases are separated into three categories, namely (a) fewer 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 areas of agreement; stippled with an asterisk ('*') symbol); and (c) at least half of the models show a significant bias but fewer than 80% of significant models agree on the sign of the bias (significant areas of disagreement; stippled with a forward slash ('/') symbol). Therefore, in non-stippled areas the biases are within the interannual variability; this is the preferred outcome. Also, a lack of forward-slash stippling indicates that, among the models, significant areas of disagreement do not appear to be widespread. For each index, the significance of biases of individual models was estimated with respect to the interannual variability by using Student's *t*-test at the 5% significance level ($P < 0.05$).

The NARCliM ensemble mean produces heatwaves that are too intense along the coast, especially in the north and south, in terms of both amplitude (HWA, by 14 to 18 $°C^2$) and mean magnitude (HWM, by 7 to 9 $°C^2$). It also simulates less extreme heatwaves peaks (HWA) and, to a lesser extent, milder mean heatwave magnitude in the south-western corner. However, most of these differences are not statistically significant compared with 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 (by 0.5 to 2.5 °C) and underestimated over limited areas in the south-west (by –0.5 to –1.5 °C). However, similar to the case with 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 that in AWAP in most regions, and only small overestimations are produced along the coast (by 1 to 3 °C). Very small biases (between –1 and 1 °C) in New England, the North West, and Murray Murrumbidgee regions are statistically significant despite their magnitude.

Comparison between the NARCliM ensemble and AWAP suggest that simulations are producing less frequent heatwaves (HWN) in the south and along the coast (by up to 1.0 to 1.4 fewer heatwaves/year). New England and the North West, and the Central West and Orana regions, are exposed to slightly more heatwaves in NARCliM simulations than in AWAP (by 0.2 to 0.6 heatwaves/year). Only small pockets in the south-eastern corner are subjected to statistically significant biases, with NARCliM showing a decrease in the number of heatwaves and number of heatwave days, together with shorter heatwaves, compared with AWAP. In terms of the number of heatwave days, NARCliM simulates slightly lower values over most of the state (0.4% to 1.2% fewer 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% fewer heatwave days per year).

Similarly to the case with the frequency of heatwave days, NARCliM tends to produce shorter heatwaves over most of the state. The longest yearly heatwaves in NARCliM last, on average, for 0.5 to 2.5 fewer days than in AWAP over large areas of NSW and the ACT. Sectors in the interior and the southern mountains show larger biases whereby heatwaves are between 2.5 and 3.5 days shorter in NARCliM than in AWAP. Except in these areas in the interior and the southern mountains, differences are generally not significant compared with 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 the NARCliM outputs were bias-corrected by using AWAP. Nonetheless, there are residual biases in the north-west (3 to 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 north-west owing to the scarcity of available monitoring stations.

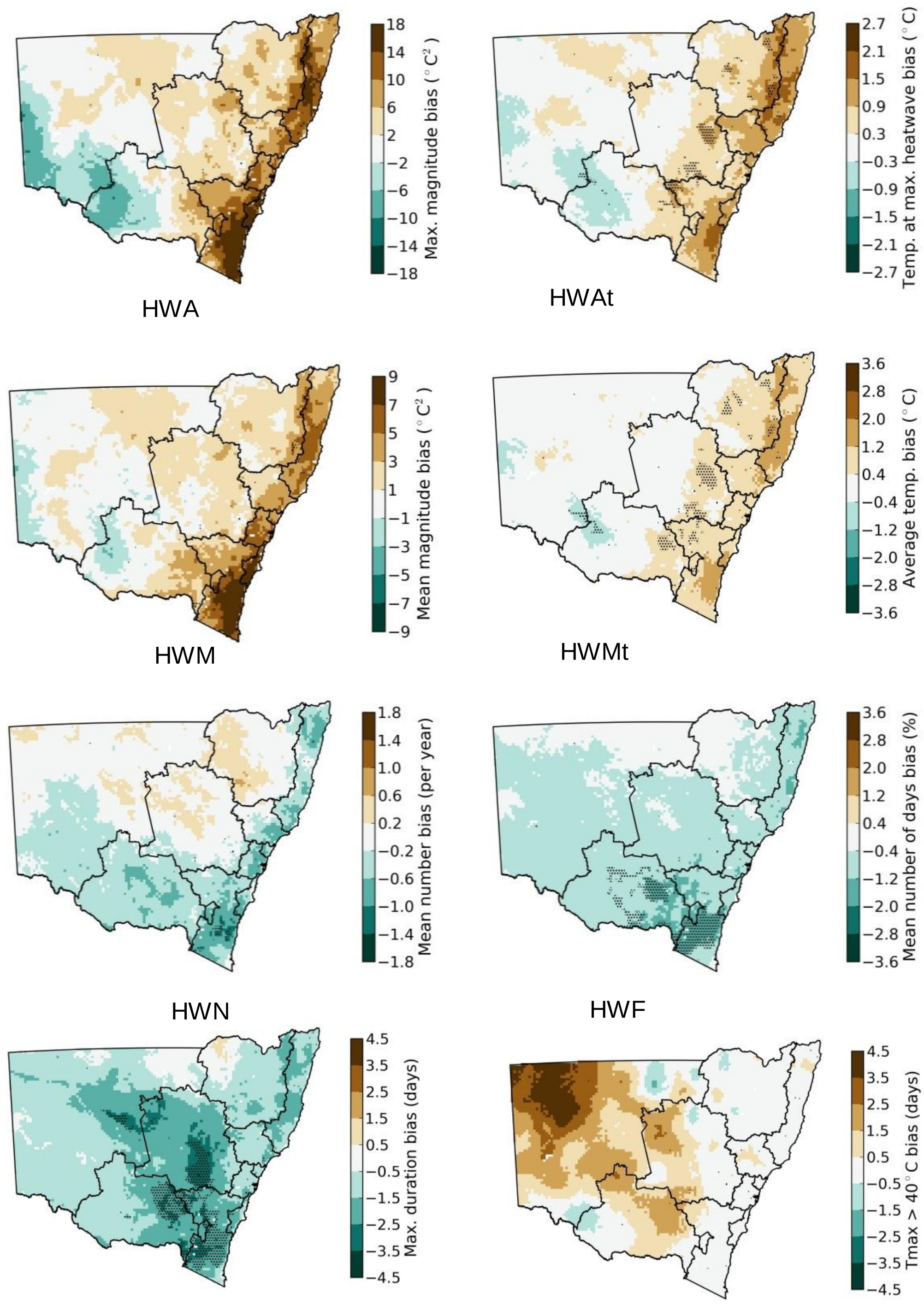


Figure 4.3: Bias of each heatwave index between the NARCliM ensemble mean and AWAP observations for present-day climate (1990–2009), as obtained by using the 1990–2009 reference period. Stippling indicates areas where the biases are significant for at least half of the models and at least 80% of them agree on the sign of the bias (see section 4.2 for details).

Figure 4.4 shows the monthly differences between the numbers of heatwave days in the NARCliM ensemble and in the AWAP dataset for the present-day climate (1990–2009). Nearly 75% of the NARCliM ensemble members show an excess of the number of heatwave days compared with AWAP in late spring and early summer, and all members show a smaller number in January and February. This suggests that the NARCliM ensemble somewhat shifts the occurrence of heatwaves to earlier in the warm season compared with AWAP.

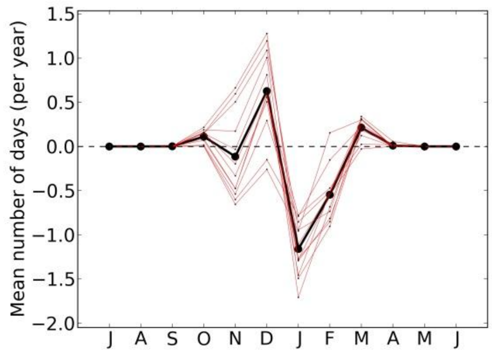


Figure 4.4: Monthly number of heatwave days from the NARCliM ensemble for the present-day climate (1990–2009) compared to heatwave days based on the AWAP dataset for this period. Black thick line shows the ensemble mean results and red thin lines show the individual members of the ensemble.

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 region names in Figure 1.2) are shown in Figure 4.5. This region-based representation also shows the variability across NARCliM ensemble members for each index (as shown by box plots) across the various regions. Values from AWAP serve as observational references and are also included (as black squares).

As with previous figures, the NARCliM ensemble tends to underestimate the intensity of heatwaves (HWA and HWM) in most regions. Such deviations in intensity are particularly noticeable in regions along or near the coast (SET, Ill, NC, CC and MSyd; see Figure 1.2 for acronym details), where the AWAP mean values lie outside the range of the NARCliM ensemble members. On the other hand, the NARCliM ensemble is very close to the 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 in the south-east; this makes some of these regions climatologically indistinguishable in terms of NARCliM although substantially different in terms of observations (e.g. Ill and CWO for the HMA index). The spread is partly associated with the definition of indices; percentiles are calculated for each location, and thus differences among regions mostly reflect their temperature variability, not relative differences in temperature magnitude.

The temperature-equivalent indices for heatwave peak (HWAt) and magnitude (HWMt) show a much better agreement of the NARCliM ensemble with the 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 4.3 the remaining biases are within the interannual variability and thus statistically non-significant. Differences among regions are more apparent in this case, because the metrics are related to absolute temperature values. Both the observations and the NARCliM ensemble produce higher values of both HWAt and HWMt in the interior (FW, MM and CWO) than on the coast, with HWAt reaching up to 33 °C (3-day temperature mean), whereas the lowest values are found in elevated regions (e.g. the ACT; HWAt ~23 °C) or in regions to the south-east (SET and Ill; HWAt ~24 to 25 °C).

The number of heatwaves (HWN) and frequency of heatwave days (HWF) are very similar across regions. According to AWAP, all regions experience ~2 to 2.5 heatwaves/year on average, whereas the NARCliM ensemble mean is slightly lower, with frequencies as low as 1.5 heatwaves/year in the Illawarra (Ill) region, where the spread across models is also quite large. Once again, NARCliM members seem to perform better in inland regions (FW, CWO, and NENW), although for most regions the observations are within the NARCliM range. NARCliM simulations show better agreement in these regions too, whereas spread across members tends to be larger in regions over the southern half of the coast. The frequency of heatwave days (HWF) presents a variability across regions that is similar to that of HWN, although differences in the NARCliM spread are not as marked among regions. NARCliM also tends to underestimate the heatwave day frequency, especially in south-eastern regions. Both NARCliM members and the observations show fewer heatwave days in regions along the southern half of the coast (Ill, CC, MSyd) than elsewhere, but they disagree in the southernmost region (SET) because observations rank it among the regions with the highest frequency (above 3% of days), in contrast to the NARCLiM mean.

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 the number of heatwave days. Nonetheless, the differences among regions observed in AWAP are reproduced well by the NARCliM ensemble, with the longest heatwaves concentrated in FW, CWO and NENW. The exception is the ACT, a region that AWAP places among those with the longest heatwaves on average (~6 days), whereas the NARCliM ensemble does not (<4 days). The spread across NARCliM is generally small in all regions, with the interquartile range being 1 day for all regions except for the Far West, where the interquartile range is about 1.5 days.

Finally, the number of days when the maximum temperature exceeds 40 °C (TX40) is very well captured by the NARCliM ensemble. Similar to the case with HWAt and HWMt, such accuracy is obtained partly through bias correction. In most regions, the 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 experiences, on average, as many as 15 days per year with temperatures above 40 °C. The temperature reaches this threshold on 4 or 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 the largest disagreement occurs in FW. For most of the other regions all models produce similar values of TX40 and are in agreement with AWAP observations.

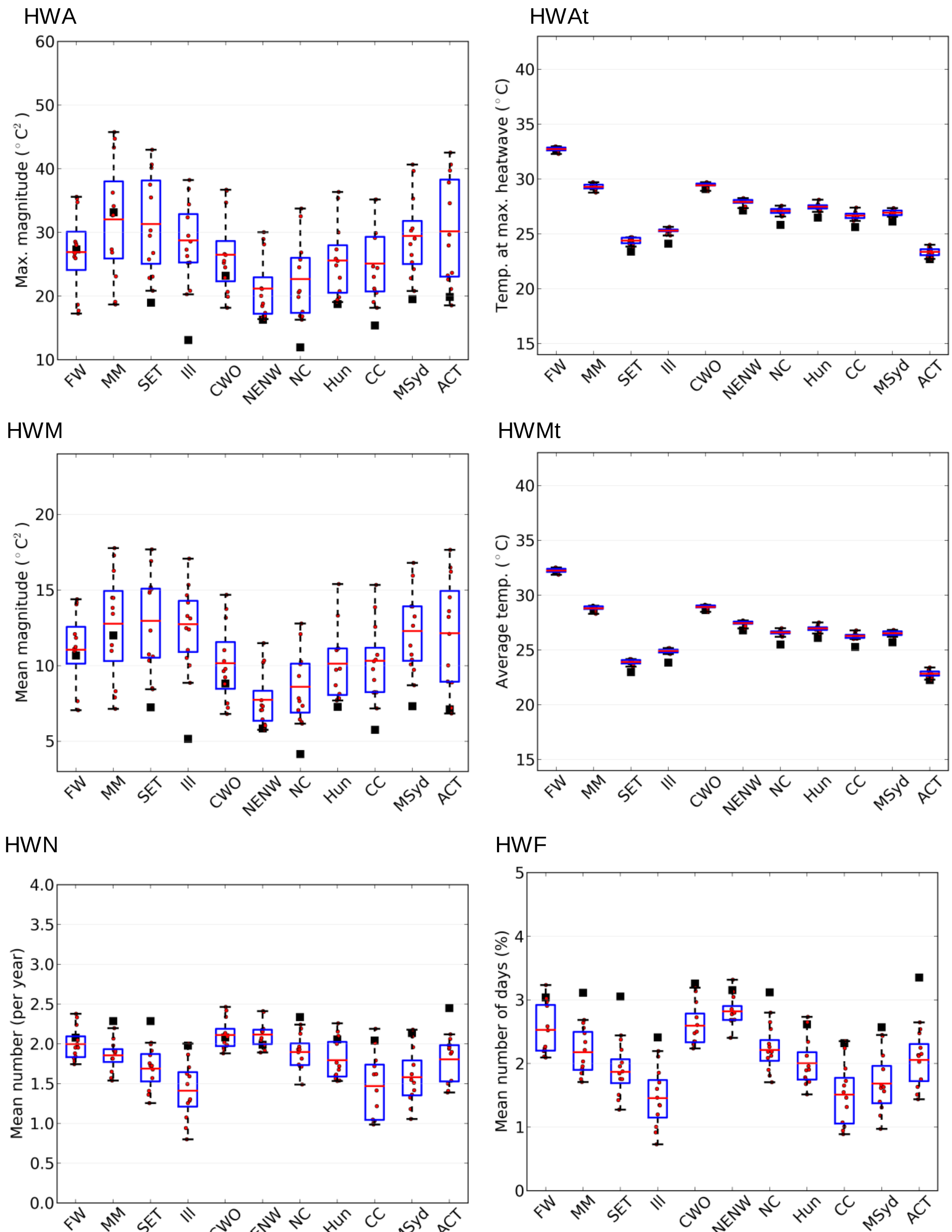


Figure 4.5: Present-day climate (1990–2009) heatwave indices obtained from the NARCliM ensemble by using bias-corrected output. The NARCliM ensemble model mean (red line), interquartile range (blue box) and ranges (whiskers) are represented for each heatwave index and region. Red circles represent values from individual models and black squares represent AWAP observations.

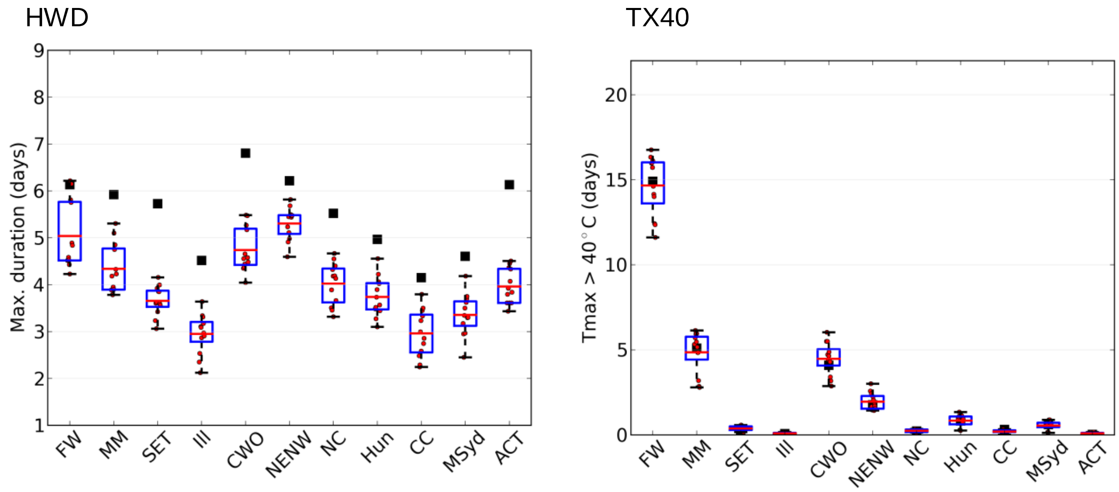


Figure 4.5 ***continued***

4.4 Summary

Comparison of the NARCliM ensemble and observations indicates that differences between the two datasets exist, but on the whole these differences 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 in 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 south-west to north-east 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 south-east regions.

Indices that rely on absolute temperature values (HWAt, HWMt and TX40) are very well reproduced by the NARCliM ensemble and by individual members (i.e. there is a very small range). This is partly due to the bias correction applied to the NARCliM ensemble.

5. Near-future simulated changes compared with the present-day period

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

5.1 Regional model output: near-future climatologies (2020–2039)

This section presents near-future (2020–2039) projected climatologies of heatwave indices. Figure 5.1 shows the NARCliM ensemble means 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 the South East and Tablelands region (up to 20 °C^2) and the lowest in the New England and North West and parts of the North Coast. As discussed in section 4.1 Regional model output: present-day climate (1990–2009) (Regional model output: present-day climate (1990-2009), this overall latitudinal gradient is explained by the larger variability in temperature at higher latitudes than in areas near the tropics; this 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 [78], with larger values in the northern Far West (34 to 37 °C for both HWAt and HWMt) and lower values in the high-elevation areas in the south of NSW (16 to 19 °C for both indices).

According to the NARCliM output, the northern interior of NSW is where the number of heatwave events (HWN) will increase (about 3.2 heatwaves/year), as will the frequency of heatwave days (HWF; ~5% of days), whereas the South Coast and the south-west show the lowest numbers 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 or 9 days) and shorter ones along the South Coast (5 or 6 days).

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

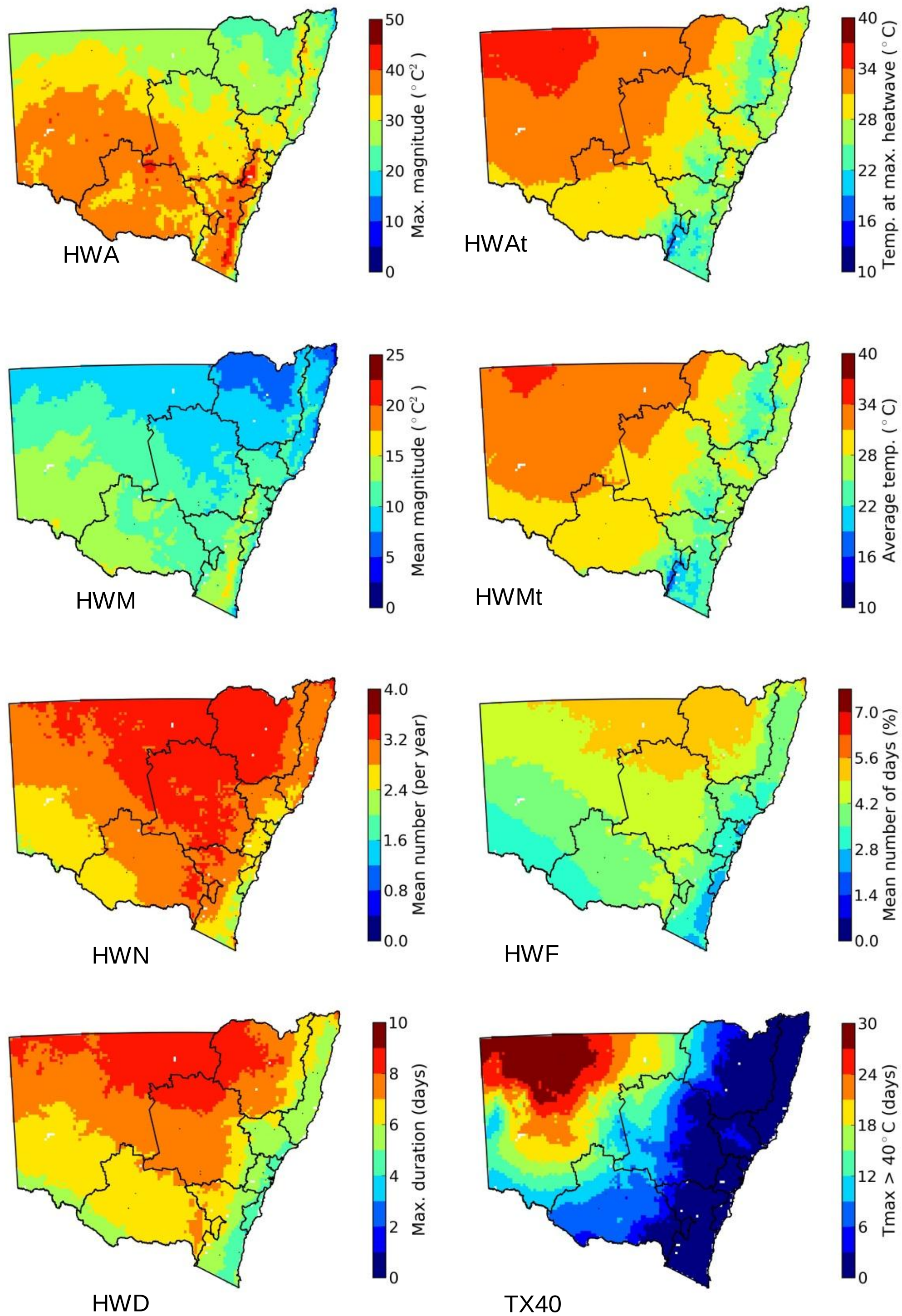


Figure 5.1: Near-future (2020–2039) projected climatologies for heatwave indices obtained from the NARCliM ensemble by using bias-corrected output

5.2 Regional model output: near-future changes (2020–2039) with respect to the present-day 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, whereas the stippling indicates the level of model agreement. The NARCliM ensemble-mean changes are separated into three categories, namely (a) less than half of the models show a significant change (insignificant areas; ensemble-mean change shown in colour); (b) at least half of the models show a significant change and at least 80% of the significant models agree on the sign of the change (significant areas of agreement; stippled with an asterisk ('*') symbol); and (c) at least half of the models show a significant change and fewer than 80% of significant models agree on the sign of the change (significant areas of disagreement; stippled with a forward slash ('/') symbol). Non-stippled areas thus indicate that changes are within the interannual variability; this is the preferred outcome. Also, a lack of forward-slash stippling indicates that significant areas of disagreement among the models do not appear to be widespread. For each index, the significance of changes in individual models was estimated with respect to the interannual variability by using Student's *t*-test at the 5% significance level ($P < 0.05$).

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. In fact, according to the NARCliM ensemble, almost the entire region will exhibit changes in HWAt and HWMt that will not exceed 0.5 °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 south-east. This is a consequence of how the index is built. The mean magnitude of heatwaves may decrease, despite a considerable increase in the number of heatwaves. This is because mild heatwaves will increase much more than severe heatwaves. A detailed explanation of this feature, with a practical example is provided in section 6.4.

On the other hand, the NARCliM results indicate that indices of the frequency (HWF and HWN) and duration of heatwaves (HWD) will undergo statistically significant changes with respect to 1990–2009 over most of NSW and the ACT, even for this 30-year time horizon. According to the NARCliM ensemble, HWN will increase by between 0.9 and 1.5 heatwaves per year almost everywhere in NSW, with the exception of the southern interior and the North Coast (NC). In terms of the number of heatwave days (HWF), all regions except the NC and parts of NENW exhibit statistically significant changes, although the northern interior would see the largest changes (an increase of 2.1% to 2.7% of days, equivalent to ~7.5 to 10 more heatwave days per year). Similarly, the longest heatwave in a year (HWD) will be 1.5 to 3.5 days longer on average over most regions, with exceptions along the coast and in the south-western corner. Such changes in the duration of heatwaves are statistically significant over most areas.

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

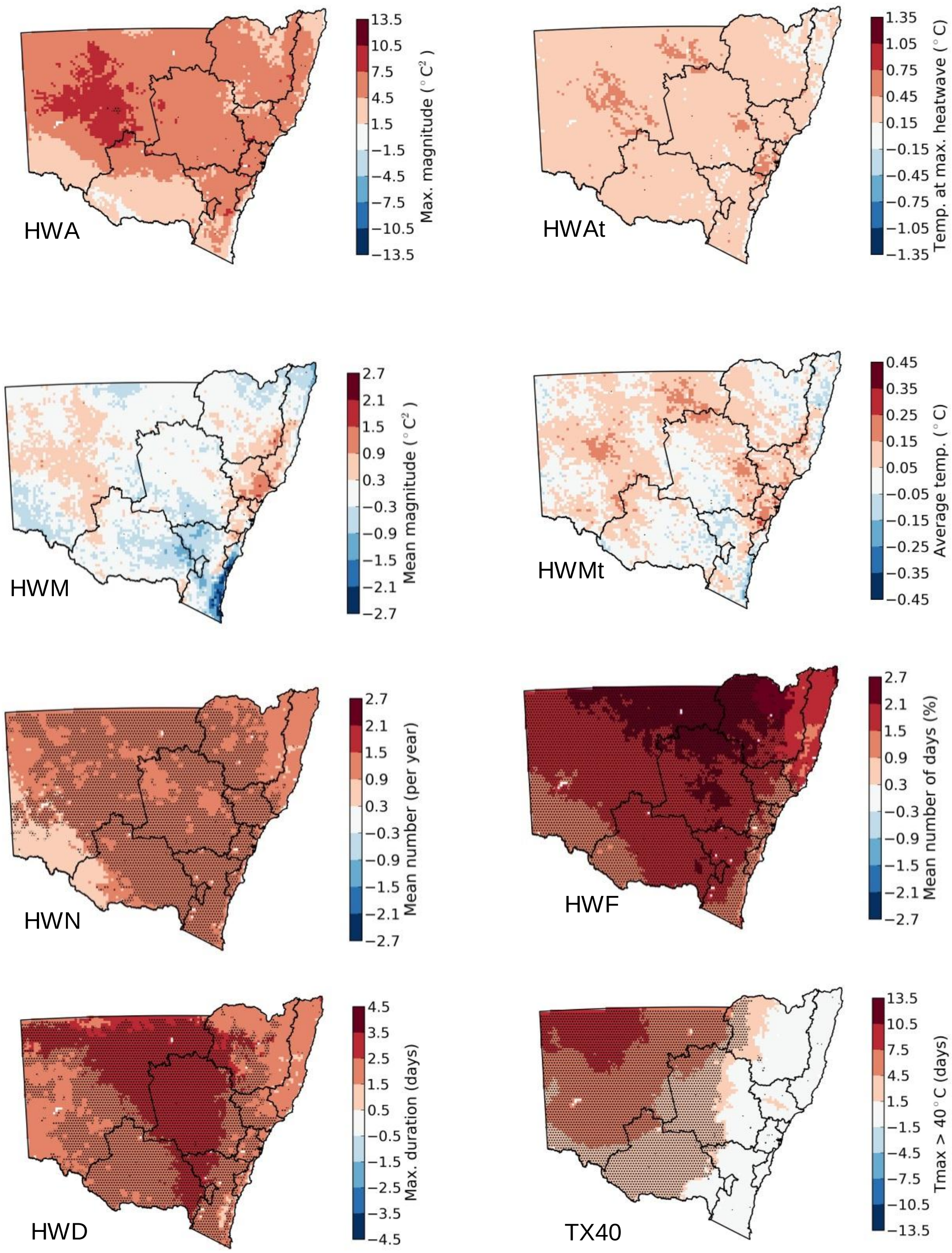


Figure 5.2: Near-future (2020–2039) projected changes for heatwave indices obtained from the NARCliM ensemble by using bias-corrected output with respect to the present-day climate (1990–2009). Stippling indicates areas where future changes are significant for at least half of the models and at least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

Figure 5.3 shows the monthly number of heatwave days for the near-future period (a) and the change compared with the present-day climate (b), as obtained from the NARCliM ensemble. Averaged across NSW and the ACT, the NARCliM ensemble mean projects an increase of about 75% in the number of heatwave days in the near future compared with present-day values. There is, however, an important spread among members of the ensemble, with some members showing modest increases of about 25% and others much stronger increases of more than 100% compared with present-day values.

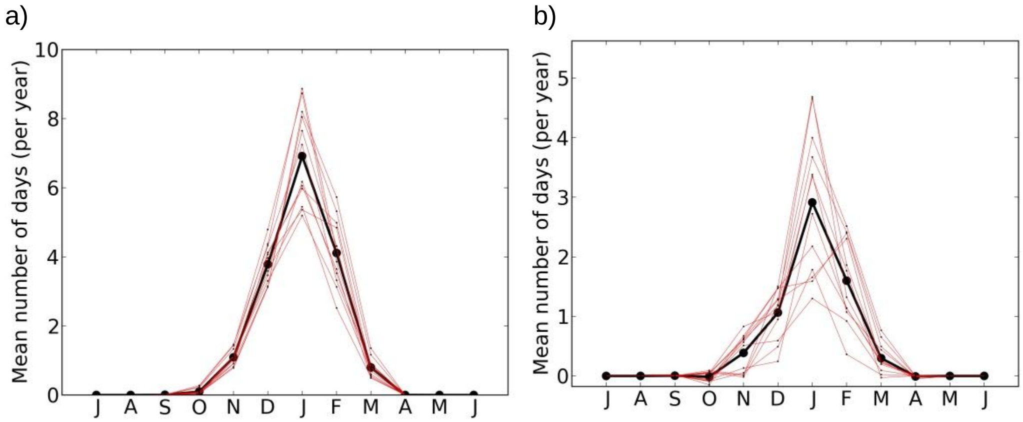


Figure 5.3: Monthly number of heatwave days from the NARCliM ensemble for a) near-future climate (2020–2039) and b) near-future changes compared with the present-day period. Black thick line shows the ensemble mean results and red thin lines show individual members of the ensemble.

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

This section presents an analysis of the near-future changes for each individual region in NSW (see Figure 1.2 for regions). Figure 5.4 shows near-future projected changes (2020–2039 minus 1990–2009) in 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 (~5 $°C^2$), although there is a substantial spread across individual members, with a few of them even projecting slight decreases in HWA. There does not seem to be a clear pattern explaining the differences in spread among regions, with FW and MSyd showing the smallest interquartile ranges (~5 $°C^2$) and MM, SET and NENW the largest (>10 $°C^2$).

Patterns are clearer in the case of 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 centre and near the coast (Hun, CC, and MSyd), together with the ACT, show the largest changes according to the NARCliM ensemble (0.4 to 0.5 °C). In these regions and NC, NARCliM members show the largest disagreement in projections, whereas the NARCliM simulations show a reduced spread in the western and southern regions.

In the case of the mean magnitude of heatwaves (HWM), the NARCliM mean projects both decreases (SET, Ill and ACT) and increases (in the rest of the regions), although this is largely explained by the way the HWM index is defined in present and future climates (see section Figure 6.4: Far-future (2060–2079) projected changes in heatwave indices, as obtained from the NARCliM ensemble by using bias-corrected outputs with respect to the present-day climate (1990–2009). The NARCliM ensemble mean change (red line), interquartile span of changes (blue box) and range (whiskers) of changes are represented for each heatwave index and region. (See Figure 1.2.) Red dots represent values from individual members.

6.4 Interpreting changes in the HWM index: Interpreting changes in the HWM index, for further details). NARCliM mean changes, however, appear to be quite uncertain, with the NARCliM ensemble showing a large spread in all regions and individual members suggesting different directions of change. In this case, models seem to agree better in the north-eastern quarter (NENW, NC, Hun, CC, MSyd and FW) and are more discordant in the south (MM) and south-east (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 most cases, the spread of models spans the zero-change line. The Hun, CC and MSyd regions, however, show that 75% of the members predict an increase in HWMt, suggesting some more robust information there.

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

On the other hand, the frequency and duration of heatwaves are expected to increase in all NARCliM models and regions. All regions except for NC are projected to experience increases of slightly more than one additional heatwave per year on average according to the NARCliM means. The distribution of individual models indicates that larger uncertainty in these changes occurs in NC, along with NENW and Hun, where the interquartile ranges are the largest. Similar results are obtained for the frequency of heatwave days, which is projected to increase by from 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, as mentioned before. In most regions the interquartile range is below 1% of days, and in some cases models tend to agree even better, with the interquartile range being ~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 occur in CWO (just below 3 days longer), followed by FW and NENW (~2.5 days longer). NC shows the lowest values, with changes hardly exceeding 1 day, although once again NC is among the regions with largest spread. According to [78], NARCliM models showed large disagreement over this region in terms of temperature and precipitation changes during summer, when most heatwaves occur. Note that the ACT shows notable and consistent increases in HWN, HWF and HWD.

Finally, Figure 5.4 shows that the number of extremely hot days (TX40) is projected to increase in the near future in all regions of NSW and the ACT according to the NARCliM ensemble means. In most regions there are few exceptions where individual models project slight decreases, and the interquartile ranges project positive changes for all regions. According to the NARCliM ensemble, regions with the largest present-day climate values will also be prone to the largest increases in TX40. For instance, the NARCliM ensemble-mean projects increases of about 6.5 days in FW and about 3 days in MM and CWO. The rest of the regions remain in the range 0 to 2 more days above 40 °C, with the ACT and Ill experiencing almost no changes. NARCliM ensemble members display substantial spread in some regions, especially over the western half of NSW, with a spread that varies between 3 and 10 days, but they agree in projecting little to no changes over eastern regions.

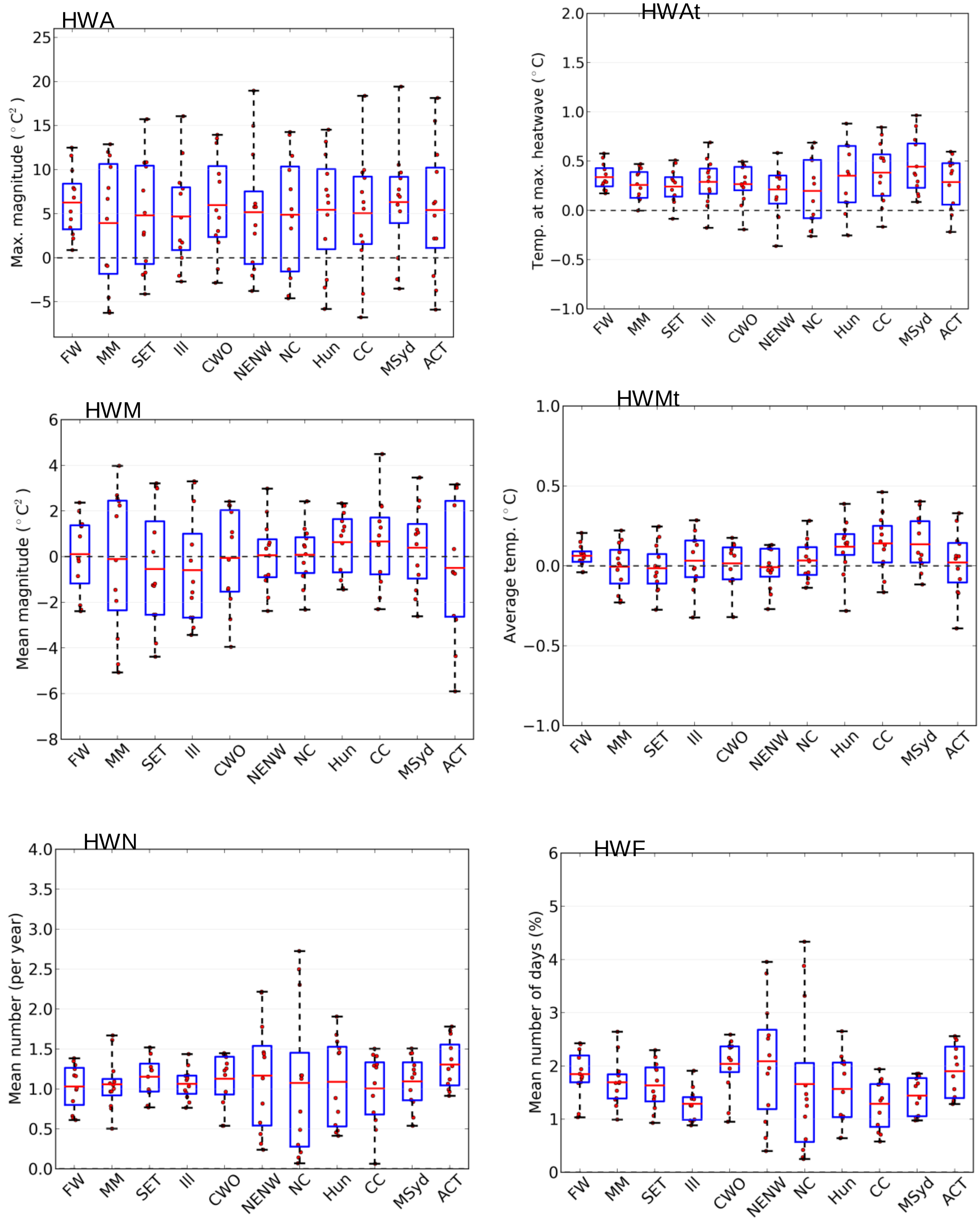


Figure 5.4: Near-future (2020–2039) projected changes in heatwave indices obtained from the NARCliM ensemble by using bias-corrected output with respect to present-day climate (1990–2009). The NARCliM ensemble mean change (red line), interquartile range of changes (blue box) and range (whiskers) of changes are represented for each heatwave index and region (see Figure 1.2). Red dots represent values from individual members.

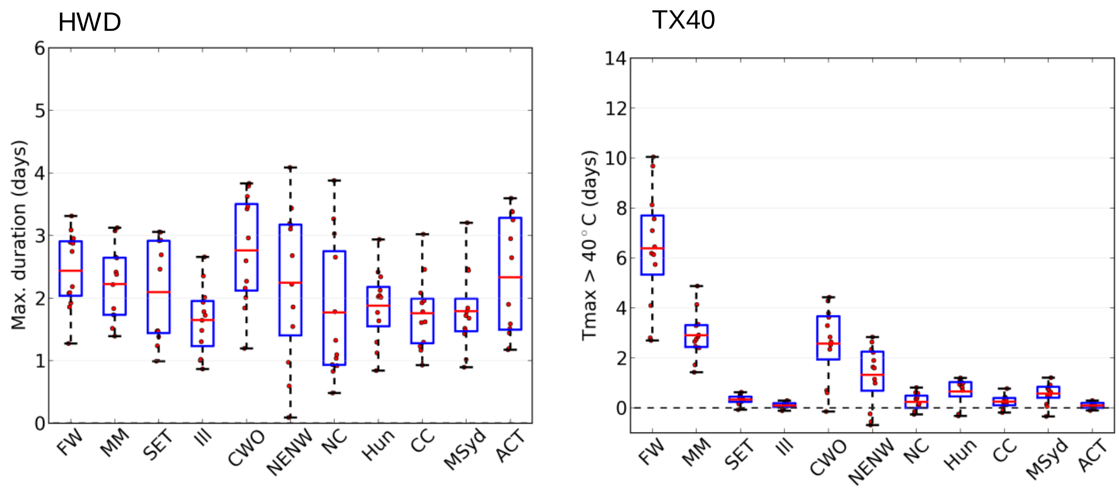


Figure 5.4: ***cont.***

5.4 Summary

Near-future (2020–2039) changes in heatwave characteristics from the NARCliM ensemble have been described in this section. Differences between the near-future and present-day climate are not strong enough to translate into statistically significant changes in heatwave intensity (as measured by HWA and HWM); therefore, the projected changes cannot be discerned from natural variability. Despite the fact that most models project increases in the peak magnitude of heatwaves (HWA), there are some individual models that indicate a decrease in HWA in the near future. In terms of mean magnitude, there are both increases and decreases projected for NSW and the ACT, although they should be interpreted carefully in light of the HWM definition. (See section Figure 6.4: Far-future (2060–2079) projected changes in heatwave indices, as obtained from the NARCliM ensemble by using bias-corrected outputs with respect to the present-day climate (1990–2009). The NARCliM ensemble mean change (red line), interquartile span of changes (blue box) and range (whiskers) of changes are represented for each heatwave index and region. (See Figure 1.2.) Red dots represent values from individual members.

6.4 Interpreting changes in the HWM index: Interpreting changes in the HWM index, for further details.)

The frequency and duration of heatwaves are projected to experience statistically significant increases over large areas of NSW and the ACT. The most remarkable exception is NC, where none of these indices is projected to change significantly, although the NARCliM models show large spreads in HWN, HWF and HWD; 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-day climate heatwaves.

The number of extreme hot days, as measured by TX40, will increase in most regions, although the significance of such changes is limited to the western half of NSW, where the NARCliM ensemble projects averages of up to 6.5 more days/year with temperatures above 40 °C. Most of the eastern regions will continue to see TX40 values very similar to present-day ones, with increases below 1 day/year.

6. Far-future simulated changes compared with the present day

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

6.1 Regional model output: far-future climatologies (2060–2079)

This section presents far-future (2060–2079) projected climatologies of heatwave indices. Figure 6.1 shows the NARCliM ensemble means 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 north-east of NSW to about 50 $°C^2$ in the south-west. A similar spatial distribution is obtained for the mean magnitude of heatwaves (HWM), with the highest values located in the southern part of SET and in FW (up to 20 $°C^2$) and the lowest values in NENW and areas of NC. In the present-day climate, the overall north–south gradient is explained by the larger temperature variability at higher latitudes than in areas to the north of NSW. Mean temperatures for the peak (HWAt) and for the mean magnitude of heatwaves (HWMt) have patterns that are consistent with the spatial distribution of maximum temperatures, with the largest values in the northern FW (~34 to 37 °C) and the lowest values in high-elevation areas in the south (~16 to 19 °C).

The number of heatwave events (HWN) and the percentage of heatwave days (HWF) are largest in the northern interior of NSW, with about 6 heatwaves a year and around 10% of days, whereas the south-west of NSW and pockets on the South Coast show the lowest number of heatwaves per year (<4.8 heatwaves a 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 to 18 days) and shorter ones along the South Coast and the south-west (6 to 8 days).

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

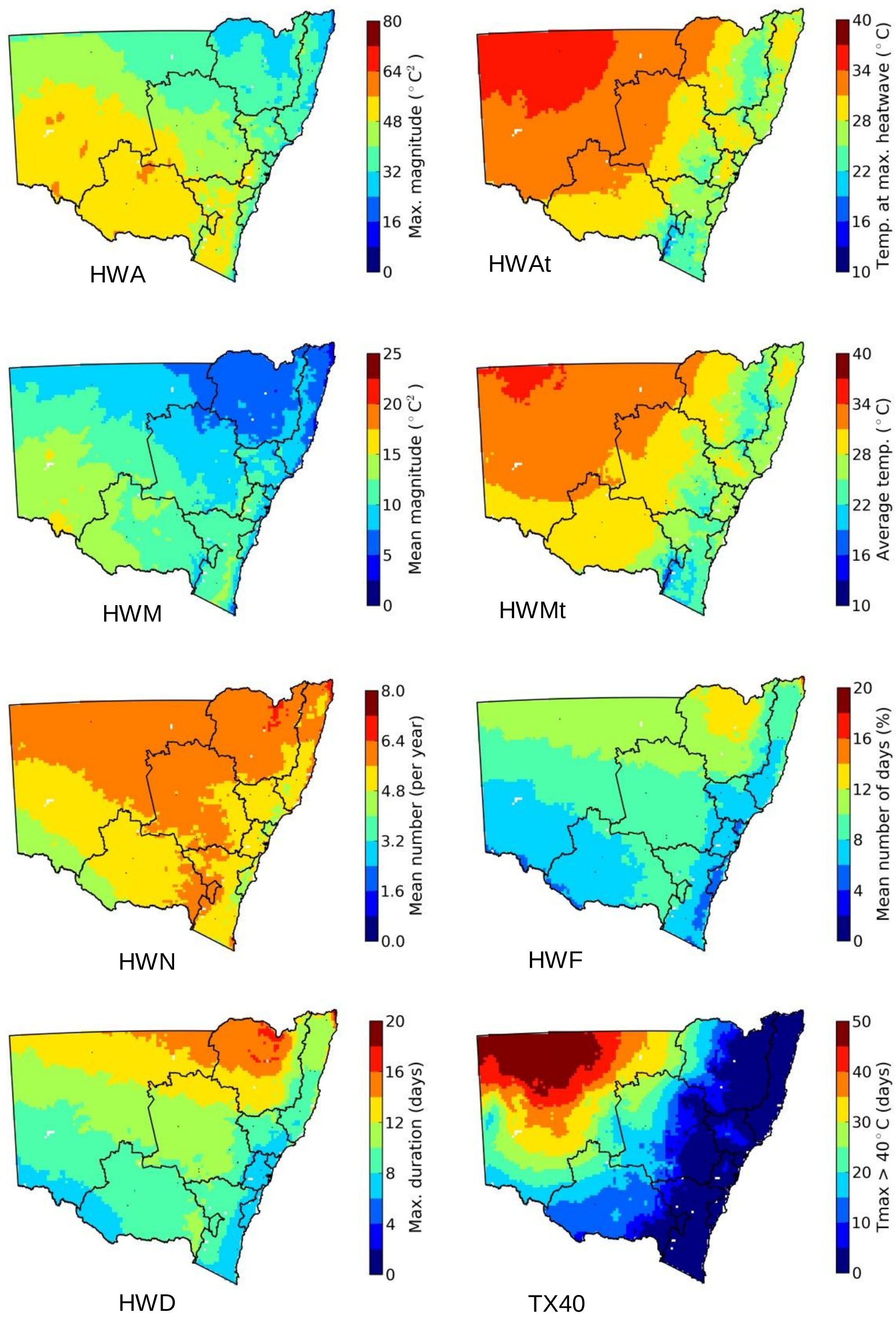


Figure 6.1: Far-future (2060–2079) projected climatologies for heatwave indices, obtained from the NARCliM ensemble by using bias-corrected outputs

6.2 Regional model output: far-future changes (2060–2079) with respect to the present-day climate (1990–2009)

This section presents far-future (2060–2079) projected changes in heatwave indices. For each index, the significance of biases of individual models was estimated with respect to the interannual variability by using Student's *t*-test at the 5% significance level ($P < 0.05$). The stippling convention is the same as that described for near-future changes. (See section 5.2 Regional model output: near-future changes (2020–2039) with respect to the present-day climate (1990–2009): Regional model output: near-future changes (2020-2039) with respect to the present-day climate (1990-2009).

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 the western regions. A similar pattern of change is observed for the temperature-equivalent HWA (HWAt), with changes ranging between 0.5 and 1.5 °C over all of NSW.

The index of the mean magnitude of heatwaves (HWM) and its temperature equivalent index (HWMt) show increases in the west of NSW and decreases in the east, with the largest reductions over the South Coast of NSW. However, none of these changes is 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. For a detailed explanation of this feature, with a practical example, see section Figure 6.4: Far-future (2060–2079) projected changes in heatwave indices, as obtained from the NARCliM ensemble by using bias-corrected outputs with respect to the present-day climate (1990–2009). The NARCliM ensemble mean change (red line), interquartile span of changes (blue box) and range (whiskers) of changes are represented for each heatwave index and region. (See Figure 1.2.) Red dots represent values from individual members.

6.4 Interpreting changes in the HWM index: Interpreting changes in the HWM index.

The NARCLiM results indicate that the indices of the frequency (HWN and HWF) and duration (HWD) of heatwaves will undergo statistically significant changes over all of NSW and the ACT with respect to the present-day period. The number of heatwaves (HWN) per year is expected to increase by 2.5 to 4.5 in the far future, with somewhat larger increases in the central and northern parts of NSW according to the NARCliM ensemble means.

The mean percentage of heatwave days (HWF) shows a clear north–south gradient, with larger values in the north (between 7% and 9% more days of heatwaves per year) and values of about 2% more days of heatwaves per year in the south-west and south-east of NSW. Far-future changes in the longest heatwave in a year (HWD) show a spatial distribution very similar to that of HWF. HWD is expected to be 2 to 14 days longer on average, depending on the region considered. Regions in the north-east (NENW) would experience the largest changes in HWD, whereas the smallest changes are expected to arise in the southern part of NSW.

According to the NARCliM ensemble, the number of days with temperatures above 40 °C will significantly increase in 2060–2079 over most of NSW, with increases of about 30 days in the north-western corner. In the eastern part of NSW and in the ACT, the changes are always equal to, or greater than, 0 but are generally smaller than 3 days/year and are not statistically significant.

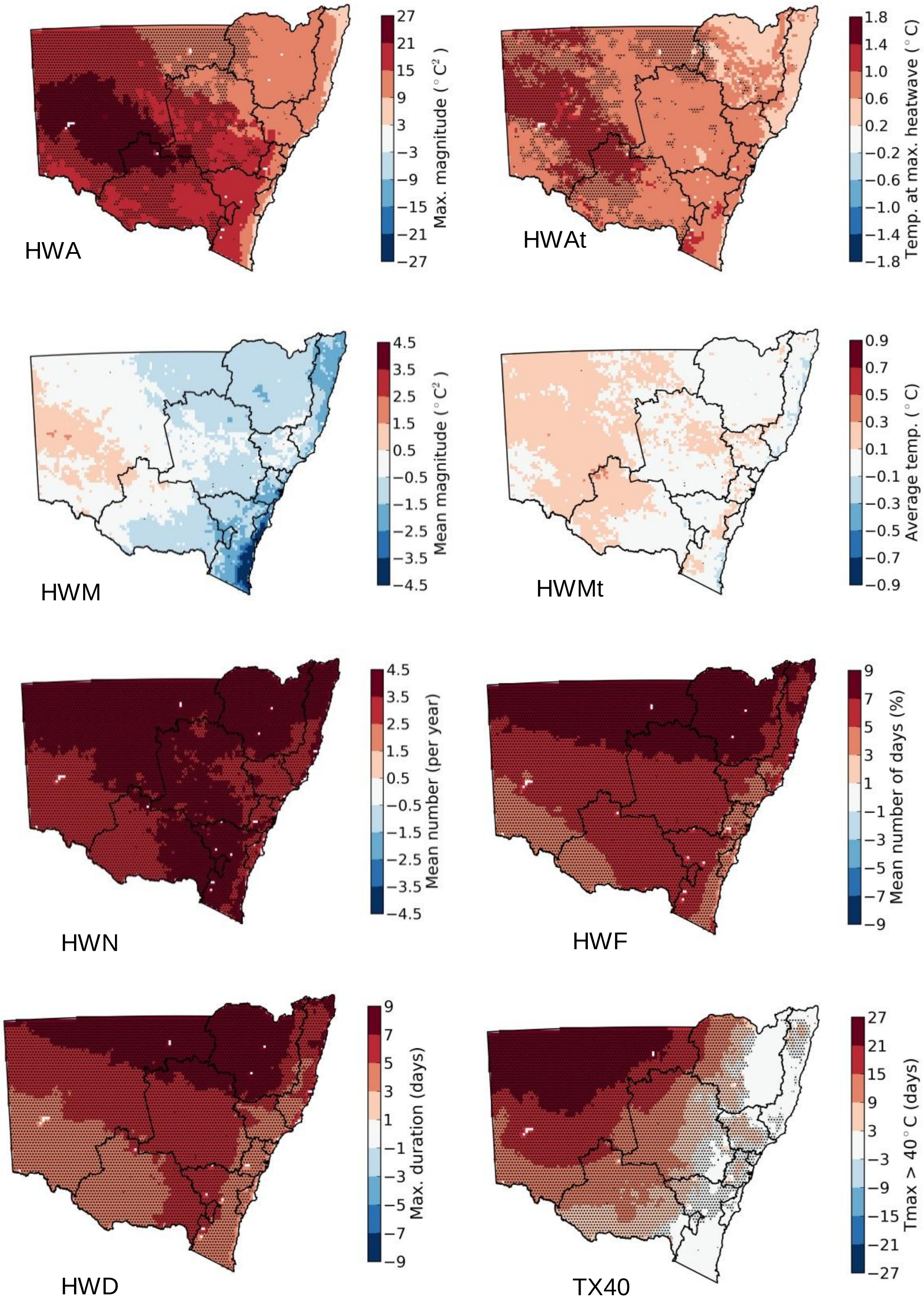


Figure 6.2: Far-future (2060–2079) projected changes for heatwave indices, obtained from the NARCliM ensemble by using bias-corrected outputs with respect to the present-day climate (1990–2009). Stippling indicates areas where future changes are significant for at least half of the models and at least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

Figure 6.3 shows the monthly numbers of heatwave days for the far-future period (a) and the changes compared with the present-day climate (b), as obtained from the NARCliM ensemble. Averaged across NSW and the ACT, the NARCliM ensemble means project more than twice the number of heatwave days in the far-future than in the present-day period. In the far-future results there is a substantial spread among members of the ensemble, with some members showing an increase of about 80% and others increases of nearly 200% compared with present-day values.

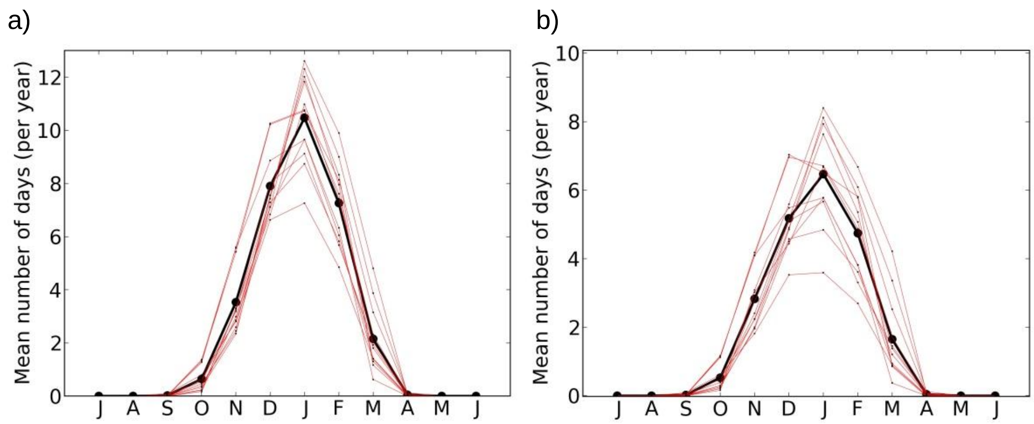


Figure 6.3: Monthly numbers of heatwave days from the NARCliM ensemble for a) far-future climate (2060–2079) and b) far-future changes compared with the present-day period. Black thick line shows the ensemble mean results and red thin lines show results for individual members of the ensemble.

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

This section analyses the far-future changes for each individual region in NSW. (See Figure 1.2 for region details.). Figure 6.4 shows far-future projected changes (2060–2079 minus 1990–2009) in heatwave indices for each of the regions, including the spread across NARCliM ensemble members.

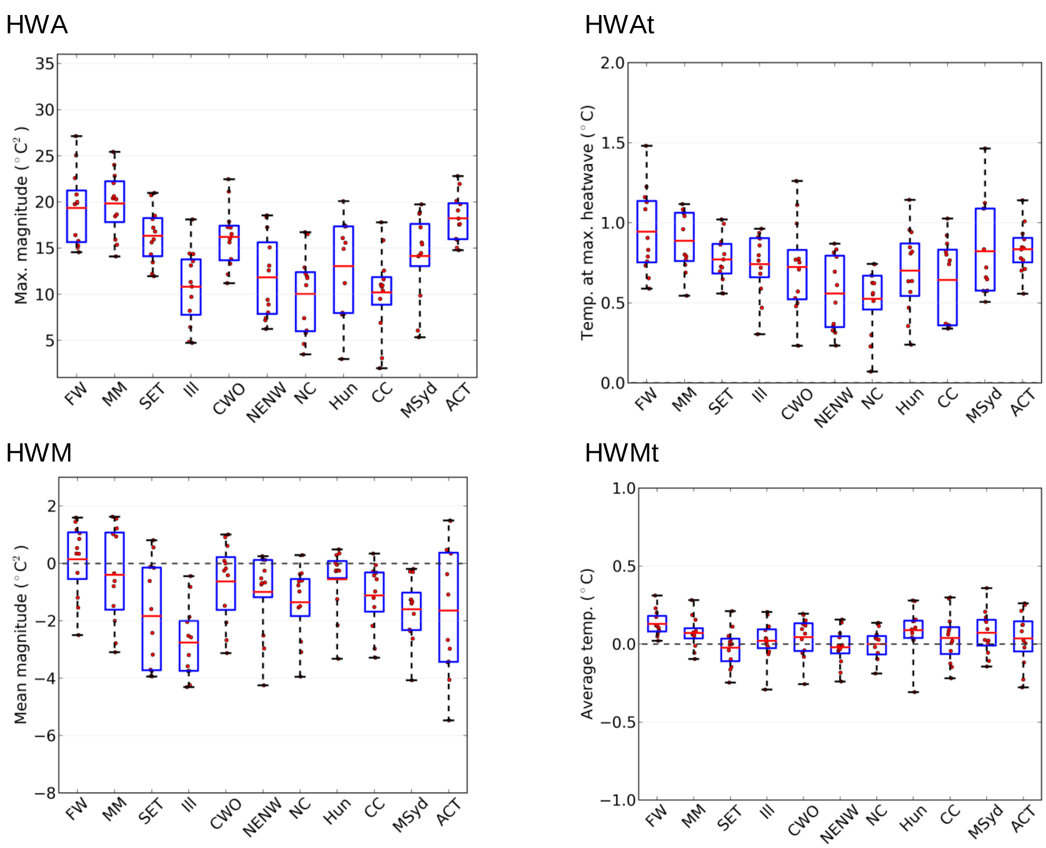
All NARCliM ensemble members project increasing changes in the yearly maximum intensity of heatwaves (HWA) and its temperature-equivalent (HWAt) for all regions of NSW. The HWA index shows NARCliM ensemble mean values that vary between ~10 °C^2 and ~20 °C^2), with the largest values in the FW, MM and ACT regions and the lowest in the Ill, NENW, NC and CC regions. Most regions show a substantial spread across individual members, reaching up to 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 the smallest changes arising over north-eastern regions of NSW.

In the case of the mean magnitude of heatwaves (HWM), most individual members and the NARCliM mean project decreases, although this is explained by the much larger number of heatwaves in the future and their relatively weak intensities, as discussed in section Figure 6.4: Far-future (2060–2079) projected changes in heatwave indices, as obtained from the NARCliM ensemble by using bias-corrected outputs with respect to the present-day climate (1990–2009). The NARCliM ensemble mean change (red line), interquartile span of changes (blue box) and range (whiskers) of changes are represented for each heatwave index and region. (See Figure 1.2.) Red dots represent values from individual members.

6.4 Interpreting changes in the HWM index: Interpreting changes in the HWM index. Far-future changes in HWMt are about 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 show that the number (HWN), frequency of days (HWF) and duration (HWD) of heatwaves are 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 the 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 percentage of heatwave days (between 4% and 10% of days compared with present values). The largest changes arise in the north-eastern regions of NSW, whereas the smallest are 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 8 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 the ACT according to the NARCliM ensemble means. A few regions show no changes simply because they do not record any days with temperatures above 40 °C in the present or far-future periods. NARCLiM far-future projections suggest that the number of days with mean temperatures above 40 °C will be more than double the present-day values for most regions. Specifically, the NARCliM ensemble suggests that there will be about 35 instead of 15 days with temperatures above 40 °C in the far future compared with the present-day period in the FW region.



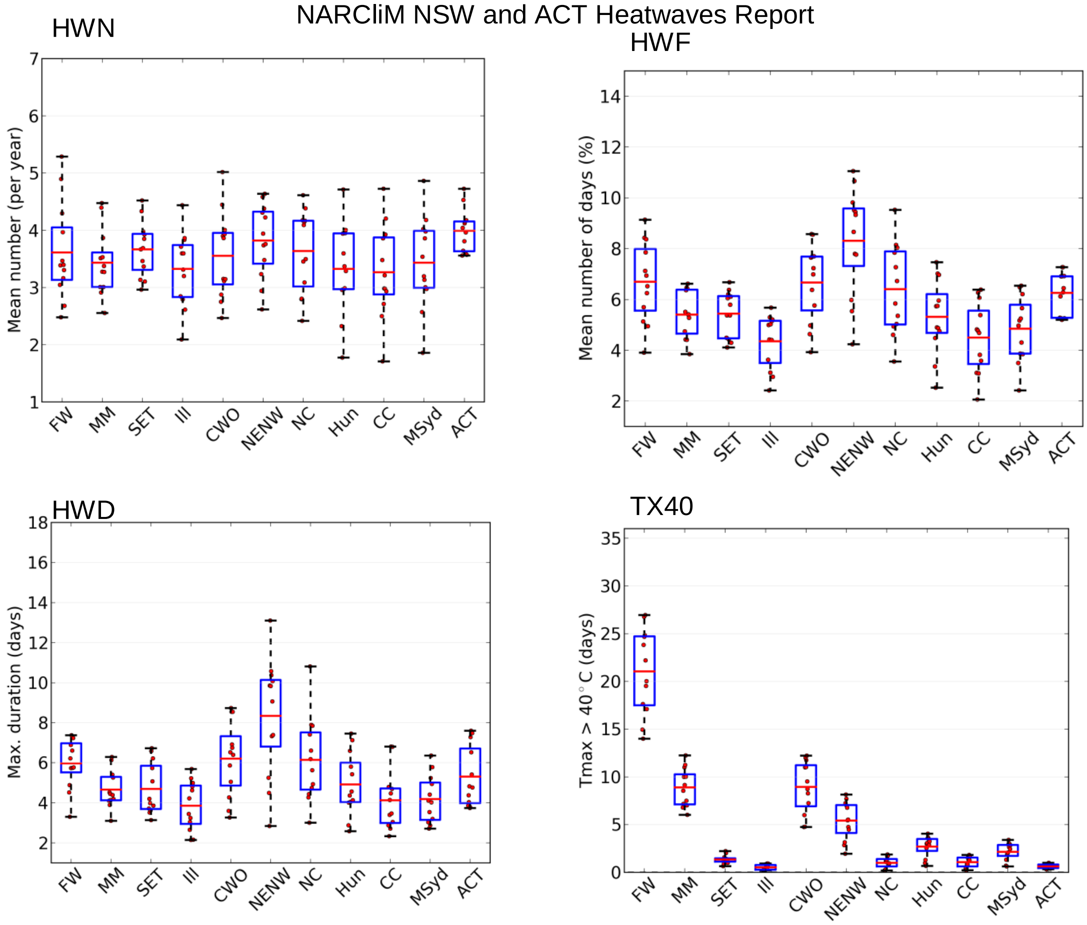


Figure 6.4: Far-future (2060–2079) projected changes in heatwave indices, as obtained from the NARCliM ensemble by using bias-corrected outputs with respect to the present-day climate (1990–2009). The NARCliM ensemble mean change (red line), interquartile span of changes (blue box) and range (whiskers) of changes are represented for each heatwave index and region. (See Figure 1.2.) Red dots represent values from individual members.

6.4 Interpreting changes in the HWM index

In this section, we discuss future changes in the mean magnitude of heatwaves, as derived by using the current implementation of the EHF metric.

Figure 6.5a is a histogram of the EHF index during heatwave days only for the present (green) and far-future (pink) periods. This figure is intended to help interpret HWM changes and thus refers to a single location (near Sydney) and a single ensemble member (ECHAM5 R1). The number of heatwave days increases in the future regardless of 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 (i.e. by a factor of 5.5) for EHF values in the range of 0 to 2 °C^2, whereas it increases only from approximately 0.6 days to 1.2 days (i.e. by a factor of 2) for intensities in the range of 20 to 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 6.5b, where the temperatures for heatwave days are represented and classified in 0.5 °C bins. Similar to the case with HWM there are increases at all intensities, but 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 (see 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.

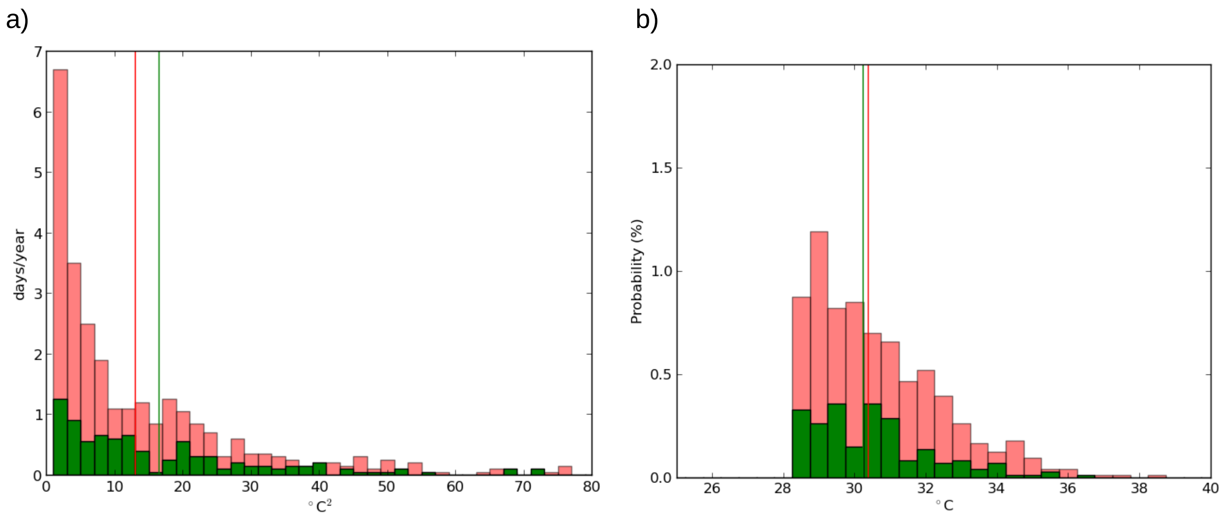


Figure 6.5: Histogram of EHF (a) and 3-day average temperatures (b) for heatwave days for 1990–2009 (green) and 2060–2079 (pink). Results shown only for one NARCliM simulation (ECHAM5 R1) over Sydney, i.e. at one grid point located at lat 33.85°S and long 151.12°E. Vertical lines represent means of all values.

6.5 Summary

Far-future (2060–2079) changes in heatwave characteristics obtained from the NARCliM ensemble have been described here. Differences between the far-future and present-day climates 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 to the specific way in which the future index is constructed and the result should therefore 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, suggest that there are relatively large uncertainties around the mean changes.

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

7. Health effects of heatwaves

7.1 Importance of definitions

As outlined in section 1.2, 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 [35, 110] or a relative temperature threshold [49, 105] or have compared both [87]. Furthermore, to define a heatwave event, some studies have used mean temperature [88]; maximum temperature [68]; apparent temperature and its variations [105]; or a combination of these metrics [7]. Using a range of definitions complicates any attempt to make comparisons among 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 depends on the heatwave definition used [7, 48, 87]. One Australian study that quantified this relationship confirmed that changes in heatwave definition do lead to differences in their associated health risk estimates [87]. This study used 10 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 to 1.73 [87].

Despite the obvious benefit of agreeing on one universal definition for heatwaves, it is likely that the debate will not quickly resolve, partly because, for some localities, different metrics are deemed more significant than others in relation to the effects on human health. Some studies have indicated that a metric based on mean temperature might be most appropriate, as it incorporates both maximum and minimum temperature [13, 48, 88, 95]. 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 that metrics incorporating humidity, such as apparent temperature, are more appropriate to define heatwaves [11, 31, 20, 80]. 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 [97]. Heatwave indices derived from daily maximum and minimum temperature might imply relative humidity, as high minimum temperatures can be a result of high humidity [66].

The recent development of the EHF may resolve some of these problems, as it includes daily maximum and minimum temperatures in its derivation. EHF is a relative measure that 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 °C during the 2009 south-east Australian heatwave event were linked to substantial increases in mortality in the region [70, 77]. Furthermore, the highest morbidity and mortality rates during the event immediately followed the highest EHF value calculated for the heatwave [54].

The acclimatisation index, which is the second component of EHF, incorporates acclimatisation factors that can affect health outcomes from heatwave events. This index (see 2) within the EHF incorporates the days immediately preceding a heatwave; it therefore suggests the ability of an individual to adapt to excessively hot temperatures [66]. 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. However, the extent of adaptation would depend on several other aspects relating to the individual, including behavioural and occupational aspects (e.g. work, recreational activities and time spent outdoors) [58].

The EHF has been shown to be well correlated with excess mortality [54, 77]. 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 metric that is suitable for evaluating the health impacts of heatwave events and that also has the 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, 82, 83, 90]. 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, the 2003 European heatwave resulted in between 40,000 and 70,000 excess deaths [29, 79], and the 1995 Chicago heatwave resulted in 485 heat-related deaths and 739 excess deaths during its most intense period [103]. In Australia, the 2009 Victorian heatwave resulted in a 62% increase in total all cause-mortality, a 12% increase in emergency department presentations, and a 25% increase in total emergency ambulance call-outs [70]. The 2004 Brisbane heatwave resulted in 75 excess deaths [87].

There is some international evidence to suggest that more intense heatwaves have considerably larger impacts on human health [6, 7, 48]. A few international studies have also provided evidence of an additional heatwave burden on human health: 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, 32]. In general, increases in mortality and morbidity are observed during the extreme temperature event, or 1 to 3 days after the exposure; that is, there is an observed lag effect [108].

The impact of heatwaves on human health can be measured by a number of different health outcomes. These include: mortality [87, 90]; hospital admissions [36, 110]; emergency department presentations [69]; and ambulance call-outs [89]. In general, derivatives of the World Health Organization's International Statistical Classification of Diseases and Related Problems (ICD-10 and ICD-9) are used to identify specific diseases of interest to examine the impacts of heatwaves on health.

Seasonality

There is some evidence 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 summer 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].

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 [107], the elderly [70, 81, 99]; individuals with pre-existing medical conditions such as cardiovascular, respiratory or renal disease, diabetes, and mental and behavioural disorders [35, 36, 58, 96, 104]; individuals living alone [110]; individuals with low socioeconomic status [110]; outdoor and occupational workers [34, 106]; and Indigenous populations [101]. It is important to note, however, that, because of projected future changes in population demographics and disease burden, those sub-populations that have been identified as vulnerable in current research have the potential to become more or less vulnerable in the future.

7.3 Health effects yielded by NARCliM simulations

In general, studies of future heat-related mortality using various scenarios and climate models have found an increase in mortality rates [52, 72]. The health effects that may be coupled with increases in heatwave duration, frequency and intensity depend on a number of factors, including the underlying health status of the population, the spatial distribution and age of the future population, the mean temperatures relative to each region and its urban structure, and the magnitudes of increases in all indices.

Although here we have not quantitatively assessed the projected health outcomes, future work may benefit in using an approach similar to that proposed by the Price Waterhouse Coopers National Framework on Protecting Human Health and Safety during Severe and Extreme Heat Events [77]. The report suggests using a model that combines climate and population projections with previous analogues of heat events linked with heat-related morbidity and mortality to quantitatively assess 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. 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, and socioeconomic and demographic factors that cannot be projected with accuracy.

Qualitative assessment of the health effects of projected future changes in heatwaves, as simulated by the NARCliM ensemble, 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.

Near-future health effects (2020–2039)

The frequency and duration of heatwaves are projected to increase significantly over large areas of NSW and the ACT (see section 5). On the basis of our current understanding of the health effects of heatwaves, we can infer from this result that this will lead to increases in excess mortality and morbidity. However, the small, as yet uncertain, changes in heatwave amplitude and mean magnitude make it difficult to predict how this would affect health outcomes. Although we know that the intensity of a heatwave is correlated with mortality and morbidity levels, we do not know how this particular heatwave characteristic would combine with projected increases in the other characteristics (i.e. frequency and duration) to affect human health.

In some regions of NSW the number of days above 40 °C will significantly increase: over the interior half of NSW this increase is projected to be in the range of 1.5 to 7.5 days/year, and potentially 7.5 to 10.5 days/year in the north-west. 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 a maximum temperature) above which there are marked increases in mortality and morbidity [56, 104]. These temperature thresholds vary significantly across regions and climatic zones and are associated with the population's ability to acclimatise. For example, the temperature threshold for Sydney appears to be within the range of 26 to 27 °C for the daily maximum temperature [12, 30]. Therefore, increases in the number of hot days exceeding 40 °C will likely lead to increases in mortality and morbidity.

By using the relationship described in [77] for heat-related excess deaths in Sydney, and observed excess deaths in 2011 as a year representing the recent past, we can provide a rough estimate of excess deaths projected by the NARCliM ensemble. Bearing in mind the many limitations of this approach, it estimates an increase in heat-related excess deaths of 13 a year in the near future.

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. This excludes the findings of some of our simulations for average heatwave magnitude, although these decreases are somewhat misleading. (See section 6.) The number of days with temperatures exceeding 40 °C is projected to increase by up to 30 in the north-west. Although this number is substantial, the health outcomes would depend on the length of time for which these temperatures persist and on 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, with smaller increases in the east. More frequent and longer events are projected for the more north-easterly regions of the state. The greatest health impacts would likely occur in regions projected to experience substantial increases across all indices, such as in the northern 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 depend largely on the persistence of high night-time temperatures during future heatwave events. Furthermore, despite the 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 agricultural area. This also makes quantitative assessments of the future health outcomes in this area more complex to interpret. Moreover, the possibility of there being a relatively small health burden is based largely on assumptions that the population density of the region will remain similar to the present.

It is likely that MSyd and the ACT will remain the most populated regions; the highest health burdens may therefore occur here, largely because of the greater numbers of vulnerable people and compounding factors such as the urban heat island effect [33, 59]. Although the increases in heatwave intensity, duration and frequency here are not as large as in more inland regions such as FW, CWO and NENW, these dense urban regions might expect increases in heat-related mortality and morbidity because of events that are of slightly higher intensity, as well as longer and more frequent.

Using the relationship described in [77] for heat-related excess deaths in Sydney, as well as the numbers of excess deaths observed in 2011 as a year representative of the recent past, can provide a rough estimate of excess deaths projected by the NARCliM ensemble. Noting the many limitations of this approach, it estimates an increase in heat-related excess deaths of 46 a year in the far future.

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 their surroundings [10]. This has implications for projections of heatwaves in urban areas: such heatwaves are expected to be more intense and frequent than their rural counterparts.

A quantitative and rigorous estimation of the urban effects on heatwaves would require cities be explicitly represented in the models. NARCliM simulations do not account for most of the urban factors that alter local climate; they consider only differences in 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; only at spatial resolutions of a few kilometres do 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] found that night-time temperature changes due to urban expansion are locally comparable to future changes that arise from increased atmospheric greenhouse gas concentrations. 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 with a range of models. Instead, they were single realisations that shed light on urban effects, assuming a large-scale change. Therefore, there is an urgent need for further studies in this direction that incorporate the methodology adopted in NARCliM to understand and robustly quantify the repercussions of heatwaves for urban populations. This would help us prepare to reduce the vulnerability of a population sector that will likely be exposed to more intense and frequent heatwaves and includes over 90% of Australians.

9. Conclusions and future work

This report has presented heatwave characteristics derived from the CAWCR Excess Heat Factor [64, 65] metric, their biases, and projected future changes for NSW and the ACT.

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

The model finds significant increases in heatwave frequency and duration in the near future for much of NSW and the ACT. Although increases in the peak heatwave amplitude are projected, these increases are not significant in the near future. The seasonal timing of increases reflects the current frequency of occurrence, with largest increases in January and smaller increases moving towards the transition seasons.

In the far future, robust 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. Most of NSW is projected to experience about 20 more heatwave days a year in the far future than in present periods. In many locations this is more than a doubling of 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 [77] suggests that these heatwave increases may produce increases in excess deaths of 13 per year in the near future and 46 per year in the far future. These estimates have been made by 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 of 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 effect is known to exacerbate high temperatures within urban environments. Urban landscape effects within future climate projections must be captured explicitly to understand potential changes in heatwaves within cities, including changes in the distribution of impacts across cities, which can be substantial for coastal cities like Sydney. Achieving this requires modelling at the kilometre scale. With a resolution of 10 km, NARCliM is not able to properly capture these effects. In a pilot study undertaken under the NARCliM project, fine scale modelling with a 2km resolution was undertaken for Sydney using one GCM-RCM ensemble to demonstrate the ability of the regional models to reach the required scales. 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 in the future. Ways to include this long-term acclimatisation in future heatwave estimations and heat–health relationships remain to be explored.

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