Measurement, impact and mitigation of heatwaves

JOHN NAIRN CF
THESIS, student number a1660619
School of Biological Sciences, University of Adelaide
APRIL 1, 2022

Thesis Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

The author acknowledges that copyright of published works contained within the thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

John Nairn

15 November 2021

Acknowledgement of Country

Whilst my studies have been carried out on kaurna country, my work has investigated heatwaves affecting all aboriginal and Torres Strait Islanders, including other first nation lands around the world.

I acknowledge weather knowledge of all first nations people, their connection to Land and the wisdom passed from generation to generation, some which is unfortunately lost.

Enquiries with Uncle Lewis O'Brien AO, kaurna Elder, revealed lost language is being reassembled from a variety of sources including the work of early missionaries. Uncle Lewis collaborated with Dr Rob Amery (University of Adelaide) to build an agreed wording for heatwave.

The following hot and weather words in the kaurna language are considered relevant.

Summer: warltati

Weather: warlta or watita

Very hot: kardla-kardlantu

Wave: wingkuru

Uncle Lewis and Dr Rob Amery supplied the following kaurna word for heatwave.

heatwave: warltawingkuru, page 81, Kaurna dictionary [1].

Acknowledgements

A 40-year career in one organisation is pretty rare. I acknowledge the immense privilege of my career in the Bureau of Meteorology and many insights into how weather and climate impact people's lives. My career experience has heavily influenced the direction of my research into heatwaves. I have enjoyed the support and tolerance of many colleagues so numerous I must apologise for limiting my direct acknowledgement. I note significant opportunities to undertake this work would not have been possible without the direct support of senior colleagues Dr Ray Canterford, Alasdair Hainsworth, Andrew Watson and Roger Deslandes. Research colleagues at the Bureau encouraged my work on heatwaves. Special recognition is reserved for Dr Beth Ebert who encouraged and supported my heatwave investigations and Dr Robert Fawcett who became a special collaborator in enabling spatial heatwave research, ultimately leading to the creation of a new operational heatwave service for Australia.

Very early investigation into a suitable heatwave service solution for Australia was supported by the Winston Churchill Memorial Trust awarding a 2012 Fellowship [2] that supported 2013 travel to England, Germany and the USA. Discussions with emergency service, health and meteorological authorities developed relationships which continue to this day, and which assisted the Australian Bureau of Meteorology to support the research covered within this thesis and adopt its results within a national heatwave service. Bureau and the Churchill Trust supported my 2013 travels over 9 weeks to the UK, Germany and USA where I investigated the state of heatwave warning services in the UK, Europe and USA. I note the surprise when Professor Virginia Murray (Public Health England) learnt I was available for a week rather than a 1-hour meeting (another one of my life-long communication skill lessons). Professor Murray has become a lovely friend and strongly advocated for exposing my work in peer-reviewed literature. Many more valuable contacts were developed during my Fellowship, including collaborators.

Supervisors at the University of Adelaide, Bertram Ostendorf (School of Biological Sciences) and Peng Bi (School of Public Health) have supported my part-time studies.

My thanks to Peng for tolerating my insistence that he co-supervise my studies. Without a multi-disciplinary focus, my work could not have adequately address the impact of heatwaves. I have enjoyed interacting with his team and the multiple challenges we have addressed in coming to terms with the impact of heatwaves on health systems and people.

Bertram has been my principal supervisor, mentor and very good friend. It has been a pleasure drawing our families together and learning from a highly accomplished academic. Bertram's considerable coding skill in R created an environment in which any questions of the data could be entertained. We have had fun cracking this chestnut open.

Friends and family have been my bedrock whilst I have lost myself in work. My distraction has no doubt come at some cost to my family. My partner Kerryn has my eternal love and respect. Without my family's support this work would not have been possible.

Contents

Peer reviewed publications included for examination

1. [56] J. R. Nairn and R. J. B. Fawcett, "The excess heat factor: A metric for heatwave intensity and its use in classifying heatwave severity," *International Journal of Environmental Research and Public Health*, vol. 12, no. 1, 2014, doi: 10.3390/ijerph120100227.

2. J. Nairn, B. Ostendorf, A. Moise. "The impact of humidity on Australia's operational heatwave warnings", submitted for publication 2021 – *Climate Services*

3. [54] R. J. B. Fawcett and J. Nairn, "The Heatwaves of the 2013/14 Australian Summer" 2015.

4. [55] J. Nairn and R. Fawcett, "Heatwaves in Queensland," *Australian Journal of Emergency Management*, vol. 32, no. 1, 2017, [Online]. Available: https://ajem.infoservices.com.au/items/AJEM-32-01-11

5. [138] J. Nairn, B. Ostendorf, and P. Bi, "Performance of Excess Heat Factor Severity as a Global Heatwave Health Impact Index," *International journal of environmental research and public health*, vol. 15, no. 11, 2018, doi: 10.3390/ijerph15112494.

6. [141] J. Nairn *et al.*, "South Australian heatwave forecasts and warnings performance and some impacts during January 2019, Australia's hottest month on record.," 2019. Accessed: Oct. 13, 2020. [Online]. Available: https://www.afac.com.au/events/proceedings/28-08-19/article/south-australian-heatwave-forecasts-and-warnings-performance-and-some-impacts-during-january-2019-australia's-hottest-month-on-record

7. [51] J. Nairn, M. Beaty, and B. M. Varghese, "Australia's Black Summer heatwave impacts," *Australian Journal of Emergency Management*, vol. 36, no. 1, pp. 17–20, 2021, Accessed: May 28, 2021. [Online]. Available: https://knowledge.aidr.org.au/resources/ajem-january-2021-australia-s-black-summer-heatwave-impacts/

8. J. Nairn, C. Mooney, M. Beatty, B. Varghese, B. Ostendorf. "Australia's transition from hazard-based to impact-based heatwave warnings and targeted services", submitted for publication 2021- *International Journal for Disaster Risk Reduction*

List of Figures

List of Tables

Abstract

Heatwaves are frequently dismissed as uncomfortable seasonal events which are of little consequence. Agreement on a definition has evaded this natural hazard, obscuring lessons from historical losses. This work establishes a robust innovative definition which has transformed management of Australia's most dangerous natural hazard.

The Excess Heat Factor (EHF) is a 3-day heatwave index which combines long- and short-term daily temperature anomalies to produce a sensitive signal to noise signature which is proportional to impact. A statistically robust percentile-based temperature-only index, the EHF measures locally significant heatwave intensity. Intensity is normalised using points over threshold (POT) from extreme value theory to measure and map heatwave severity.

City, regional and national epidemiological studies have used EHF to measure heatwave vulnerability by location across Australia. Local, national and international health, emergency services and meteorological authorities now operate within a common framework for the delivery of coordinated heatwave services based on EHF.

The Excess Heat Factor is introduced and evaluated for its effectiveness as a heatwave intensity and severity index. The utility of EHF in monitoring and forecasting heatwaves is investigated, as is its effectiveness in predicting impact.

This study underpinned the general utility of EHF as a heatwave hazard for health outcomes. Further investigations have found it an effective tool in understanding the impact of severe and extreme heatwaves on infrastructure and utilities. Many collaborative epidemiological studies have now utilised EHF to study the impact of heatwaves, including a national Reducing Illness and Lives Lost for Heatwaves (RILLH) project which has developed heatwave vulnerability data for Australia at local (SA2), regional, major cities and by individual morbidity.

We have found EHF to work as an effective warning index across Australia's diverse mid-latitude and subtropical climate zones. It is also effective in the tropics, particularly in unusually dry environments or in humidity conditions normal for each location. Unusually humid heatwaves have been examined and are not always warned by the current operational temperature-only EHF index.

Application of EHF across historical and future climate scenarios, and for multi-day and seasonal predictions is developed in support of a comprehensive heatwave service framework that allows for coordinated heatwave warnings and targeted services.

Chapter 1. Introduction

Climatically extreme weather phenomena are normally associated with warning services and meteorological disciplines for data collection, boundary conditions, objective algorithms, climatologies, synoptic, thermodynamic and dynamical analysis, and prognostic guidance. At the beginning of this study, heatwaves in Australia had a name but no objective definition, analysis methodology, climatology, forecasts nor warning services. Australia's national weather agency possessed strong skills in analysis and prediction of a heatwave's core ingredients but lacked objective insight or knowledge of heat as a hazard or its impacts. Heatwaves were hidden in plain sight.

In Australia's past, high impact heatwaves appear to have been tolerated due to apparent infrequency and poor impact attribution. Even rarer very intense heatwaves resulting in mortality, morbidity, injury and property damage were reported as the inevitable consequences of living in a hot country. Somehow the concept of measuring the dimensions of a heatwave escaped the collective conscience. Australians considered the burden of infrequent heatwaves tolerable which is a likely consequence of immature or inconsistent impact data collection.

At the beginning of this study Australia lacked agreement on a national atmospheric heatwave definition which would allow the community to plan, prepare, respond and learn from exposures to this dangerous hazard. Whilst Australia was not ready to recognise nor enact mitigation strategies to combat the impact of hazardous heatwaves, heatwave early warning systems (HEWS) were already in place and being evaluated [3] in overseas national settings. Developing the capacity to measure, track and forecast heatwaves [3]–[7] is required to establish HEWS, a target outcome for Sendai disaster risk reduction obligations [8]. This thesis has been designed to remediate this problem.

Australia has recorded a rapid increase in duration, frequency and intensity of extreme atmospheric temperatures [9] consistent with the experience of global warming elsewhere around the world [10]–[13]. High mortality in heatwaves across the United Kingdom [14] and USA [15] during 1995 marked an upturn in published injury and death attribution studies. Excess deaths attributed to the 2003 Western European heatwave eventually exceeded 70,000 people [16]. In particular, the 2003 Paris extreme heatwave human health impacts [17] spurred European research, mitigation and HEWS, subsequently amplified by the exceptional duration of the 2010 Russian heatwave with estimates of over 55,000 excess deaths and losses of $15B US dollars to the economy [18].

Heatwaves in Australia have a disproportionate impact on human health, accounting for more lives lost than all other natural hazards combined [19] with loss of life and injury every summer [20]–[25]. The exceptional 2009 heatwave in south east Australia [26] resulted in over 400 excess deaths in South Australia and Victoria immediately before the catastrophic Black Saturday Bushfires which resulted in 173 deaths. Whilst the bushfire impacts on human life, business, infrastructure, environment and social capacity were examined by a national Royal Commission [27], heatwave impact lessons were limited to examination of impacts on human health [28], [29] despite significant impacts to security of energy supply, transport systems, major sport, environment and business sectors [30]–[35]. The contrast in examination of bushfire and heatwave hazards and uneven scrutiny of heatwave impacts provided motivation for the creation of a heatwave definition capable of contextualising heatwave severity irrespective of the sector impacted.

Atmospheric heatwaves form through descending, drying air within an anticyclone producing a dry and warming environment under clear skies. These clear skies allow radiative heating of the underlying surface during the daytime. This is most effective over land with diabatic heat exchange into the overlying air. What would be a normal warming cycle ahead of the next cool air mass change can become stagnated when a slow-moving anticyclone prolongs the heating cycle, occasionally producing a heatwave. McBride et al. [36] notes mechanisms for heat build-up in a heatwave include advection from lower latitudes, large-scale subsidence transporting higher potential temperature air from upper levels and surface heating through development of the diurnal mixed layer, and replacement from below by the new mixed layer for the successive day, with evidence for surface heating as the dominant contributor. The sensible heat component of the land-surface radiation budget rises when the latent heat flux (evaporation) reduces due to drought. Nicholls and Larsen [37] noted a 1-3 °C rise in Melbourne's maximum temperatures for situations typically associated with high temperatures following periods of drought. Diurnal variation in boundary-layer depth features in the morphology of intense heatwaves. Daytime mixing will reach greater heights as surface sensible heat increases. In events where high surface temperature arises from dry soils, sensible heating into the shallow nocturnal boundary layer continues, contributing to anomalously high overnight temperatures, a feature of extreme heatwaves noted in radiation balance studies for the 2003 European extreme heatwave [38] and in compounded heatwave intensity preceding Australia's catastrophic 2009 Black Saturday fires [39]. Severe Southern Australian heatwaves have been characterised by Pezza et al. [40] with the southeast and southwest of Australia impacted by slow-moving anticyclones centred in the Tasman Sea and western Great Australian Bight respectively, noting heatwaves are driven by large scale synoptic events which derive their structure and longevity from planetary scale Rossby wave dynamics. Predicting heatwave seasonality, onset and longevity is tied to the predictability of stationary Rossby waves. The rising incidence of northern hemisphere weather extremes has recently been tied to a slackening of mid-tropospheric temperature gradients which are conducive to standing Rossby waves attributed in turn to Arctic amplification [41]. In contrast to the northern hemisphere, the Antarctic continent maintains relatively stable surface fluxes. Southern hemisphere Rossby wave structure appears to be driven by anomalous mid to low latitude heat fluxes resulting in excitation of a stable wave train [42]. Southern Ocean temperature structures establish anomalous mid to low latitude meridional sea surface heat fluxes that have statistical significance for severe heatwaves [40]. It is possible to associate the anomalously cool (warm) SST to long-wave ridge (trough) positions favourable for a stable, stationary Rossby wave train.

Heatwaves are observed in the atmosphere and oceans, and can be reasonably described as sustained periods in which unusually high temperatures occur. Many atmospheric heatwave definitions also require the presence of high humidity [43]–[47], with a potential bias toward heatwaves with significance to human health. Whilst the protection of human health from atmospheric heatwaves is a significant theme in this thesis, development of a temperature-only, percentile-based heatwave definition has been prioritised to broaden adoption through the use of high-quality climatic variables commonly recorded and forecast across the globe. This has enabled a heatwave definition that is easily understood and utilised by multi-disciplinary planning teams, meteorological and sector specific early warning systems, and developers of policy frameworks, working seamlessly across spatial and temporal scales within the climate record, current observations and prognostic systems.

The temperature-only, percentile-based sensible heat accumulation formulation adopted in this thesis creates a heatwave intensity scale unique to every location, an attribute which inhibited one of the key requirements of this study; the ability to map and compare heatwaves and their impacts across locations. A key benefit of a temperature-only, percentile-based heatwave intensity population probability function is the preservation of temperature-alone climate population statistical properties. As a consequence, Points Over Threshold properties (temperature extremes/heatwaves) from extreme value theory were utilised to normalise local heatwave intensities into generalised heatwave severity categories. Application of the Generalised Pareto Distribution Function to heatwave intensity data under this theorem was pivotal in the development of heatwave severity categories. The Pareto effect provided a lexicon for communicating heatwave severity, or impact to the community. The slow rise within the first 85^{th} percentile of heatwave intensity was labelled as low-intensity. This distribution of heat was a common experience at each location with a reasonable expectation that local practices would protect most individuals, and infrastructure would be engineered to operate effectively in this heat. Intensity rose rapidly above this inflection point in the distribution for each location and could affect people vulnerable to heat health problems. This effect is demonstrated in this thesis. Heuristic operational experience identified extreme heat risk at three times the local threshold for risk to vulnerable people, where normally reliable infrastructure, utilities and healthy people were impacted. This thesis provides examples around the globe where this level of severity has led to unusually high impact. Significantly, the application of extreme value theory to the local climatology of sensible heat matched the vulnerability of human and natural systems independent of other variables, such as humidity. Where humidity is normal at a location, the statistical properties of a temperature-only, percentile-based index was sufficient to scale the impact of heatwaves measured as a severity metric. Severity categories are comparable in time and space, permitting maps of heatwave severity and a generalised scale for the heatwave hazard. Derived from statistical properties of sensible heat, this measure of heatwave hazard permits risk analysis for all impacted human and natural systems, which is amenable to separate consideration of natural and anthropogenic climate change, and socioeconomic processes in assessments of adaptive and mitigation capacity in a warming climate [48].

Droughts, heatwaves and fires exist as cascading compound hazards in a dry environment [49]. Interaction between these hazards can amplify the scale of impact. Rapid growth in mega-fires across Australia, Europe, North and South America [50] is linked to global warming, particularly where drought contributes to drier fuels and more significant heatwaves which exacerbates spread and size of wild fires and subsequent persistent smoke, as witnessed in Australia's 2019/20 Black Summer [51]. This thesis aims to introduce a multidisciplinary heatwave impact analysis capacity to accurately reflect the interaction of heatwaves with other cascading compound hazards. Improved understanding of these interactions contributes to climate resilient heatwave action plans within mitigation and adaptation policy, emergent multi-hazard early warning systems, and development of tailored services and warnings for health, utility, infrastructure, business and community sectors.

Validation of the rising incidence and severity of heatwaves resulted in increased demand for tailored heatwave services and early warnings for a wide range of users in emergency services, health, infrastructure, utility, business and community sectors. Simple inclusion of heatwaves into existing hazard-based warning systems would not address the unique needs of each sector. Each sector experiences unique vulnerabilities to heatwave severity that can vary by location. Some of these vulnerabilities can be managed through behavioural actions included in community wide warnings. Other sector impacts require tailored warnings that are intimately linked to the location and exposure of vulnerabilities to heatwave severity. Plans for the introduction of multi-hazard early warning systems [52] will manage the inclusion of new hazards (such as heatwave) and some of their cascade and compound risks.

This thesis aims to advance the introduction of a heatwave early warning system. This complex task must take into consideration international covenants for the introduction and operation of multi-hazard warning systems whilst meeting the unique needs of impacted domestic sectors.

Much of this study focused on fostering adoption of a heatwave measurement, impact assessment and mitigation system in order to reduce injury and lives lost from heatwaves in Australia. Concentration on health impacts reflected demand and access to data for this task. Creation of heat health vulnerabilities requires multi-disciplinary collaboration within an ethical governance framework [53]. Lessons learnt from development of Australia's climate resilient impact-oriented heatwave warning service centred around safe, secure management of sensitive data. National heatwave health vulnerability data is key to the creation of national and tailored heatwave services and impact-oriented early warning systems.

The thesis comprises 4 results chapters. Chapter 2 quantifies heatwave intensity and severity and considers the potential confounding effects of humidity, Chapter 3 introduces new heatwave services and measures their efficacy, Chapter 4 examines the impact of heatwaves with these measures whilst Chapter 5 examines implication for mitigation, adaptation, and national and tailored services and early warning systems. All chapters contain one or more published or submitted articles.

Preamble

In Chapter 1 the rising menace of heatwaves is presented alongside emergent awareness of their impact and the need for an effective heatwave early warning system (HEWS).

Development of an Australian national HEWS required adoption of a heatwave measurement system that would support effective planning, preparation (mitigation), response and recovery disaster management activities. Chapter 2 presents two papers. Paper 1 introduces the Excess heat Factor (EHF), an innovative temperature-only percentile-based heatwave index which measures local heatwave intensity which in turn is normalised into universal heatwave severity categories. Paper 2 examines whether the absence of humidity in the EHF limits its usefulness to warning decision makers across Australia's diverse climate zones.

Paper 1.

J. R. Nairn and R. J. B. Fawcett, "*The excess heat factor: A metric for heatwave intensity and its use in classifying heatwave severity*," International Journal of Environmental Research and Public Health, vol. 12, no. 1, 2014, doi: 10.3390/ijerph120100227

Paper 2.

John Nairn, Aurel Moise, Bertram Ostendorf, "*The impact of humidity on Australia's operational heatwave warnings*". Submitted Climate Services

Effective adoption of a new warning system is dependent upon trust. Users must invest in decision making and will quickly lose confidence and discount warning services when they are perceived to over warn, or miss events. Consequently, validation of forecast and warning services is extremely important and helpful in building confidence when full disclosure of a hazard forecast and warning system is shared. Paper 3 provides an overview of the 2013/14 summer heatwave system using EHF heatwave guidance. Forecast performance is examined and severe heatwaves are documented to permit new users to assess their ability and effectiveness in preparation and response to discrete events. Similarly, the historical exposure and trend in heatwave frequency and severity is examined for Queensland in paper 4. This paper demonstrates the utility of EHF is exposing policy challenges for current of future heatwave exposure.2

Paper 3.

R. J. B. Fawcett and J. Nairn, "The Heatwaves of the 2013/14 Australian Summer". 2015 AFAC Conference.
https://www.bnhcrc.com.au/sites/default/files/managed/downloads/fawcett.pdf [139]

Paper 4.

J. Nairn and R. J. B. Fawcett, "Heatwaves in Queensland", Australian Journal of Emergency Management, vol. 32, no.1, 2017. https://ajem.infoservices.com.au/items/AJEM-32-01-11 [55]

Chapter 4 considers evidence for heatwave impacts. EHF was developed for application in Australia. However, its application is only limited by the availability of maximum and minimum dry bulb temperature records. Application to extreme heatwaves across the globe is presented in paper 5, revealing the usefulness of an objective intensity/severity heatwave index for comparison of impact and vulnerability to extreme heatwaves across diverse climatic locations around the globe. The 2018/19 South Australian heatwave season is examined in paper 6. Early adoption and adaptation of EHF forecast warning decision support guidance is examined, documenting impacts and mitigation actions based on heatwave intensity/severity forecasts. Published for an emergency services conference, lessons learnt were shared in a national forum. Finally, the role of heatwaves during Australia's 2019/20 Black Summer is presented in paper 7. The amplification and cascading natural hazards of extreme drought (and dust), extreme heatwaves, mega-fires and hazardous smoke are documented, identifying the need for greater research as climate change increases the frequency and intensity of these hazards in Australia.

Paper 5.

John Nairn, Bertram Ostendorf and Peng Bi, "Performance of Excess Heat Factor severity as a global heatwave health impact index". International Journal of Environmental Research and Public Health, 2018, 15(11). https://doi.org/10.3390/ijerph15112494

Paper 6.

John Nairn, Chris Beattie, Sara Pulford, Robert Fawcett, Paddy Phillips, Neil Langlois, Jai O'Toole, Bertram Ostendorf, Dorothy Turner, Peng Bi, Evan Morgan, "South Australian heatwave forecasts and warnings performance and some impacts during January 2019, Australia's hottest month on record". Extended abstract, 2019 AFAC Conference.

Paper 7.

John Nairn CF, Dr Matt Beaty, Dr Blesson M. Varghese, "Australia's Black Summer heatwave impacts". Australian Journal of Emergency Management, Vol 36 No. 1, January 2021. https://knowledge.aidr.org.au/resources/ajem-january-2021-australia-s-black-summer-heatwave-impacts/

Paper 8 in Chapter 5 examines emergent collaborations required for the adoption of an effective early warning system. For many years warnings have been based on forecasts of the scale of a hazard. Whilst sophisticated users who frequently interact with weather data have competent hazard management systems which can utilise this information effectively, many users fail to make effective use of these forecasts. Development of impact-based early warning systems forecast expected impacts, communicating more effectively with a wider community, leading to broader adoption of effective mitigation and response actions. Whilst this is not a comprehensive treatment within the impact-based warning system environment, the collaborative development of national heatwave vulnerability maps with data custodians has built a capability which will allow warnings to be targeted according to types of vulnerability and where people live. Tailored warnings by multiple authorities can be coordinated to build a safer community.

Paper 8.

John Nairn, Carla Mooney, Matt Beaty, Blesson Varghese, Bertram Ostendorf, "Australia's transition from hazard-based to impact-based heatwave warnings and targeted services". Submitted International Journal of Disaster Risk Reduction

Chapter 2. Quantifying heatwaves: a new method

Chapter 2 contains the fundamental peer-reviewed publication describing the Excess Heat Factor (EHF) methodology that was created to capture heatwave intensity and severity, which allowed heatwaves to be mapped and the generation of heatwave climate data that could be used by epidemiologists to study the impact of heatwave severity.

The Excess Heat Factor (EHF) percentile-based heatwave algorithm combines long (30-year) and short (30-day) term daily temperatures anomalies to measure heatwave intensity over a three-day period. Heatwave intensity is location specific as it references the local temperature climatology. Intensity is normalised as heatwave severity using Points Over Threshold, Extreme Value Theory. Heatwave severity is comparable at any location, which allows mapping and a common exposure metric across epidemiological studies, irrespective of location.

The role of humidity in heatwave severity.

The choice of the EHF temperature-only, percentile-based index for a heatwave measurement, impact assessment and mitigation system needed to be sensitive to human health impact, and exhibit seamless prediction skill to aid widespread adoption in climate assessments, epidemiological studies, in warnings, and response and mitigation plans for meteorological, emergency and health agencies.

The premise that the percentile-based approach to the use of temperature-only data would accommodate the normal incidence of humidity in Australia was not able to be adequately tested until the creation of reliable humidity data within an Australian reanalysis data set. The ability to assign reliability of heatwave warnings generated within Australia's official heatwave service underpins which operational attributes are available to the community. When the presence of higher humidity undermines the accuracy of the official (temperature-only) heatwave services, an alternate humidity dependent service may be required, albeit limited by climate data quality and seamless prediction range.

Australia's high quality 29-year numerical model reanalysis dataset is used to understand the influence of humidity on heatwave warnings based on Australia's operational EHF severity algorithm. Due to Australia's exposure to unusually dry and unusually humid heatwaves in the wet-tropics, both temperature-only and Heat Index versions of EHF severity are required for an effective warning service. The remainder of the continent is well served by the current operational temperature-only, percentile-based heatwave service.

Title of Paper	The Excess Heat Factor: A Metric for Heatwave Intensity and Its Use in Classifying Heatwave Severity [56]
Publication Status	Published
Publication Details	*Int. J. Environ. Res. Public Health* 2015, *12*(1), 227-253; https://doi.org/10.3390/ijerph120100227

Principal Author

Name of Principal Author (Candidate)	John Nairn		
Contribution to the Paper	Nairn developed original idea for the heatwave intensity and severity methodology, developing the concept using site data. Both authors revised the technique and designed the gridded data system. Fawcett drafted the manuscript, which was revised by both authors. Both authors read and approved the final manuscript		
Overall percentage (%)	50%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in t ıper.		
Signature		)ate	8/11/2021

Co-Author Contributions

Name of Co-Author	R J B Fawcett		
Contribution to the Paper	Both authors revised the technique and designed the gridded data system. Fawcett implemented the methodology within the Bureau of Meteorology's gridded climate and NWP forecast data. Fawcett was responsible for generating the case study and appendix analyses. Fawcett drafted the manuscript, which was revised by both authors. Both authors read and approved the final manuscript		
Overall percentage (%)	50%		
Signature		Date	7 Nov. 2021

Int. J. Environ. Res. Public Health **2015**, *12*(1), 227-253; https://doi.org/10.3390/ijerph120100227
OPEN ACCESS

International Journal of
Environmental Research and
Public Health
ISSN 1660-4601
www.mdpi.com/journal/ijerph

Article

Paper 1: **The Excess Heat Factor: A Metric for Heatwave Intensity and Its Use in Classifying Heatwave Severity**

by J R Nairn [1*] and R J B Fawcett [2,3]

[1] South South Australian Regional Office, Bureau of Meteorology, Adelaide, South Australia, Australia
[2] Bureau of Meteorology, Melbourne, Victoria, Australia; E-Mail: r.fawcett@bom.gov.au
[3] Bushfire Cooperative Research Centre, Melbourne, Victoria, Australia

***** Author to whom correspondence should be addressed; E-Mail: j.nairn@bom.gov.au.

Academic Editors: Kristie L. Ebi and Jeremy Hess
Received: 16 September 2014 / Accepted: 17 December 2014 / Published: 23 December 2014

Abstract: Heatwaves represent a significant natural hazard in Australia, arguably more hazardous to human life than bushfires, tropical cyclones and floods. In the 2008/2009 summer, for example, many more lives were lost to heatwaves than to that summer's bushfires which were among the worst in the history of the Australian nation. For many years, these other forms of natural disaster have received much greater public attention than heatwaves, although there are some signs of change. We propose a new index, called the excess heat factor (EHF) for use in Australian heatwave monitoring and forecasting. The index is based on a three-day-averaged daily mean temperature (DMT), and is intended to capture heatwave intensity as it applies to human health outcomes, although its usefulness is likely to be much broader and with potential for international applicability. The index is described and placed in a climatological context in order to derive heatwave severity. Heatwave severity, as characterised by the climatological distribution of heatwave intensity, has been used to normalise the climatological variation in heatwave intensity range across Australia. This methodology was used to introduce a pilot national heatwave forecasting service for Australia during the 2013/2014 summer. Some results on the performance of the service are presented.

Keywords: heatwave; heatwave intensity; heatwave severity; excess heat factor; heatwave monitoring; heatwave forecasting; heat acclimatisation; heatwave adaptation;

1. Introduction

Despite heatwaves being one of the most common natural hazards experienced across the Australian community, they remain imprecisely defined events with little understood varied impacts across different community sectors. The increasing availability of high-quality climate and weather-forecast temperature datasets offers an opportunity to build a shared understanding of the hazard posed by sequences of high temperature days.

Historically, heatwaves have been responsible for more deaths in Australia, Europe and the United States of America than any other natural hazard, including bushfires, storms, tropical cyclones and floods [57], [58]. While heatwaves are not unusual for Australians, the trend towards more frequent and intense heatwaves [11], [59], [60] is of significant concern at home and abroad. McMichael *et al*. [21] has estimated that extreme temperatures currently contribute to the deaths of over 1,000 people aged over 65 each year across Australia. The number of heat-related deaths in temperate Australian cities is expected to rise considerably by 2050, as the frequency and intensity of heatwaves is projected to increase under climate change from global warming. Underpinning this view is the building evidence supporting the notion of a warming planet [61], [62].

Heatwaves are frequently defined as a period of unusually or exceptionally hot weather. Extreme events typically occur in mid-summer, although severe and low-intense heatwaves are also experienced during spring and early autumn. We make a distinction between *heatwaves*, as periods which are hot in an absolute sense, and *warm spells*, as periods which are hot in a relative sense. Warm spells in this sense may occur at any time of the year, even in the middle of winter, whereas heatwaves as intended here are necessarily restricted to the summer half-year. In climate terms, heatwaves are associated with unusually high temperatures, warm spells with unusually high temperature anomalies. Both concepts (heatwaves and warm spells) are intrinsically meaningful, and deserve study, but they are clearly not the same thing.

Several other definitions of heatwaves have been proposed previously for use in Australia. One by Pezza *et al*. [40] requires that the maximum temperature be above the 90th percentile for three consecutive days, with the minimum temperature being also above the 90th percentile for the second and third days. If the 90th percentile thresholds are calculated with respect to the entire year, then heatwaves will be diagnosed, whereas if the percentile thresholds are relative to the calendar month or season, then warm spells will be diagnosed. In the former case, the heatwaves diagnosed by the Pezza *et al*. [40] method will have much in common with the heatwaves diagnosed by the EHF method proposed here. In the latter case, the warm spells diagnosed will have much in common with our heatwaves in the summer months, but less so during the rest of the year. Perkins and Alexander [43] have compared a wide range of warm spell and heatwave indices, noting the utility of differing indices dependent upon their intended use. In this regard warm spell indices provide information relevant to seasonally dependant temperature requirements in agriculture, whilst heatwave indices are relevant to timing adaptive measures when dealing with unusual temperature extremes.

Heatwaves in Australia are driven by slow-moving synoptic-scale events that allow the continuous development of hot air masses to persist over large areas for a period of days and in rare events, weeks. Fortunately, modern numerical weather prediction (NWP) models are quite good at forecasting such slow-moving systems and provide good guidance on the evolution of high temperature events on the one to seven-day time scale. As a consequence, heatwaves as a meteorological phenomenon are readily predicted by current operational standards.

Several recent studies [40], [63]–[68] have looked at the climatic, synoptic and dynamic mechanisms responsible for causing intense heatwaves. Dry soils result in greater sensible heating of the lower atmosphere during the day through the reduction in evaporative cooling. Slow-moving deeply formed anticyclones recirculate deeply mixed hot boundary-layer air resulting in an environment that accrues excess heat. Additional dynamical links to tropical cyclone development at lower latitudes have also been shown to enhance the transport of heat from the upper tropical atmosphere to the boundary layer over Australia [63].

In Australia, heatwaves have traditionally been defined by the achievement of a minimum sequence of consecutive days where daily maximum temperatures reach a designated threshold. However, daily maximum temperatures are only part of the story when considering impacts on human health, agriculture, infrastructure, the demand on utilities (water, electricity, *etc.*) and other environmental hazards such as fire. Previous research has highlighted the importance of incorporating minimum temperature through the utilisation of daily mean temperature [69], [70], a line of thought we follow here. The extent to which heat is dissipated overnight following a very hot day dictates the accumulating thermal load impacting vulnerable people and systems. The accumulation of this heat which is not being dissipated overnight results in “excess heat”.

Heatwave intensity occupies a continuum on which low-intensity heatwaves have little impact whilst more intense events inflict severe consequences upon the community and business sectors. Rising intensity leads to extreme outcomes where widespread adverse impacts are experienced. Impacts will vary according to each location’s experience or climatology of excess heat and each community’s capacity to develop resilient strategies. By measuring heatwaves within a scale that captures intensity, it becomes possible to differentiate between heatwave events. This in turn permits a sensible analysis of resilient strategies that can be usefully shared between communities learning to mitigate the escalating impact of increasingly intense heatwaves.

We propose a new index, called the excess heat factor (EHF), which is based on three-day-averaged daily mean temperature (DMT). This index is suitable for a nationally consistent heatwave service and could help inform emerging World Meteorological Organization (WMO) guidelines on the development of national heatwave/heat health services. A heatwave service utilising this measure of intensity would provide information to enable the Australian community to self-assess thresholds of vulnerability to periods of excess heat, and for the Bureau of Meteorology to forecast and warn when severe or extreme heatwaves threaten. Analysis and forecasts of low-intensity heatwaves would also be included in a heatwave service. Measurement and tracking of more frequent low-intensity heatwaves reinforces that the community possesses resilient adaptation strategies for sequences of normal hot summer days. Acknowledgement of the community's inherent adaption to low-intensity heatwaves provides an opportunity for cultural acceptance that increasingly intense heatwaves are more hazardous and require adaptive and subsequent protective responses.

The choice of a three-day period (TDP) over which to calculate heatwave indices is motivated by studies of human responses to the onset of extremely hot weather. Epidemiological studies in Australia have identified health impact delays of between one day in Melbourne [70] and three days in Adelaide [71]. Adelaide's mean summer (December, January and February) temperature is 3 °C higher than Melbourne resulting in a more resilient heat-adapted city capable of withstanding the impact of extreme heat for longer. This is consistent with lags of three and two days identified in Barcelona [72] and London [73] respectively. This is also illustrated in Nairn and Fawcett [74] (Figure 9 therein), in terms of heat-related mortality in South Australia during the 2009 heatwave, using data obtained from Langlois *et al*. [75]. In that event, it takes three days of very hot weather for the mortality rate to rise significantly above its antecedent rate.

Relative humidity can be an important consideration in assessing the human health effects of heatwaves. It is not observed and forecast as well as air temperature, however. On this basis we have chosen not to include it explicitly in our new heatwave metric. It does, however, have an implicit presence through our inclusion of daily minimum temperature. High humidity tends to result in high minimum temperature, and low humidity in low minima, and this will be reflected in our DMT calculation.

The heatwave literature has predominantly focussed on human health outcomes. Consequently, sensible and latent heat are invariably combined together in order to account for effectiveness of thermo-regulation of biological systems. Frequently, regression equations [21], [76]–[79] or synoptic air masses [80] are used to relate and measure impacts on human health outcomes at city or regional scales. At this level of interplay between multiple variables, units and outcomes it is difficult to visualise or compare heatwaves across time or compare the severity of local, national or international events. The use of heatwave indices that consider radiation balances at the human level such as PET (Physiologically Equivalent Temperature) [60] rely upon humidity data of variable quality.

Taking a step back from human impact, it is interesting to consider heatwaves as events where excessive sensible heat accumulates, resulting in a rising thermal load. Robinson [44] adopted a de facto heatwave definition based on heat watch and warning criteria developed by the US National Weather Service. Robinson's approach incorporated frequency of exceedance of a fixed percentile of all observed heat index values [81]–[83].

Whilst an advance in developing an objective heatwave definition, heat index is difficult to employ in climate assessments and projections as past and projected records of humidity are difficult to create and quality control. Robinson's work established a baseline climate description of heatwaves for the United States of America, but was not considered able to provide a complete time series of events nor be suitable for epidemiological purposes. Characterising and carrying out comparative investigations across heatwaves is desired.

The constituents of the EHF calculation (*i.e.*, daily maximum and minimum temperature data) have been reliably recorded and corrected in high-quality climate monitoring systems. Looking forward, surface temperature is projected with sufficient skill [84], [85] in general circulation models (GCM), and indeed our new index has been used in climate studies [43], [62] as a means of analysing heatwave trends in historical data. In consequence, the new index provides a new set of tools informing policy makers on global and Australian trends in heatwave frequency, intensity and distribution.

The new index supports an intensity and classification scheme which is relative to the local climate. Such an approach is clearly necessary given the abundant evidence that people are largely adapted to the local climate, in their physiology, culture and engineered supporting infrastructure [86]. The climate record is used to produce a significant heat intensity population sample suitable for classifying heatwaves by their level of severity. This is a subtle but significant shift from epidemiological studies that commence their investigation from the perspective of human population impacts. This allows our investigation to exploit the tools available to climate, weather prediction and climate projection science to develop a physical interpretation of heatwaves. This new perspective offers spatial and temporal coherence of heatwave intensity and severity by characterising heatwave intensity through a universal independent energy index. This allows for analysis and comparison of heatwave impact whilst considering the effectiveness of alternate mitigation strategies. The spatial evolution of heatwave intensity provides a new metric for assessment of impact. We can now investigate sensible heat impact before other contributors to human health impacts are considered.

Understanding the climatological recurrence of heatwaves across Australia's diverse climatic regimes, from the tropical north to the near mid-latitudes of Tasmania in the south creates an understanding of Australia's incidence of heatwave and differing levels of intensity. The ability to compare heatwave severity across jurisdictions, regions and cities provides an opportunity to compare resilience strategies and their relevance to other locations. This guidance has not been available to Australian policy makers previously, and provides a platform for development of mitigation strategies. The capacity to forecast the severity of heatwaves and monitor the regions affected provides intelligence that has not been available to the Australian community previously.

The structure of this paper is as follows: the new index is defined in Section 2. The datasets we have used in the construction of the index are presented in Section 3. Section 4 presents some basic climatological results for the index, with further discussion in Section 5, and an application of the index to a significant Australian heatwave is given in Section 6. Concluding remarks are given in Section 7. A separate paper currently in preparation will expand on this by illustrating the performance of the new index in relation to some notable Australian and international heatwaves. We note that the methodology described here is readily adapted to provide an analogous formulation for coldwave monitoring and prediction [74], but in this paper we restrict our attention to heatwaves.

A pilot heatwave forecasting service for Australia based on the EHF was introduced in January 2014 for the latter part of the 2013/2014 Australian summer. We present in the Appendix some calculations on the performance of the forecasts across the summer. Subsequent consultation with State and Territory health and emergency sector stakeholders from across Australia found the service appropriately matched their requirements. Recommended service adjustments are under consideration for improved alignment across the sector's mitigation and response plans. The Australian jurisdictions (State and Territory) and locations mentioned in the text are shown in Figure 1.

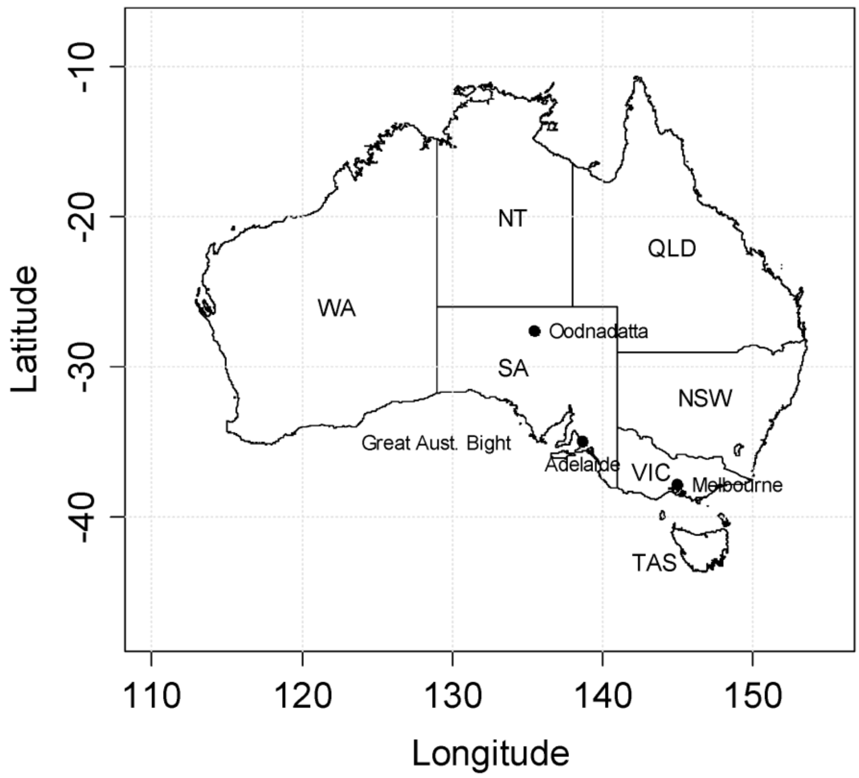


Figure 1. Map showing the Australian States/Territory and other locations mentioned in the text.

2. Methodology

The EHF is a new measure of heatwave intensity, incorporating two ingredients. The first ingredient is a measure of how hot a three-day period (TDP) is with respect to an annual temperature threshold at each particular location. If the daily mean temperature (DMT) averaged over the TDP is higher than the climatological 95th percentile for DMT (hereafter T_{95}), then the TDP and each day within in it are deemed to be in heatwave conditions. On average, around 18 days per year will have a DMT exceeding T_{95}, but it is necessary to have three high DMTs in succession in order to form a heatwave according to this characterisation. The second ingredient is a measure of how hot the TDP is with respect to the recent past (specifically the previous 30 days). This takes into account the idea that people acclimatise (at least to some extent) to their local climate, 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.

In Australia, daily maximum and minimum temperatures are measured in degrees Celsius (°C) and in relation to 24-h periods ending at 9 am local clock time (LCT), which means local standard time (LST) in those States/Territories which do not observe daylight saving time practices, and a combination of LST and local daylight time (LDT) in those States/Territories which do. In terms of the archiving of those daily temperatures, daily maximum (*minimum*) temperatures are archived for the 24 h from (*to*) 9 am LCT on the nominated day. This means that the daily maximum and minimum temperatures attributed to a particular calendar date typically (but not always) occur within the midnight-to-midnight calendar day, because the daily minimum is typically attained around sunrise and the daily maximum typically attained in the mid to late afternoon.

In terms of Australian historical data, daily maximum and minimum temperatures are available over long periods, but synoptic temperatures equally spaced throughout the day are not. Thus, in Australia DMTs are typically calculated as the simple average of the daily maximum and daily minimum temperatures. There are consequently two possible choices for doing this calculation. The first choice has the daily minimum typically preceding the daily maximum, and because of the Australian data archiving conventions described above, this is the methodology normally used by the Bureau of Meteorology in its various climate monitoring activities, even though as far as the DMT is concerned the maximum and minimum temperatures used in the calculation actually occur in separate (adjacent) 9am-to-9am 24-h periods. The second choice, and the one adopted here, has the daily maximum typically preceding the daily minimum, and the two observations relate to the same 9am-to-9am 24-h period. We make this choice because of the human physiological response to a hot night following a hot day is more significant than the other way around [70].

Hence, let T_i denote the DMT calculated in this way as the average of the maximum and the minimum which occur in the 24-h period from 9am LCT on day *i*. (In those parts of the world where there are equally spaced (around the clock) synoptic temperature observations extending back over many decades, it would be quite feasible to instead calculate the DMT using those synoptic observations, rather than the daily maximum and minimum temperatures, and that this approach might well be the preferred option where both options are available). Further, let T_{95} denote the 95th percentile of this DMT calculated across 1971–2000, using all days of the year in the calculation. Hence, on average T_i will exceed T_{95} on around 18 days each year.

The two ingredients in the EHF calculation, as described above, are called excess heat indices (EHIs) and calculated as follows:

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

and:

$$EHI_{\mathrm{accl}} = (T_i + T_{i+1} + T_{i+2})/3 - (T_{i-1} + \ldots + T_{i-30})/30. \qquad (2)$$

In the first index, called the significance index, a three-day-averaged DMT is compared directly against the 95th percentile for DMT. If EHI_{sig} is positive, then the TDP is unusually warm with respect to the local annual climate. Conversely, if EHI_{sig} is negative or zero, then the TDP cannot be considered unusually hot, and so in order for a heatwave to be present we require EHI_{sig} to be positive. In terms of typical annual climates, this means that heatwaves according to this definition typically will not occur in the winter half-year.

In the second index, called the acclimatisation index, the same three-day-averaged DMT is compared against the average DMT over the recent past. Human physical adaptation to higher temperatures may take between two to six weeks [87], whilst engineered systems have a heat capacity design limit which frequently rely upon decision-support environmental precursors to apply adaptive measures to ensure reliable operation under higher temperatures. We have adopted the previous 30 days for this purpose. If EHF_{accl} is positive, then the three days are warmer (on average) than the recent past, and consequently there is now a lack of acclimatisation to the warmer temperatures and potential for adverse outcomes. Both of these EHIs can be thought of as temperature anomalies, the first with respect to the long-term climate, the second with respect to the recent past, and so both have temperature units (*i.e.*, °C).

We then propose to calculate our EHF as a product of these two indices, subject to the constraint that the EHF must have the same sign as the significance EHI. We do this via:

$$EHF = EHI_{sig} \times \max(1, EHI_{accl}), \tag{3}$$

with the units of EHF therefore being (°C)^2, or alternatively and perhaps more conveniently K^2. This formulation ensures that:

$$\text{sign}(EHF) = \text{sign}(EHI_{sig}), \tag{4}$$

Implying that a heatwave is present if EHF is positive (but not otherwise), but if additionally, the acclimatisation EHI is positive, then that property amplifies its impact upon the EHF calculation. The duration of the heatwave comprises those days for which the significance index is positive, whether or not those days individually exceed T_{95} in their DMT. We note that it will be the case at the start and end of a heatwave for the EHF to be positive for one TDP and negative for an adjacent TDP (which overlaps the first by two days), with the potential for the overlapping days to be both in and not in heatwave. Accordingly, we propose the classification rule mentioned above, that if a TDP has a positive EHF, then all the days within the TDP are considered to be heatwave days. Only if all three TDPs for which an individual day may fall have non-positive EHF do we consider the day to not be a heatwave day. By implication, an isolated hot day with DMT > T_{95} is not a sufficient condition for a heatwave.

In southern Australia, a heatwave will often end by the passage of a cold front and its associated rapid temperature drop. Thus, some part of a TDP characterised as in heatwave conditions may not be hot, or even “cool” in terms of actual temperature, through being at the end of a heatwave, thus requiring some nuanced communication from the operational weather forecaster. Part of that communication will necessarily involve the fact that the DMT is falling or has fallen below T_{95}. On the other hand, from the human impacts perspective, the fact that houses and other elements of the built environment may take several days following the cool change to cool down to pre-heatwave internal temperatures should not go unregarded.

The choice of the “1 °C” in equation 3 is somewhat arbitrary, at least for short heatwaves: essentially it is required to be small but positive. Negative EHF values signify the absence of a heatwave for that TDP, and we are not placing any interpretation at present on the magnitude of the negative values. Hence a re-specification in the form:

$$EHF = \max(0, EHI_{sig}) \times \max(1, EHI_{accl}), \quad (5)$$

that is, a resetting of all negative values to zero, would not change the interpretation of the index as made in this paper.

During the spring months, TDPs with positive acclimatisation EHI should be relatively common (and analogously uncommon in the autumn months), but it is unlikely that the significance EHI will be simultaneously positive (except between November and March, as will be shown), hence the threshold for a heatwave would not be reached.

A short summer heatwave would typically occur within the context of a period of generally rising temperatures, so that the short period of positive significance EHI would occur within the context of a larger period of positive acclimatisation EHI. This is illustrated schematically in Figure 2, with an actual example shown in Figure 3. The DMT exceeds T_{95} for a short period (three days in the schematic example, four days in the actual example), which leads to the three-day-average DMT being above T_{95} for a likewise short period (comprising three overlapping TDPs in the schematic example, five overlapping TDPs in the actual example). The pattern of rising temperatures results in the acclimatisation EHI being positive for a much longer period, and provides a motivation for not allowing it to dictate the length of the heatwave (the three overlapping TDPs).

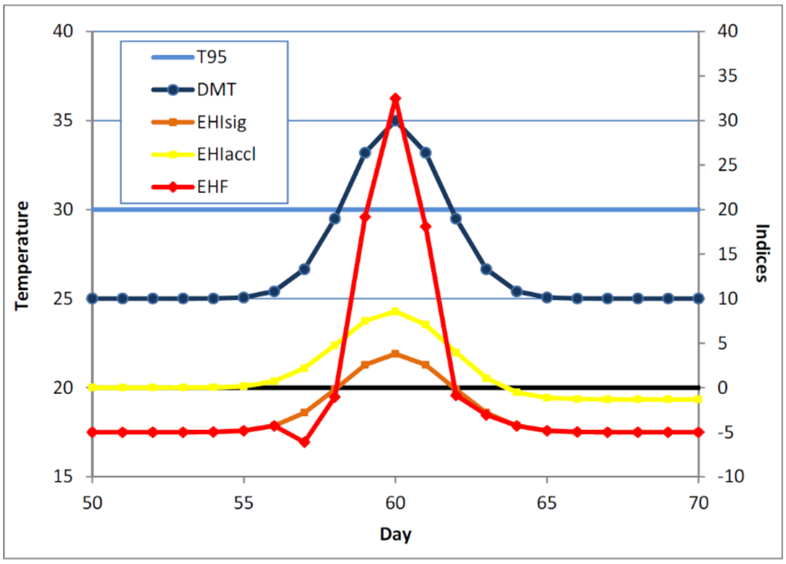


Figure 2. Schematic representation of a short heatwave early in the summer season. The DMT and 95th percentile thereof (both in °C) are plotted against the left hand axis, while the three heatwave indices (in °C and K^2) are plotted against the right hand axis. The heatwave indices are plotted against the middle day of the TDP, to facilitate comparisons with the DMT profile. The zero line for the indices is shown as a thick black line. Because of the shortness of the heatwave, the acclimatisation EHI is positive for rather longer than is the significance EHI. The notional T_{95} value in the schematic is 30 °C.

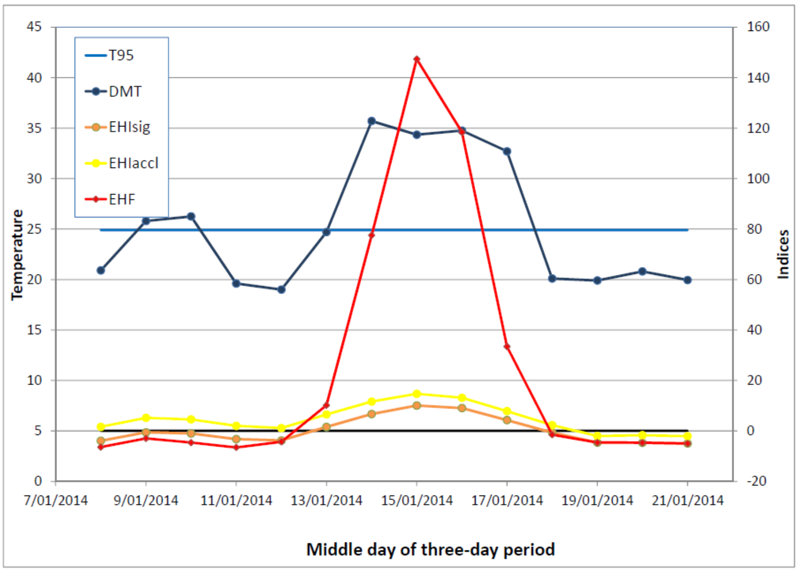


Figure 3. As per Figure 2 but for an actual short heatwave occurring in January 2014 in Melbourne, Australia. Data from the Melbourne Regional Office site (Bureau of Meteorology station number 086071). T_{95} value at this site is 24.9 °C.

Figure 4 shows a schematic example of a much longer heatwave, one in which the period for which the DMT exceeds T_{95} is no longer short with respect to the acclimatisation window of 30 days. While the acclimatisation EHI is positive well before the significance EHI becomes positive (and the onset of the heatwave is deemed to have arrived), we can see that it is possible in a long heatwave for EHI_{accl} to go negative *before* the end of the heatwave, with the implication that because of the length of the heatwave there may be some acclimatisation or adaption occurring within the duration of the heatwave. This raises the difficulty of how to characterise the heat impact of a waning heatwave, where the DMT has started to fall, but not so much below T_{95} that the heatwave can be deemed to have ended. A consideration of this issue has influenced the form of our EHF definition, particularly the aspect of it where the EHI_{accl} only affects the magnitude of the EHF if it exceeds some minimum positive value. Accordingly, our previous statement about the "1 °C" in Equation (3) needs further elaboration: it should be small and positive, but not too small. A now-superseded construction of the EHF is given in Nairn *et al*. [88].

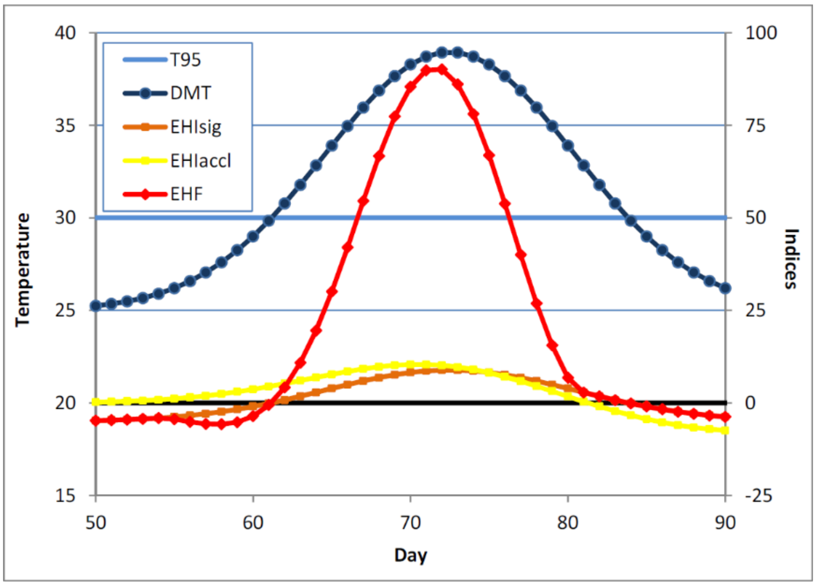


Figure 4. As per Figure 2, but for a long heatwave. Because of the length of the heatwave, the acclimatisation EHI can go negative before the end of the heatwave.

This issue, of EHI_{accl} becoming negative while heatwave conditions are still in place (*i.e.*, $EHI_{sig} > 0$), can also occur in the context of repeated shorter heatwaves, as illustrated in Figure 5. The data for Oodnadatta in inland Australia are obtained from gridded analyses (described in Section 3https://www.mdpi.com/1660-4601/12/1/227/htm - sec3-ijerph-12-00227). They show an extended period of around six weeks where the DMT hovers around T95, causing repeated short heatwaves of low intensity. This episode is preceded by a period of cooler weather, and so EHIsig < EHIaccl in the first half of the period represented in Figure 5, but by the end of the period the opposite is the case (EHIsig > EHIaccl), and indeed EHIaccl is negative at times while EHIsig is still positive. The assumed acclimatisation to the protracted high temperatures is reflected in the declining amplitude of the EHF in Figure 5.

A threshold for severity is obtained at each location by counting all the TDPs within a climatology period (we have adopted 1958–2011 for this purpose), and computing the 85th

percentile of all the positive EHF values within the climatology period, noting that the distribution of EHF is well described by the generalised Pareto distribution [74]. We denote this severity threshold EHF_{85}. We will see that the severity threshold is far from being uniform across Australia, and that in fact there is a strong dependence of the severity threshold upon latitude. Hence it becomes useful to map the EHF for individual three-day heatwave periods as a multiple of the severity threshold.

Lastly, we have chosen to designate a heatwave as being extreme if $EHF \geq 3 \times EHF_{85}$.

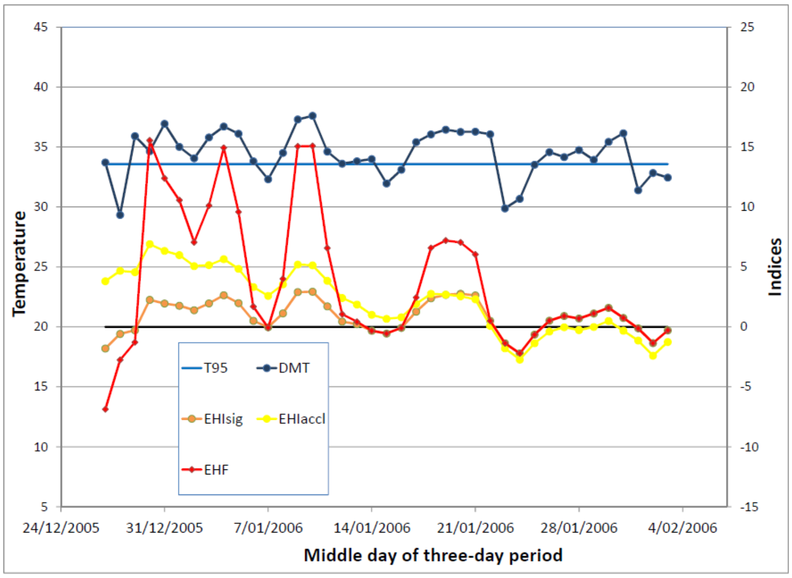


Figure 5. An actual period of extended heatwave activity at Oodnadatta (South Australia) in late 2005 / early 2006. The DMT hovers around the heatwave threshold for the EHI_{sig} to exceed the EHI_{accl}, and for EHI_{accl} to become negative while heatwave conditions are in place. Data are obtained from interpolated gridded analyses.

The intent of these definitions is to create a heatwave intensity index and classification scheme which is relative to the local climate. Such an approach is clearly necessary given the abundant evidence that people and supporting infrastructure are largely adapted to the local climate, in physiology, culture and engineered supporting infrastructure.

3. Data

While excess heat indices may clearly be computed from site observational data, our principal dataset has been the 0.25°-resolution daily temperature analyses produced operationally by the Bureau of Meteorology [89]. These analyses are available back to 1911, but the underlying observational network is much sparser prior to 1957 in terms of its availability in digitised form. Therefore, for most purposes, in particular climatological calculations, we only use the analyses from 1958 onwards. The analyses are near-whole-network analyses of site data that have been subjected to a considerable amount of quality control but no specific data homogenisation procedures.

These daily temperature analyses allow us to compute the EHIs and EHFs for all TDPs from 1958 onwards. Within the climatology period, statistics such as the mean positive EHF, the number of TDPs with positive EHF, and so on, may be calculated. The earlier data obviously may still be used to characterise particular heatwave events, in spite of the sparser observational network which lead us to exclude them from our climatological calculations.

4. Results

Climatologies of heatwave intensity and severity are described in this section. The location-specific heatwave methodology utilised establishes a baseline for the characteristics of heatwave severity across Australia. Figure 6 shows the mean positive EHF across Australia in the climatology period 1958-2011. Mean values are lowest in the tropical north, and highest around the southern continental coastline, resulting in a strong dependence of mean EHF upon latitude. This broadly reflects daily temperature variability.

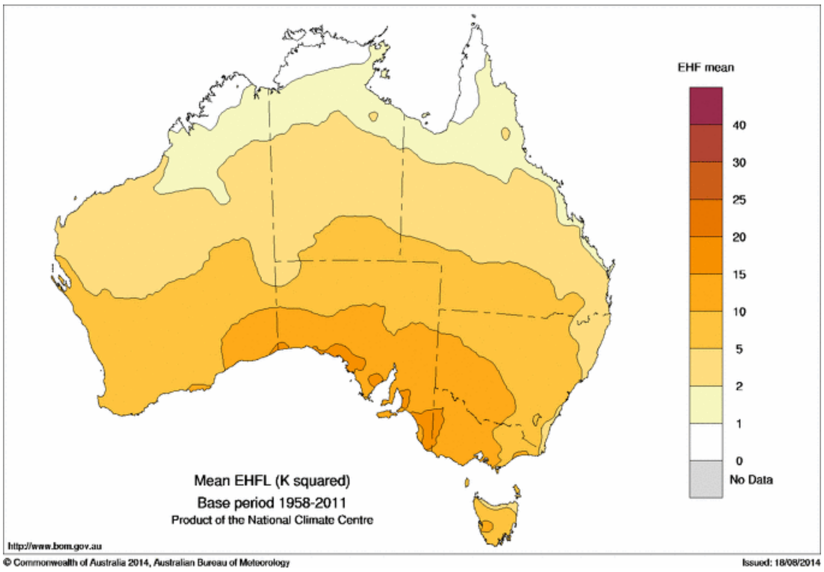


Figure 6. Mean positive EHF, in K^2, based on all positive EHF values in the period 1958-2011, calculated using the gridded analyses of Jones et al. [88].

Figure 7 shows the average annual number of TDPs with positive EHF across Australia in the period 1958-2011. The highest values are in the northwest and north, peaking at around 20 events per year. The lowest rates are in Tasmania and around the southern and southeast coasts of continental Australia.

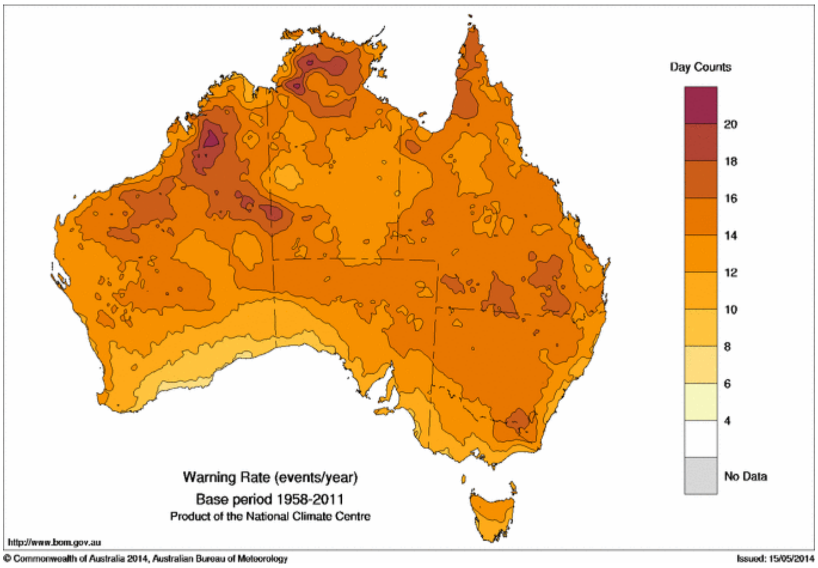


Figure 7. Average annual number of TDPs with positive EHF in the period 1958-2011.

The spatial pattern of the severity threshold EHF_{85} across this same period (Figure 8) is fairly similar to that of the mean positive EHF (Figure 6), and consequently there is a strong dependence of EHF_{85} upon latitude. Hence large temperature excursions are required in the south to cause a severe heatwave, according to the definition proposed here, while the corresponding temperature excursions required for the tropical north are much smaller. In consequence heatwave severity is likely to be more readily predicted in the south, assuming that the ability to predict temperature itself (in terms of mean forecast errors) is approximately uniform across the country.

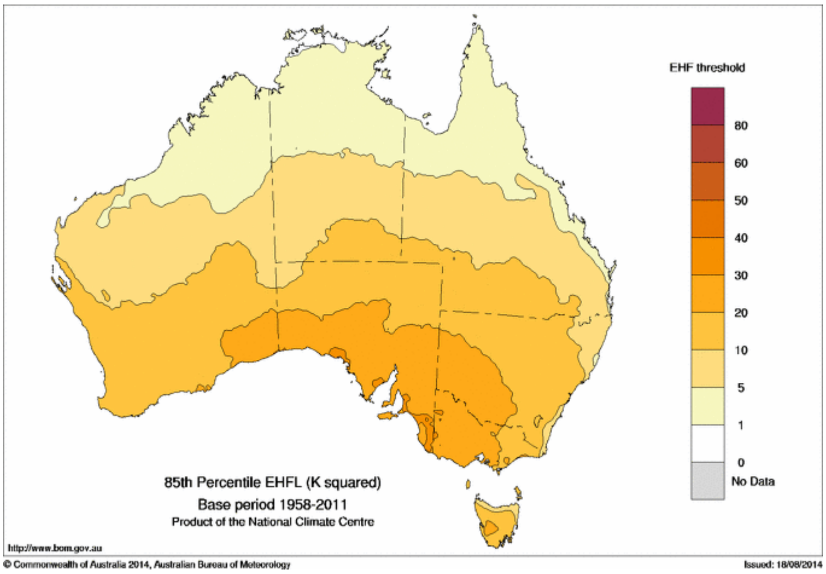


Figure 8. 85^{th} percentile of positive EHF values in the period 1958-2011 (in K^2). These values are used as the threshold for a heatwave to be designated severe. The threshold for an extreme heatwave is taken to be three times the threshold for a severe heatwave.

Having chosen the severity threshold as shown in Figure 8, we calculate the average annual rate of TDPs with EHF exceeding the severity threshold. This calculation is shown in Figure 9, and shows a considerable degree of similarity to Figure 7. It is interesting that severe EHF TDPs occur more frequently in the tropical north, with the lowest rates being around the southern continental coastline, in spite of this being the region where the positive EHF values are typically largest. The occurrence rate for TDPs with positive EHF will be influenced by both the shape of the annual cycle and the short-range autocorrelation in DMT. A low short-range autocorrelation in DMT implies that a hot day is not likely to be followed by another hot day, thereby reducing the chance of a positive EHF and consequently the chance of a severe EHF.

An analogous calculation is done for the average annual occurrence of TDPs in the extreme range across the period 1958-2011 (Figure 10). Not surprisingly, extreme events occur much more infrequently than severe events at individual locations. The pattern in Figure 10 is also spatially much noisier than that shown in Figure 9, a statistical consequence of the rareness of these events.

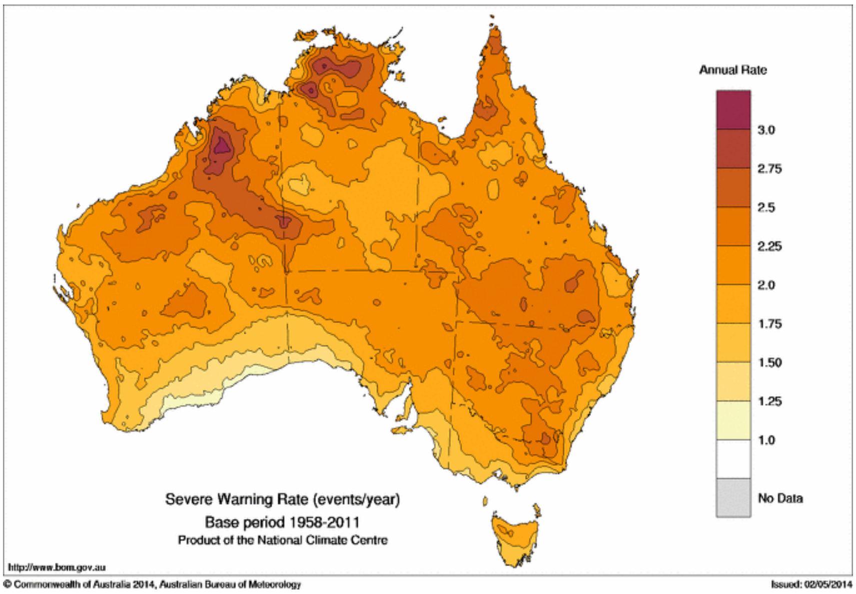


Figure 9. Average annual occurrence of TDPs with EHF above the severity threshold EHF_{85} in the period 1958-2011. Values are expressed in the form of TDPs per year.

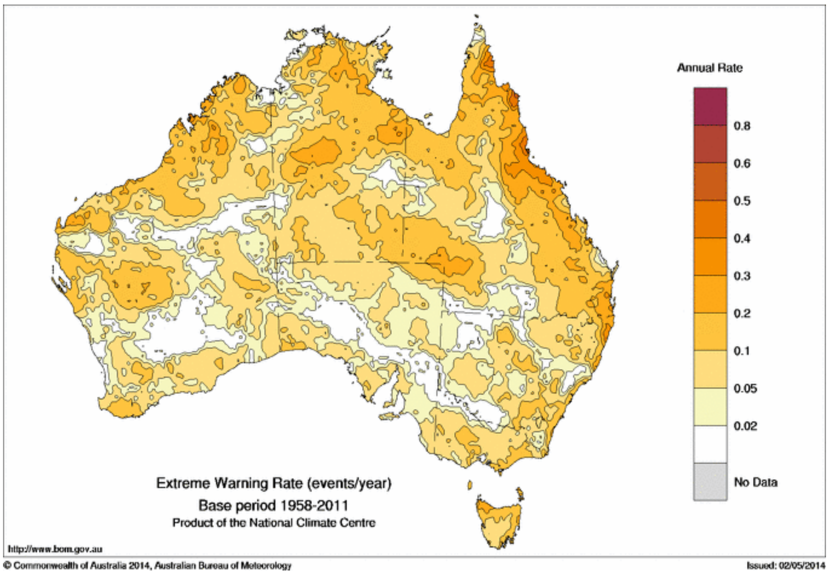


Figure 10. Average annual occurrence of TDPs with EHF above the extreme threshold in the period 1958-2011. Values are expressed in the form of TDPs per year.

Figure 11 shows the linear trend in the intensity of EHF-positive events across the period 1958-2011. The trend is calculated in the usual way, using the ordinary least-squares (OLS) method, on points of the form (t_i, EHF_i) where t_i represents the time variable and EHF_i the corresponding EHF value, but only those points where the EHF value is positive are included in the calculation. The trends are positive across most of New South Wales and South Australia, but elsewhere in the country the spatial pattern is less consistent. The highest trends are around coastal South Australia, where they approach 0.15 K^2/year. This implies an increase in the average intensity of heatwaves of up to 8 K^2 across the study period. Not surprisingly, the strongest trends occur in the places of highest mean positive EHF (Figure 6).

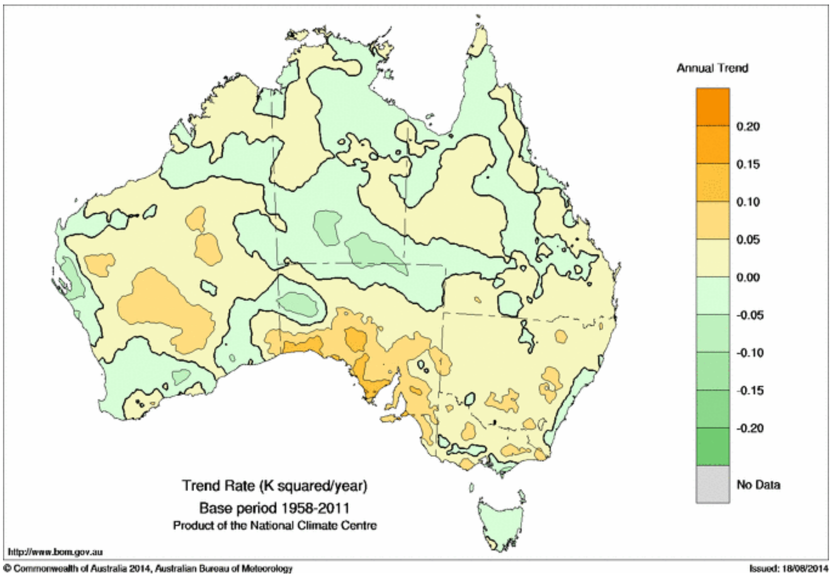


Figure 11. Trend in the intensity of EHF-positive events across 1958-2011. Values are expressed in units of K^2 per year.

An alternative way of approaching the trend question is to calculate the annual maximum EHF value in each 12-month period, and then calculate the linear trend in those annual maxima. For the purposes of this calculation, we do this calculation over 12-month July-to-June periods, so that the summer period is in the middle of the 12 months. Figure 12 shows the trend in the annual maximum EHF, expressed in units of K^2/year, while Figure 13 shows those trends in severity units per year. The calculation uses data from July 1958 to June 2014, and as before uses the OLS method.

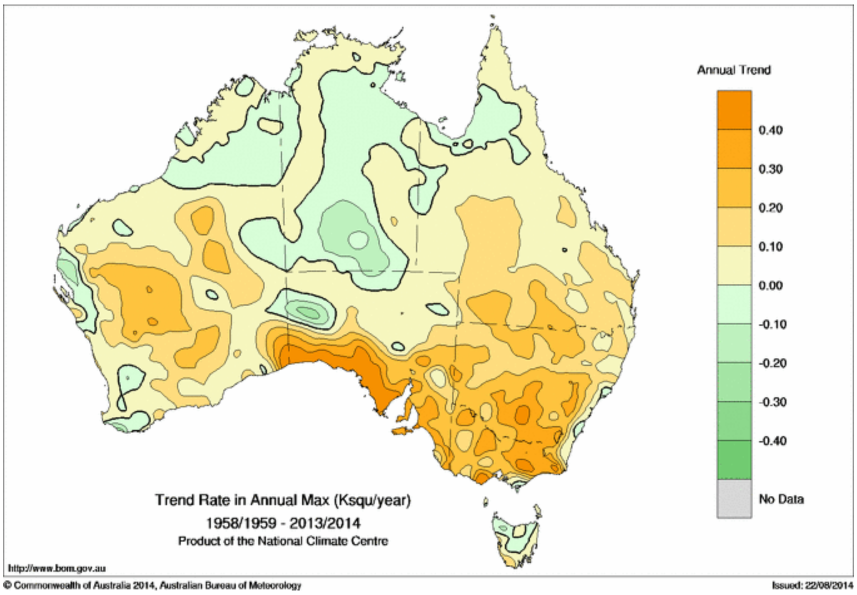


Figure 12. Trend in the annual maximum EHF across the period 1958/1959 to 2013/2014 (in K^2/year).

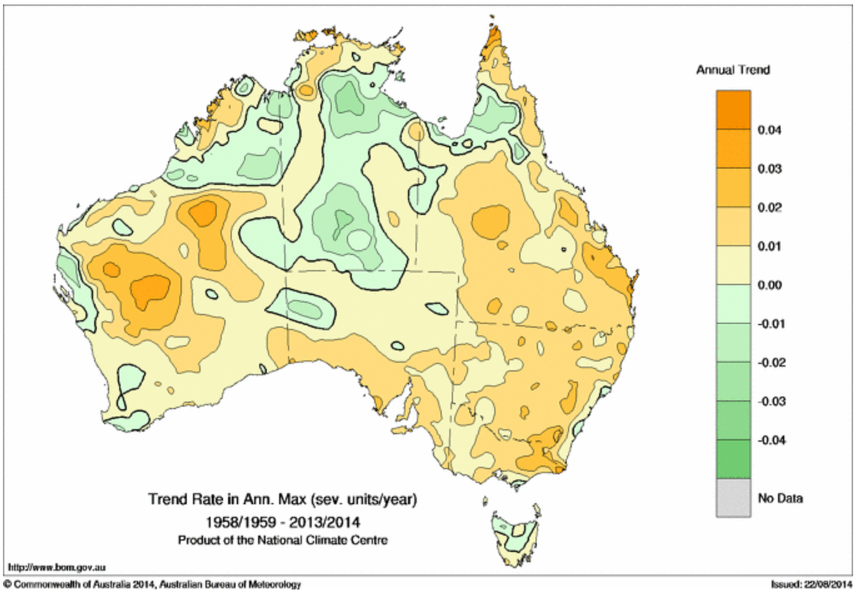


Figure 13. As per Figure 12 but in severity units per year.

Consistent with Figure 6 and Figure 8, the trend in the annual maximum is largest around the top of the Great Australian Bight, when expressed in units of K^2/year. When the trend is expressed in severity units per year (Figure 13), we see that over a large part of eastern Australia, the annual maximum EHF has risen by around one half of a severity unit across the period represented by the calculation. Trends in the northern part of the country are more variable, with some negative trends seen. The stronger trend in the maximum heatwave intensity (Figure 12) compared to that of average heatwave intensity (Figure 11) suggests that heatwaves are becoming more intense. Heatwave extremes are rising faster.

The robustness of the trends shown in Figure 12, and consequently those shown in Figure 13, has been assessed by comparing the results of the OLS trend calculation with analogous calculations following the Sen [90] and Siegel [91] methodologies. The comparisons (not shown), while spatially noisier than the OLS calculation, suggest that the OLS calculation is robust.

5. Discussion

The distribution of mean EHF across Australia in Figure 6 reflects a narrower climatic temperature variation in the tropics during the warm season compared to southern Australia where northerly flow of hot air from the interior and cool changes sweeping in from the Southern Ocean generate a much wider temperature range. The same aspects of the synoptic climate led to the 85th percentile of the positive EHF climate record (Figure 8) having similar characteristics. For this reason, maps of EHF are difficult to interpret unless normalised to an impact or severity scale, something which we recommend doing.

Our interpretation of heatwave severity relies upon an expected local adaptation to low-intensity heatwaves which are frequently experienced, leading us to nominate the 85th percentile of all heatwaves in the climate record as a representative point at which we consider heatwaves to be no longer of low intensity. In earlier work, we found that heatwave intensities investigated for locations in Australia and elsewhere (including North America and Europe) are well modelled by a generalised Pareto distribution [74], and so the rapid rate of increase in intensity for the remaining 15% of heatwaves in the upper tail of the distribution is regarded as progressively more challenging for vulnerable people, requiring increasingly greater adaptive responses. For the last few percentage points of the heatwave population the remaining heatwave intensities are so extreme and rare that normally resilient people and engineered systems are vulnerable unless protective measures are adopted.

Historical Australian examples of extreme heatwaves occur chiefly between mid-December and late-February [74], coinciding with regional drought and longer days. The loss of evaporative cooling in dry soils and reduced radiative cooling due to shorter nights has been shown [92] to contribute to elevated minimum temperatures and higher levels of retained environmental heat during heatwaves.

Warning rates for low-intensity, severe and extreme heatwaves are shown in Figure 7, Figure 9 and Figure 10. The increased rate of warning in the tropics is likely to occur with seasonally drier soils prior to the arrival of warm-season rains. More intense heatwaves occur when warm-season rains are delayed with dry soils in combination with shorter nights contributing to higher minimum temperatures and more intense heat conditions. Extreme tropical heatwaves are most likely to occur when failed monsoon rains result in dry soils during January and February. Dry environments associated with extreme heatwaves present an interesting phase switch for northern (tropical) and eastern (sub-tropical) Australia, where low-intensity heatwaves occur in humid air masses. The transition from humid to dry conditions through the severe to extreme heatwave spectrum poses an interesting question. Adaptation strategies for humid heatwaves may not be appropriate for higher-intensity dry heatwaves. The spatial and temporal relationship between dry soils and more intense heatwaves will be explored in future investigations.

Southern Australian heatwaves away from the eastern sea board are normally dry, although occasional low-intensity heatwaves may be more humid according to the synoptic situation. As a consequence, dry-atmosphere adaptation strategies are employed throughout the heatwave intensity range. The lower incidence rate for low-intensity and severe heatwaves (Figure 7 and Figure 9) over the southern coastal areas of the continent are counter-balanced by this strip experiencing a relatively higher extreme incidence rate (Figure 10). The episodic nature of heatwaves is more evident for this region. The rising trend in extreme heatwaves is evident for most of this area (Figure 12 and Figure 13) and large areas of eastern Australia, although the southwest of the continent has been experiencing a slight falling trend. This falling trend in the west may be a shift over time to synoptic conditions that permit more frequent coastal wind changes. Trends in heatwave patterns across Australia associated with trends in synoptic conditions will be explored in future investigations.

Australia's heatwave climatology maps presented in Section 4 have set the stage for further heatwave discussion. It is now possible in Australia's highly variable climate to examine the alternate antecedent conditions that result in differing rates of heatwave incidence and intensity.

6. Case Study: Southeast Australia 2009 Extreme Heatwave

In this section we explore a significant heatwave which occurred across southeast Australia in January/February 2009 using the EHF and its associated metrics, noting that the graphical representations of the data shown in Figure 14, Figure 15, Figure 16, Figure 17 and Figure 18 could readily be adapted to a real-time weather forecasting context. At the end of January 2009, Adelaide (at the Kent Town site) saw five consecutive days with daily maximum temperatures above 41°C (27-31 January), with the first four of them exceeding 43°C. A maximum temperature of 40.6°C on 1 February made six consecutive days above 40°C. In consequence, the EHF exceeded the severity threshold in the Adelaide region by a factor of four (Figure 14) at the peak of the heatwave, placing the event well into the "extreme" range. Two further hot days (06-07 February) caused a minor resurgence of the heatwave index after the main event.

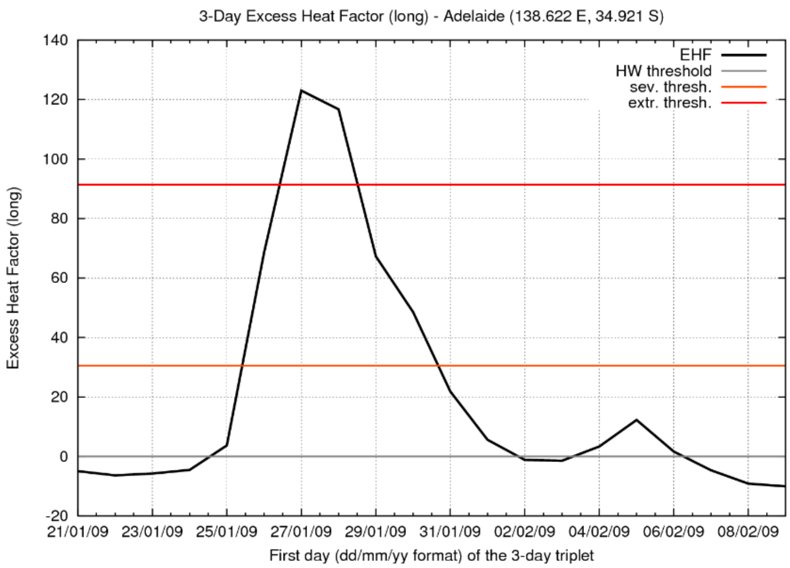


Figure 14. EHF for Adelaide (South Australia) across the period 21-23 January to 09-11 February 2009 (black line). The horizontal axis indicates the first day of each TDP. The horizontal grey line marks the threshold for a low-intensity heatwave (i.e., zero EHF), while the orange and red horizontal lines mark the thresholds for severe and extreme heatwaves respectively. Data are derived from interpolating gridded analyses of EHF. T95 = 24.9 °C, with the severity threshold being 30.5 K^2.

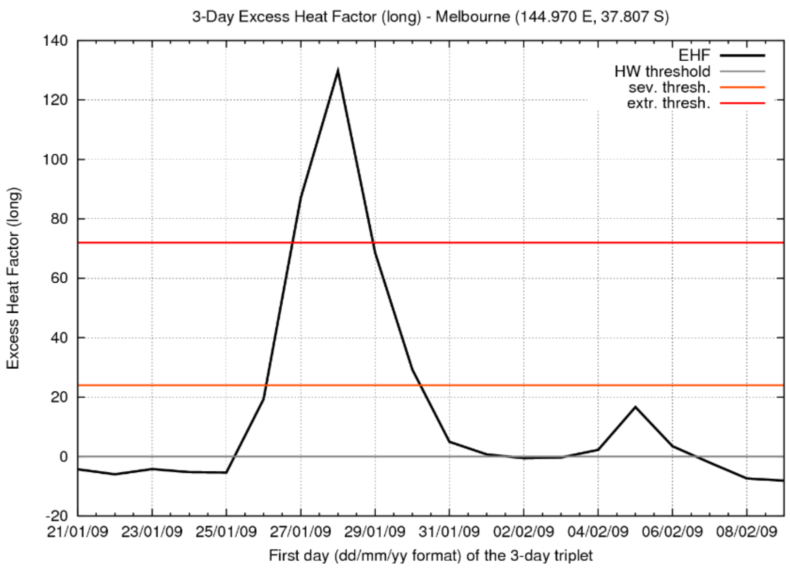


Figure 15. As per Figure 14 but for Melbourne (Victoria). T95 = 24.1°C, with the severity threshold being 24.0 K^2.

Melbourne (Victoria) saw three consecutive days with daily maximum temperatures above 43°C (28-30 January) at the official weather site (Bureau Station Number 086071), and in the Melbourne area more generally the severity threshold was exceeded by a factor of more than five (Figure 15) at the peak of the heatwave. The resurgent heatwave was shorter in Melbourne than in Adelaide, effectively only lasting one TDP (ending 07 February), but that day saw the

Melbourne official weather site's hottest day on record (46.4°C) and bushfires of appalling severity.

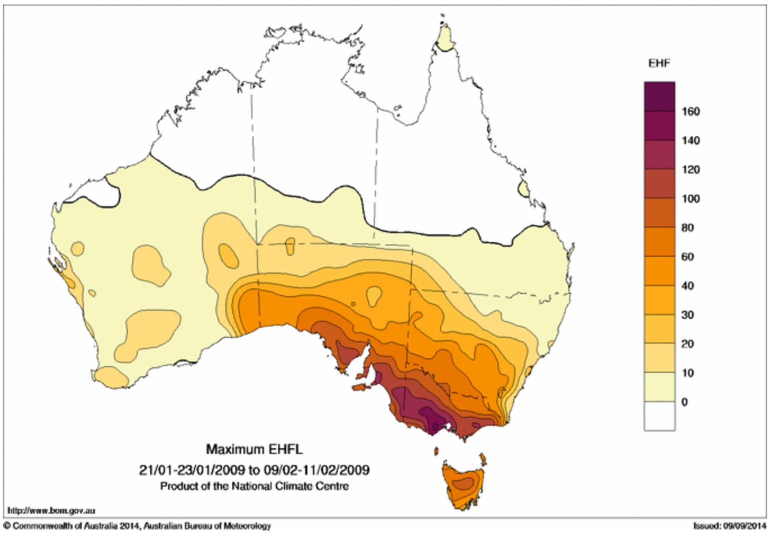


Figure 16. Maximum EHF for the period 21-23 January to 09-11 February 2009 (in K^2).

We present two different methods for ranking the scale of the heatwave. The first method is in terms of the maximum EHF value seen at each location within the heatwave period, to characterise the peak intensity. These maximum values at each location can be expressed either in actual values (Figure 16) or as multiples of the local severity threshold (Figure 17). The second method integrates or sums the positive EHF values across the heatwave period, to calculate the heat load of the entire event (Figure 18).

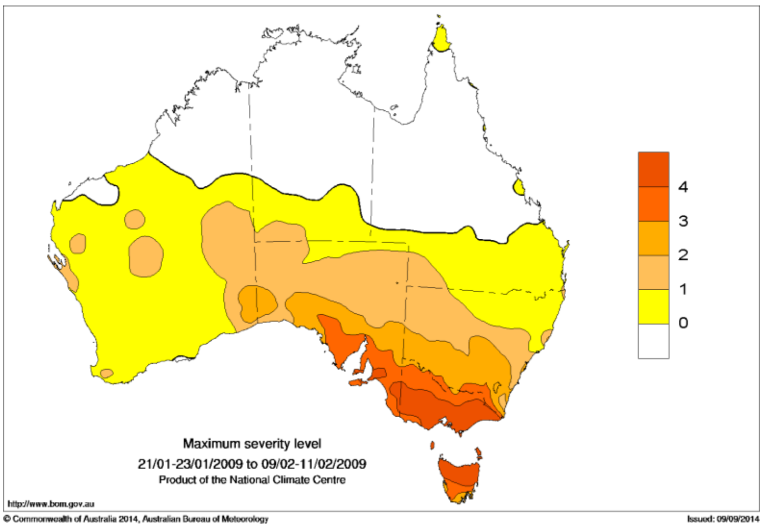


Figure 17. As per Figure 15 but expressed in multiples of the severity threshold. Yellow denotes a low-intensity heatwave (ratios between 0 and 1). Dark orange colours denote an extreme heatwave (ratios of 3 and higher). Ratios between 1 and 3 denote a severe but not extreme heatwave.

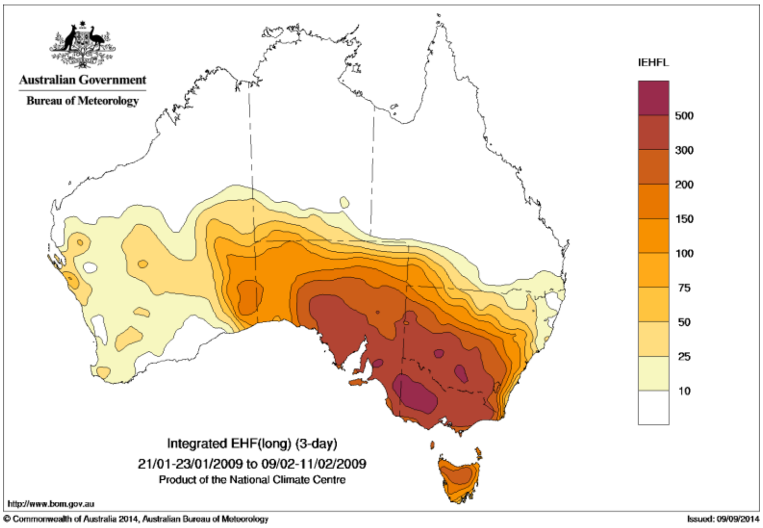


Figure 18. Integrated EHF across the period 21-23 January to 09-11 February 2009.

In terms of the integrated heat load (Figure 18), the heatwave extends across almost all of Victoria, southeast South Australia, southwestern New South Wales, and to a lesser extent northern Tasmania. The peak intensity in terms of actual EHF values (Figure 16) is highest in western Victoria, although in terms of severity (Figure 17) the heatwave reached "extreme" levels (ratios of three or higher) across most of Tasmania, almost all of Victoria and much of south eastern South Australia. Only parts of New South Wales close to the Victorian border experienced an "extreme" heatwave according to this metric. It should be noted though that much of Victoria and the northern half of Tasmania experienced particularly extreme conditions at the peak of the heatwave (as seen in the severe threshold multiples in Figure 17) where the severity threshold was exceeded by a factor of four.

Peak intensity and heat-load recorded for Adelaide (South Australia) and Melbourne (Victoria) in 2009 ranked amongst the top four heatwave events in their respective climate records. All of these events occurred at the end of significant multi-year droughts and were associated with significant bushfire outbreaks. Nairn and Fawcett [74] show how Adelaide's peak intensity preceded the mortality peak by three days, with the intensity and mortality displaying similar characteristics. Ambulance heat-related tasks in Melbourne demonstrated a similar response.

Southeast Australia's 2009 extreme heatwave resulted in South Australia recording 58 heat-related [74], [93] deaths whilst Victoria reported 374 excess deaths [94]. By contrast the comparable 2003 extreme heatwave [74] in France recorded approximately 15,000 excess deaths [95]. The population ratio for France and Victoria is approximately 11:1 whilst the excess mortality ratio for these two extreme heat events is about 40:1. France's approximate 4:1 excess mortality when compared to Victoria for these two extreme heatwave events provides context for comparison of resilience and adaptation measures employed during these events.

7. Concluding remarks

A two-step process involving the calculation of heatwave intensity, and the normalisation of this intensity via a severity classification scheme has allowed an assessment of the spatial and temporal characteristics of low-intensity, severe and extreme heatwaves.

Heatwave intensity has been calculated as the product of the long-term and short-term daily mean temperature anomaly. Quality assured maximum and minimum temperature climate, forecast, seasonal and climate projection data present the opportunity to seamlessly assess how the intensity characteristics of heatwaves are changing for any location.

Impacts of past and future heatwaves across sectors with and without thermo-physiological vulnerability can be analysed coherently.

Whilst this heatwave intensity and severity percentile methodology has not involved humidity it has successfully categorised extreme heatwave events for both dry and humid climate regimes, where the highest heatwave impacts are observed across people, livestock, utilities, transport and economic activity. In Australia's site-based daily temperature climate record (not shown) and in more recent, contemporary gridded climate and forecast data these high impact extreme heatwaves are found during periods of drought.

Future work will examine how severe and extreme heatwave classifications translate into levels of impact. In early studies it would appear that vulnerable populations are threatened as heatwaves become severe and that many more people and their supporting infrastructure are exposed as heatwaves become extreme. The value of identifying low-intensity heatwaves should also be emphasised. Most cultures value periods of lower-intensity heat, particularly if this comes as a shift in season from uncomfortably cool weather. Affirming cultural value for a level of heatwave that is not threatening to life provides a foothold for engaging and educating the public and business sectors in the dangers of more intense heatwaves.

The Appendix that follows demonstrates the performance of a heatwave service that has been piloted by the Australian Bureau of Meteorology utilising the heatwave intensity and severity methodology. The Bureau is also adapting the same methodology to sub-seasonal timescale as an experimental forecast product [96].

Acknowledgements

This work was partially funded by the Bushfire Cooperative Research Centre.

Author Contributions

Nairn had the original idea for the heatwave intensity and severity methodology, developing the concept using site data. Both authors revised the technique and designed the gridded data system. Fawcett implemented the methodology within the Bureau of Meteorology's gridded climate and NWP forecast data. Fawcett was responsible for generating the case study and

Appendix analyses. Fawcett drafted the manuscript, which was revised by both authors. Both authors read and approved the final manuscript.

Conflicts of Interests

The authors declare no conflict of interest.

Appendix

The Australian Bureau of Meteorology (the Bureau) utilised the EHF heatwave intensity and severity methodology to provide a pilot heatwave forecast service [97] for the summer of 2013/2014. Public distribution of the pilot products commenced on 8 January 2014, but the underlying forecasts were generated throughout the entire summer, and accordingly results for the period November 2013 to March 2014 are presented here. Daily maximum and minimum temperature forecasts were generated using the Bureau of Meteorology's gridded optimal consensus forecasting system [98], allowing forecasts with lead times of around 12 ("day 1"), 36 ("day 2"), 60 ("day 3"), 84 ("day 4") and 108 ("day 5") hours between NWP model initialisation and the start of the TDP being forecast. This service provided images of heatwave severity with accompanying text for the next five TDPs. The forecasts are verified against EHF calculations derived from the Bureau's operational daily temperature analyses. An example of such a verifying analysis is shown in Figure 19. The forecasts were issued in largely the same format.

Figure 20 shows a comparison of the percentage area of Australia forecast and observed to be in heatwave during the 2013/2014 Australian summer. Figure 21 shows the corresponding results for severe heatwaves, and Figure 22 for extreme heatwaves. The comparison of the percentage areas gives a basic insight into whether the forecast system is over-forecasting or under-forecasting, although obviously it does not indicate if the forecasted heatwaves are in the correct places.

There was a considerable degree of heatwave activity during the summer, but two episodes were particularly outstanding. Those were in Queensland and the Northern Territory around the start of the New Year, and in southern Australia around two weeks later. The comparisons show that there is considerable skill in the ability to forecast non-severe and severe heatwaves, although perhaps less so for extreme heatwaves. There are some tendencies towards over-forecasting and under-forecasting, likewise some false alarms, but no significant events went unforecast.

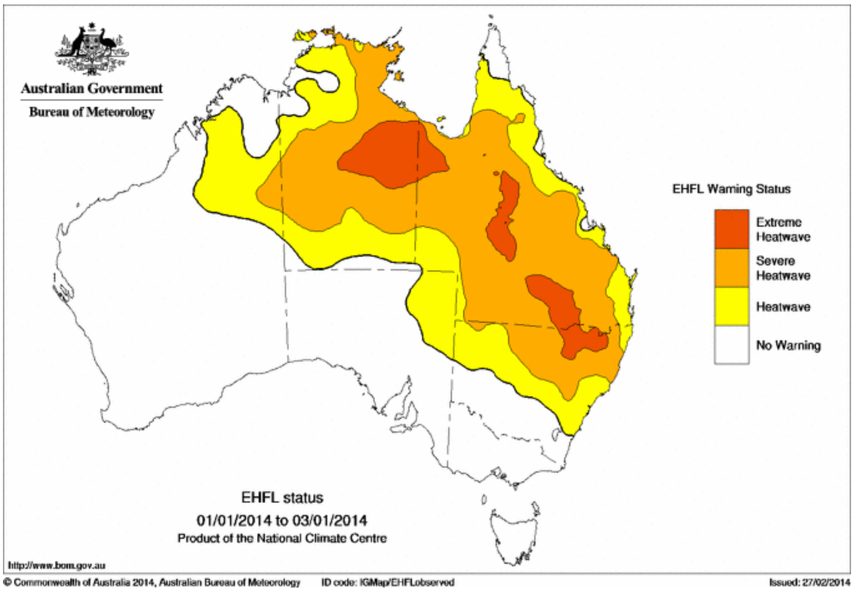


Figure 19. Heatwave observational analysis for the TDP 1 to 3 January 2014. The map shows the EHF expressed as a multiple of the severity threshold EHF_{85}, thereby indicating four categories; no heatwave (white), non-severe or low-intensity heatwave (yellow), severe but not extreme heatwave (orange), and extreme heatwave (red). The forecasts were issued in largely the same format.

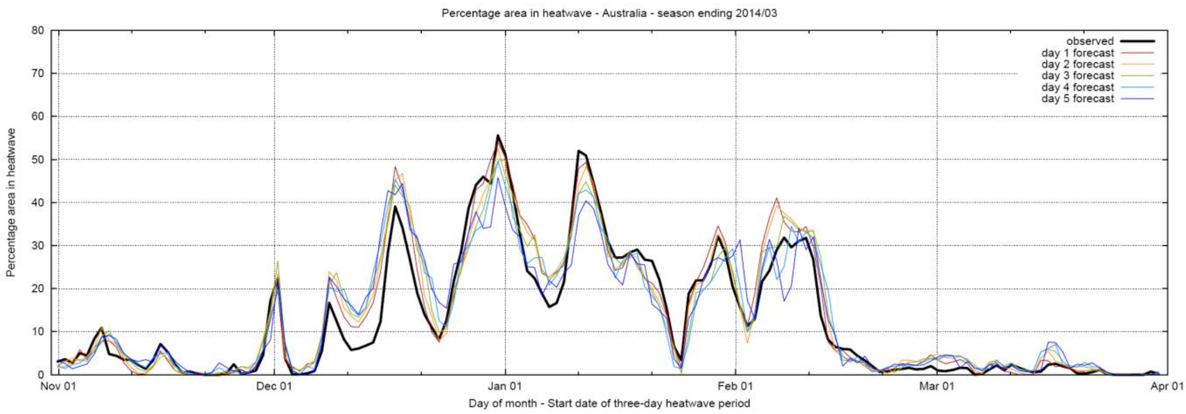


Figure 20. Percentage area of Australia in heatwave, as observed and forecast, across the period November 2013 to March 2014. The calculation is performed across continental Australia and the main island of Tasmania. Meridional convergence is taken into account when calculating the percentage areas.

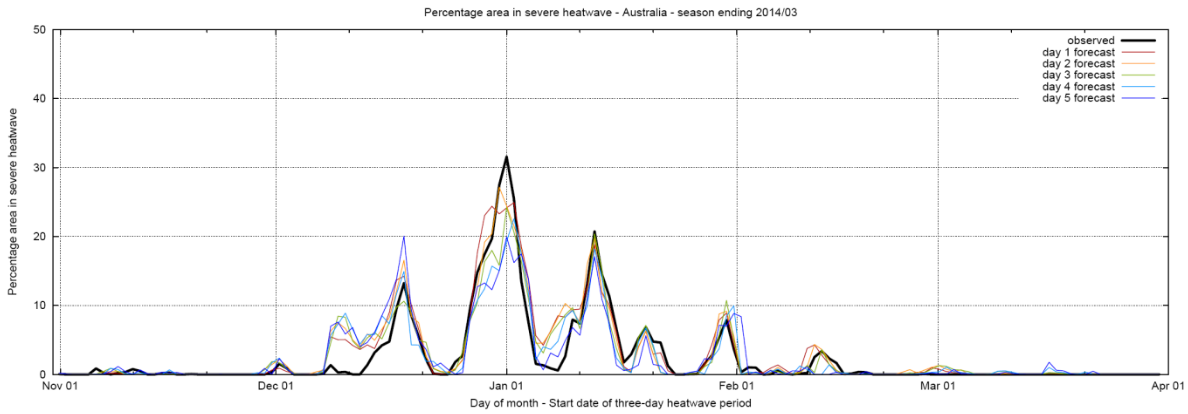


Figure 21. As per Figure 19 but for percentage area in severe heatwave.

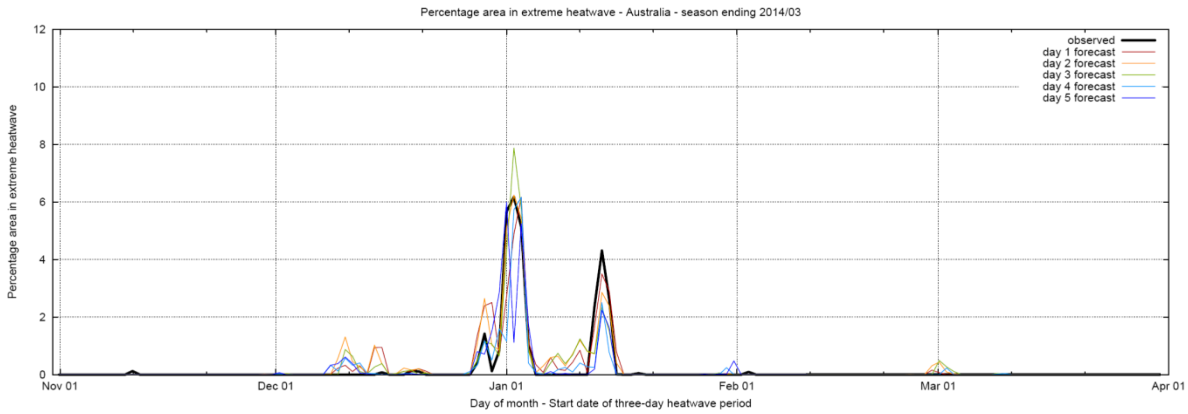


Figure 22. As per Figure 19 but for percentage area in extreme heatwave.

The Bureau convened a national workshop on 30 April 2014 to review the performance of the pilot service. Invited stakeholders from health, emergency services, power utility and media sectors agreed to form a Heatwave Services Reference Group (HSRG). Feedback from this group has been incorporated into an updated heatwave forecast service for Australia's 2014/2015 warm season which will commence during November 2014.

The Bureau is developing plans to upgrade the pilot heatwave forecasting service to the official forecast and warning system that supplies Australians with gridded forecasts and warnings that are quality controlled by forecasters and made available in a navigable, digital product suite that can be rendered for modern dissemination channels.

Statement of Authorship

Title of Paper	The impact of humidity on Australia's operational heatwave warnings
Publication Status	Submitted for Publication
Publication Details	*Climate Services*

Principal Author

Name of Principal Author (Candidate)	John Nairn		
Contribution to the Paper	Developed scientific questions, and conceived method for analysis. Wrote original paper. Participated in development of R code. All authors read and approved the final manuscript		
Overall percentage (%)	70%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	05 November 2021

Co-Author Contributions

Name of Co-Author	Bertram Ostendorf		
Contribution to the Paper	Curated data and developed code for data analysis in R. All authors read, reviewed and approved the final manuscript		
Overall percentage (%)	15%		
Signature		Date	05 November 2021

Name of Co-Author	Aurel Moise		
Contribution to the Paper	Contributed method for climate analysis. All authors read, reviewed and approved the final manuscript		
Overall percentage (%)	15%		
Signature		Date	05 November 2021

Paper 2**: The impact of humidity on Australia's operational heatwave warnings**

John Nairn[a], Aurel Moise[b], Bertram Ostendorf[a]

[a] *University of Adelaide, Adelaide, South Australia, Australia*

[b] *Centre for Climate Research Singapore, Meteorological Service Singapore, Singapore*

Corresponding author: John Nairn, john.nairn@bom.gov.au

ABSTRACT

More frequent and intense heatwaves in the last decade have challenged humanitarian, health and meteorological authorities to mitigate impact. Meteorological heatwave monitoring and prediction services vary between heatwave definitions which either include humidity or are based only on temperature. Incorporation of humidity into human health heatwave studies and warning services has been variable. Whilst higher humidity is a known stressor during heatwaves, humidity is known to confound interpretation of heatwave data and can be difficult to monitor and forecast.

This study examines the effect of humidity on diagnosed heatwave severity across Australia's diverse climate zones. Dry bulb temperature is used as the only input into the Bureau of Meteorology's current operational Excess Heat Factor (EHF) index. Alternative humidity-affected temperature indices (Apparent Temperature, Wet Bulb Globe Temperature and Heat Index) are examined for suitability as input to EHF to compare the incidence of dry and humidity-affected heatwave severity within Australia. This paper uses maximum and minimum dry and humidity affected temperature indices extracted from Australia's Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA).

Our investigation demonstrates Australia's operational temperature-only percentile-based heatwave severity service provides effective heatwave warning guidance for 5 of Australia's 6 diverse climate zones. However, rare very dry or very humid heatwaves in the tropics require both dry bulb temperature-only and Heat Index versions of Excess Heat Factor (EHF) severity index to provide competent operational heatwave early warning guidance.

Practical Implications

Heatwave studies and services have rapidly expanded around the world in the last decade, yet there is no agreement on how they should be defined. This may be a feature of available data, heatwave stress attribution or how people were exposed at the time of enquiry. Definitions can alternatively focus on maximum, minimum or daily temperature values, include humidity, be threshold- or percentile-based and persistent for differing consecutive day periods.

Inclusion of humidity may be important for heatwave warning systems as higher vapour pressure increases heat stress due to reduced evaporative cooling. Some National Meteorological and Hydrological Services heatwave services include humidity in their operational heatwave service. However, measurement, prediction and hazard communication of humidity is burdened with problems. Measurement of humidity or dew point is more demanding than measuring temperature alone. Records are frequently incomplete or can suffer from poor quality control. Modern humidity measurement systems are more reliable but have relatively short records. Consequently, quality of humidity-included heatwave climatologies will be reduced compared to the temperature-only equivalent, which may affect diagnosis of heatwave severity.

Disaster Risk Reduction (DRR) and Forecast-Based Financing (FBF) benefit from extended forecast ranges that are only possible with temperature-only heatwave indices because of lack of skill in seasonal and multi-week humidity forecasts. Cascading drought, heatwave, fire, smoke, water quality and landslip vulnerabilities have been exposed by increasing frequency, intensity and severity of heatwaves under the influence of global warming. This has led to the development of Australia's Excess Heat Factor heatwave index (EHF). Australia's temperature-only percentile-based heatwave index provides a common framework in which a comprehensive heatwave service supports communication across climate analysis and multi-day warning to multi-week preparedness disaster management time scales.

This study helps identify the most effective heatwave service by investigating the impact of including humidity in EHF across Australia's diverse climate and suggests a differentiated approach for heatwave warnings. The study has revealed that most of Australia's climate zones are well served by the current operational temperature-only version of EHF. Results support ongoing use of a local temperature-only percentile-based heatwave index for detection of both dry and humid severe heatwaves in 5 of Australia's 6 climate zones. This differs in Australia's hot and humid tropical climate zone. This region experiences rare, very dry and very humid heatwaves. A comprehensive heatwave service in the tropics needs to operate the temperature-only and humidity-included versions of Australia's Excess Heat Factor heatwave index (EHF) in order to capture these unusual heatwave events for an effective warning service.

This work builds on Australia's long history of heatwave exposure and experience in heatwave services development. Recommendations for Australia's heatwave warning service are highly relevant for the ongoing development of comprehensive heatwave services around the globe and heatwave warning systems in tropical climates.

1. Introduction

Whilst human health impacts arising from heatwaves vary across the world, their impacts manifest quickly [45], [99]–[101] and pose a significant challenge for unprepared communities [102].

Disaster-risk reduction, mitigation and preparedness are critical in reducing the impact of natural disasters, including heatwaves [8], with adaptation and early warning systems critical to support an effective heatwave management strategy [5], [103].

Increases in frequency and intensity of heatwaves have been observed over recent decades and will continue in a warming climate based on future projections [11], [13], [104]–[109] leading to further expected increases of human health impacts [110], [111].

A heatwave can be defined as a protracted period of unusually hot weather that is extreme for each location [43]. The wide variety of existing heatwave definitions and indices [5], [43], [45], [112], [113] can be attributed to differences in demographic vulnerability, impact sector and meteorological parameters in climate and forecast systems at the time of development.

Observations and prediction of dry bulb temperature are the highest quality and most widely available meteorological parameter in climate records, forecast services and climate projection data. A single heatwave index across broad time scales is useful for contextualising historical heatwave impacts with respect to planning and response on multi-day to multi-week time scales as well as policy development to address possible scenarios for future decades. A common index allows interaction between long-term policy, education, mitigation, preparation, and response to and recovery from heatwaves. Preparedness is improved when communities activate planned mitigation based on trusted forecast products. Similarly, verification of heatwave severity during an event linked to forecast guidance, enables appropriate calls for community action [114].

Many diverse heatwave definitions employ only temperature to define intensity and combine event duration to study and forecast heatwaves [115]–[117] and are generally reported to be effective in identifying human health impacts [43], [115], [118]. The absence of humidity within these definitions seems counterintuitive when considering the dominant role of vapour pressure in human thermo-regulation, and led to recommendations for inclusion of humidity in heat-health studies [119]. This study focuses on whether humidity is a necessary parameter within a heatwave definition for the operation of an effective heatwave warning and management strategy in Australia.

The Excess Heat Factor [56] was commissioned as Australia's continental scale heatwave severity forecast index in 2014. Epidemiological studies for both city and regional areas have demonstrated EHF heatwave intensity has skill in predicting rising heatwave-related human health impact [120]–[126]. Heatwave severity normalises EHF using the 85th percentile of the heatwave intensity record, where severity > 1 (intensity higher than 85th percentile) is associated with risk of death amongst vulnerable people. Heatwave severity >1 is recommended as the threshold for a heatwave warning. Heatwaves with severity >3 are labelled extreme, and have been associated with wider health impacts, including the failure of utilities and normally reliable infrastructure [56].

As the EHF is calculated using daily (average of maximum and minimum) temperature, quite reasonable questions have been raised regarding its efficacy for tropical locations which experience much higher humidity, especially during the warm season [127].

It has been argued that humidity is implied within the EHF through the incorporation of the minimum temperature [56]. Lower minima permit a larger diurnal cooling cycle. Higher minima limit the diurnal cooling cycle which is common in a humid environment due to the greenhouse effect of water vapour. EHF's use of local temperature climatology implies a diurnal temperature range which is affected by the local climatology of humidity. The use of each location's PDF of heatwave intensity to create heatwave severity ideally preserves this local information. The inclusion of additional humidity information within a heatwave index may be redundant. The local climatology of dry bulb temperature may already represent most of the critical information required for a heatwave warning and management system.

In order to clarify this issue, humidity driven equivalent temperature indices are investigated for the additional value they could contribute to the diagnosis of heatwave severity using the Excess Heat Factor. Such indices used by the Australian Bureau of Meteorology and the USA's National Weather Service are evaluated to identify a suitable index that might provide added value.

2. Method

Early heatwave index studies established absolute temperature thresholds for human health impacts by city or region through epidemiological statistical analyses [69], [73], [86] but were not easily generalised into early warning systems as results were specific to the demographic and climatological attributes at each location. Humidity-affected temperature indices are more specific to an individual person's ability to lose heat and have a similar absolute threshold attribute. These include Wet Bulb Globe Temperature [128], Apparent Temperature and Heat Index [81] and Universal Temperature Comfort Index [129]. Percentile-based maximum, minimum or daily temperatures have commonly been adopted for more consistent and greater regional coverage, and account for adaptation to local climate, and normally include a requirement for duration [43], [100], [130].

There are technical reasons for excluding humidity from warning systems. Difficult instrument maintenance, variable measurement standards and record quality of humidity has resulted in regular gaps in the long-term climate record. The quality of time series is impaired when compared to what can be achieved with long-term temperature-only (dry-bulb) climate records. Similarly, humidity forecast skill is significantly impaired when compared to dry bulb temperature [131]. Furthermore, adoption of daily temperature (average of maximum and minimum) and a percentile-based heatwave index accommodates the local humidity influence on the minimum temperature and the temperature distribution, respectively. As a consequence, the distribution of the dry bulb heatwave index should reflect the local humidity pattern.

Initially we consider dry bulb temperature (T), apparent temperature (AT), heat index (HI) and wet bulb globe temperature (WBGT) and discuss climatological attributes of these parameters, averaged over a three-day period. These temperature indices were developed to assess how temperature is perceived by humans and have previously been compared for efficacy in predicting health impacts [45], [47], [112], [132], [133]. We then include HI into the calculations for the Excess Heatwave Factor to quantitatively compare how the inclusion of humidity affected temperature indices would influence decision support for heatwave warnings.

2.1 Temperature Indices:

We considered three humidity affected temperature indices, Apparent Temperature (AT), Heat Index (HI) and Wet Bulb Globe Temperature (WGBT). HI is based upon an earlier version of AT [82], [83] compared to that used by the Bureau of Meteorology [134] with the latter also requiring 10 metre wind speed ($\boldsymbol{v_{10}}$). Both versions of AT require ambient temperature ($\boldsymbol{T_a}$), vapour pressure (**e**), which in turn require relative humidity (**rh**) and saturation vapour pressure ($\boldsymbol{e_s}$). The Bureau of Meteorology's simplification of WBGT also uses $\boldsymbol{T_a}$ and vapour pressure (**e**).

Apparent Temperature (AT, as used by the Bureau of Meteorology) has been calculated as a shaded exposure where shaded temperature, vapour pressure and wind speed are included in the calculation of the equivalent shaded temperature [134].

$$\boldsymbol{AT = T_a + 0.33 * e - 0.70 * v_{10} - 4.00} \qquad \text{Equation 1}$$

This calculation requires screen vapour pressure $\boldsymbol{e}$, wind speed at 10 metres $\boldsymbol{v_{10}}$ and screen dry bulb temperature $\boldsymbol{T_a}$ in °C.

Vapour pressure, **e** is calculated:

$$\mathbf{e} = \mathrm{rh} * \boldsymbol{e_s} \qquad \text{Equation 2}$$

Which requires relative humidity $\boldsymbol{rh}$ and saturation vapour pressure ($\boldsymbol{e_s}$).

$$\boldsymbol{rh = 100 \frac{w}{w_s} \approx 0.263\, p \cdot q\, [exp(\frac{17.67(T_a - T_0)}{T_a - 29.65})]^{-1}} \qquad \text{Equation 3}$$

Where $\boldsymbol{T_a}$ is ambient temperature in Kelvin (K) and $\boldsymbol{T_0}$ is 273.16 °C and

$$\boldsymbol{e_s = 6.112 * exp\,((17.67 * T_a)/(T_a + 243.5))} \qquad \text{Equation 4}$$

The Heat Index formulated (HI) as used by the U.S. National Weather Service within NOAA, is a series of AT regressions using a shaded temperature and humidity (no wind speed) decision tree [135]. HI has been calculated using the coded function "heat.index" from the R package "weathermetrics" [135].

Wet Bulb Globe Temperature (WBGT) has been calculated using the approximation employed by the Bureau of Meteorology:

$$\boldsymbol{WBGT = 0.567 \cdot T_a + 0.393 \cdot e + 3.94} \qquad \text{Equation 5}$$

Where $\boldsymbol{T_a}$ is the ambient temperature in °C and **e** as calculated in Equation 2.

Heatwave intensity and severity were calculated using the technique described by Nairn and Fawcett. The heatwave intensity (EHF) [56] is calculated (Equation 6) by combining long (Equation 7) and short-term (Equation 8) daily temperature anomalies. Finally, the dimensionless heatwave severity index is created by using the intensity PDF to normalise intensity for each location (Equation 9).

$$\boldsymbol{EHF} = \boldsymbol{EHI_{sig}} \cdot \boldsymbol{max}\,[\mathbf{1}, \boldsymbol{EHI_{accl}}]$$ Equation 6

$$\boldsymbol{EHI_{sig}} = \boldsymbol{DMT_{3-day}} - \boldsymbol{DMT_{95}}$$ Equation 7

$$\boldsymbol{EHI_{accl}} = \boldsymbol{DMT_{3-day}} - \boldsymbol{DMT_{30-day}}$$ Equation 8

$$\boldsymbol{EHFsev} = \boldsymbol{EHF} \div \boldsymbol{EHF_{85}}$$ Equation 9

Where DMT95 is the 95th percentile of daily mean temperature (average of maximum and minimum) for all days in the 1990-2019 climate record. DMT3-day is the average DMT over the three-day heatwave period, DMT30-day is the average DMT over the preceding thirty-day period and EHF85 is the 85th percentile of the 1990-2019 EHF climate record.

Heatwaves are detected when EHI_{sig} is positive and max [1, EHI_{accl}] >1 amplifies heatwave intensity. EHF_{85} is used to normalise EHF to produce heatwave severity which is comparable across all locations, and can be mapped.

2.2 Meteorological data

Meteorological variables were sourced for Australia from the Bureau (of Meteorology) Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) archived at the National Computational Infrastructure (NCI). The BARRA reanalysis data set presents high-quality model derived humidity climate data, which we use to test how the temperature-only heatwave index compares to a humidity-affected temperature index across Australia's diverse climate zones. The 29-year (1990 to 2018) 12km grid resolution temperature and moisture data has been shown to be reliable in the tropics when validated against automatic weather stations [136].

City locations were grid interpolated for locations at least 10 km inland from the coast to eliminate over water temperature grid contamination. Locations are identified in Table 1.

Hourly mean sea level pressure (av_mslp), screen specific humidity (av_qsair_scrn) and screen dry bulb temperature (av_temp_scrn) were sourced from the NCI repository. These variables were required to calculate hourly apparent temperature (AT: in shade, includes wind), Heat Index (HI: in shade, no wind) and Wet Bulb Globe Temperature (WBGT: Bureau of Meteorology approximation for midday sun, no cloud, includes wind and globe temperature). Hourly values were calculated to derive daily maximum and minimum HI and AT. Daily maximum WBGT was calculated, while minimum WBGT was not attempted as diurnal variability is contaminated by inclusion of midday insolation in the formulation sourced from the Bureau.

Climatological heatwave analysis has previously been performed on the 90th percentile of three-day temperature averages of maximum, minimum and daily values [43]. This has been extended in our analysis to include mean, 10th and 90th percentiles of T, HI, AT and WBGT.

Daily values of T and HI were then used to derive Excess Heat Factor severity. For this purpose, the 29-year record (1990-2018) is used for the 95th percentile (while a 30-year period, 1971-2000, has been used in prior studies) and for computational simplicity UTC daily temperatures are used instead of local daily temperatures. Daily WBGT (using the Bureau's approximation) was not derived as the fixed inclusion of sidereal noon radiative effect introduces an error for low sun angle when minimum temperatures normally occur [137].

2.3 Dry and humid versions of Excess Heat Factor

Two versions of EHF severity have been calculated using the BARRA data set and were then compared to understand how humidity affects the assessment of heatwave severity. One version uses daily dry bulb temperature (T) whilst the humidity effect is captured in a version which uses daily heat index (HI).

Calculation of EHF severity is dependent upon validity of the calculated Generalised Pareto Distribution Function (GPDF) using empirical data. Small fluctuations in T and HI empirical CDFs in Figure 23 are considered to be a good fit due to the use of a shorter sample period than used in previous studies [56], [138]. The 85th percentile of the calculated GPDF is used to create EHF_{sev} as shown in Equation 9, and labelled as the threshold for a severe heatwave ($EHF_{sev} > 1$) which is the recommended threshold for heatwave mitigation actions and future warnings in Australia [56], [114], [117].

In Brisbane, the values of EHF_{HI} are approximately 25% higher than EHF_{T} and in Darwin EHF_{HI} is almost five times higher than EHF_{T}. The variability in EHF_{HI} shown in Figure 23 and Table 2 is consistent with Melbourne's warm dry summer, Brisbane's warm humid summer and Darwin's hot humid summer.

3. Results and Discussion

3.1 Climatologies of dry bulb T, AT, HI and WBGT temperature indices

Statistical attributes of T, AT, HI and WBGT have been used independently to investigate heatwave behaviour. Their climatological distributions are examined to assess the accuracy of their measurement or formulation. Comparison of these climatologies is used to select the best index for application as a humidity-affected temperature variable in EHF.

Australia's 29-year climate record for three-day average maximum and minimum Heat Index (HI), Apparent Temperature (AT) and Wet Bulb Globe Temperature (WBGT, maximum only) are shown as deviations from three-day average maximum and minimum dry bulb temperature (T) in Figure 24 and Figure 25.

Maximum HI is slightly cooler than maximum T across most of the continent, apart from northern coasts where it is warmer. This effect is more pronounced during the warm season where the HImax P90 and Tmax P90 anomaly (Figure 24) is warmer in a thin strip on the east coast of the continent and substantially warmer across the tropics. The remainder of the continent is slightly cooler, a consequence of the Heat Index formulation which constrains maximum temperature when the air mass is very dry [135]. The HImin P90 and Tmax P90 anomaly (Figure 25) is similar, although over a narrow temperature range with the exception of a markedly warmer region in northern Western Australia. The three-day maximum and minimum warm HI P90 and T P90 anomaly in Figure 24 and Figure 25 indicate that the humid thermal stress is largely constrained to the tropics. Application of Daily HI within the EHF percentile heatwave severity index is likely to provide additional heatwave severity information for the tropics. The small difference between maximum (minimum) T and HI suggest Australia's operational heatwave service (EHF(T)) is an adequate heatwave severity guidance index for most of the continent (climate zones 1-5).

The inclusion of wind in the calculation of AT has produced a notably cooler maximum temperature climatology when compared to the other parameters. The ATmax P90 and Tmax P90 anomaly in Figure 24 is similar to the anomaly between HImax and Tmax, although the warm anomaly is smaller and contracted to the coastal margins of the tropics and east coast. The ATmin P90 and Tmin P90 warm anomaly in Figure 24 is much larger than the HI equivalent, extending further south than the tropics and further inland on the east coast. In their usage of AT, the Bureau of Meteorology adopted Steadman's recommended AT regression equation for Australia [134] and a review of the nomogram from which this approximation was derived shows that it was selected for the mean, rather than the warm season climate. Therefore, the ATmin Mean and Tmin Mean anomaly in Figure 25 is a better fit for the Bureau's AT calculation, and demonstrates how the warm season ATmin P90 and Tmin P90 anomaly in Figure 25 has been artificially amplified. Thus, the Bureau's adopted AT calculation produces a wind chill under all circumstances which is not appropriate for heatwave conditions. This is best demonstrated in the nomogram [134] where hot, dry, and windy conditions result in equivalent temperatures that are higher than the dry bulb temperature. This is an instance of a wind heating effect which is not captured by the Bureau's version of AT. Therefore, this version of AT is unsuitable for heatwave purposes and is excluded from our EHF analysis.

Maximum WBGT is markedly cooler and deviates significantly from the distributions of T, HI and AT. WBGT is not a temperature equivalent index. It would be better titled as Wet Bulb Globe Index (WBGI) as the 'temperature' range is lower than for either T, Heat Index or Apparent Temperature. WBGT's assumption of clear skies progressively fails with higher latitude due to the frequency of frontal rain bands and persistent shallow stratiform cloud during winter contributing to the large warm WBGTmax P10 and Tmax P10 anomaly across southern Australia. The warm bias in the WBGTmax P90 and Tmax P90 anomaly over Tasmania (Australia's southern island state) is unusual, a likely combination of Southern Ocean impacts on clear skies and lower sun angle at higher latitude.

For these reasons, it is not possible to use the Bureau of Meteorology's approximation of WBGT to generate a minimum value due to inclusion of midday insolation. WBGT is not a good candidate for this experiment and is excluded from further analysis.

Heat Index is a good candidate for this experiment as it is a shielded temperature, equivalent to the standard for dry bulb temperature and is derived via a multiple regression of the humidity equivalent temperature nomogram developed by Steadman which accommodates changes in the effect of humidity on human thermal stress as temperature increases.

The spatial distributions of maximum and minimum HI P90 and T P90 anomalies demonstrate latitudinal stratification of temperature that resembles the climate zones shown in Figure 26. HI shows a closer fit to Figure 26, accommodating the more humid tropical and subtropical climate zones. Incorporation of Daily T and Daily HI within the EHF heatwave index was chosen to compare the effect of humidity in evaluating heatwave severity (EHF_{SEV}) across Australia.

Australian epidemiological studies [24], [75], [121], [123], [125], [138], [139] have established $EHF_{SEV} > 1$ as a threshold for significant impact on vulnerable people. Low-intensity heatwaves below this threshold occur frequently and have significantly less impact consistent with the Pareto effect [140]. In agreement with the Pareto effect, rarer and more intense heatwaves have greater impact. Australia's national heatwave service [114], [117], maps low-intensity (pale yellow), severe (orange) and extreme (red) categories, for EHF_{SEV} ranges (0 to < 1), (1 to ≤ 3) and (> 3) respectively. Operational warnings are issued by several jurisdictions (Nairn et al., 2019; NSW Government, 2011; Queensland Health, 2019) based on spatial and temporal attributes of severe (category) heatwaves forecast by the Bureau's operational national heatwave service. Australia's operational warning threshold has been used for analysis of warning efficacy.

3.2 Dry Vs humid EHF severity

Comparisons of $EHF_{SEV(T)}$ against $EHF_{SEV(HI)}$ are shown in Figure 27, Figure 28, Figure 29 and Figure 30 for the period 1990 to 2018 for cities across Australia. A LOESS regression line with confidence bands has been applied to show statistical relationships between the two EHF_{SEV} estimates, noting only $EHF_{SEV} > 0$ indicates the presence of heatwaves. Apart from the tropics (LOESS not applied) Australian cities show a close fit between daily $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ values, although increasing scatter is evident for cities closer to the equator.

Additional tests have been applied to these plots to investigate how parity between $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ might break down.

In the first instance, the pale blue lines in Figures 5-8 correspond to heatwaves where both T and HI based indices produce a heatwave warning ($EHF_{sev} > 1$) and their absolute difference is greater than 1. Bold coloured lines correspond to heatwaves where either T or HI based indices has not generated a warning.

Heatwave sequences (consecutive days with $EHF_{sev} > 1$) are plotted with an additional day added to either end to emphasise the presence of shorter events. This is evident for Adelaide in Figure 27 where a two-day event has been identified, and for Perth where two events have been captured. The pale blue lines in the Adelaide and Perth plots show the incidence of rare very humid heatwaves. In these instances, whilst $EHF_{SEV(T)}$ has provided a lower severity value than $EHF_{SEV(HI)}$, it is in the severe category and would have raised a warning alert.

Similarly, Brisbane has very humid and very dry (light blue lines) events, but again the alternate index exceeds the warning threshold.

Cairns shows two 2-day events in Figure 28 where $EHF_{SEV(HI)}$ failed to warn for very dry severe heatwaves. Otherwise, pale blue lines demonstrate a series of very humid and very dry heatwaves where both severity indices warned of a severe heatwave, even though their values were greater than 1 apart.

Both Darwin and Port Hedland (Figure 29 and Figure 30) show many very humid and very dry events (cold coloured lines) where the alternate index failed to generate a warning, each annotated in the legend for start and length of the severe heatwave sequence.

An interesting teleconnection between Cairns and Darwin missed events is evident, where the 1992 and 2007 $EHF_{SEV(HI)}$ warning detection failures (very dry severe heatwaves) in Cairns correspond to $EHF_{SEV(T)}$ failures (very humid severe heatwaves) in Darwin. Australian heatwave climate driver modelling [144] shows distinctive dipoles in sensible and latent heat across North and Northeast Australia which accounts for this teleconnection. Loughran, Pitman and Perkins-Kirkpatrick (2019) did not investigate northwest Australian heatwave climate drivers. However, ENSO impacts are evident where very humid heatwaves can be associated with El Niño in Darwin, and La Niña for Port Hedland. Table 3 and Table 4 show these drivers are reversed for very dry severe heatwaves. Interestingly, the state of the IOD is highly inconsistent for both Darwin and Port Hedland very dry or very humid heatwaves.

The following spatial time series case studies explore this relationship further.

3.3 Tropical Case studies

Over the 29-year study period Darwin recorded 61 humid severe heatwave warning days ($EHF_{(HI)}$ >1), with 12 of the 19 (= 63%) heatwave warning events (sequences with at least one severe heatwave day) being missed by the operational dry $EHF_{(T)}$. There were 61 dry severe heatwave warning days ($EHF_{SEV(T)}$ > 1), with 10 of the 31 (= 30%) heatwave warning events (sequences with at least one severe heatwave day) missed by the humidity-included $EHF_{(HI)}$ (Supplementary data, Australian_Cities.csv).

Port Hedland recorded 69 humid heatwave warning days ($EHF_{(HI)}$ > 1), with 12 of the 28 (= 43%) heatwave warning events (sequences with at least one severe heatwave day) being missed by the operational dry $EHF_{(T)}$. There were 57 dry heatwave warning days ($EHF_{SEV(T)}$ > 1), with 8 of the 31(= 26%) heatwaves warning events (sequences with at least one severe heatwave day) missed by the humidity-included $EHF_{(HI)}$ (Supplementary data, Australian_Cities.csv).

Roughly half (42 to 63%) of Darwin and Port Hedland severe HI heatwaves failed to be detected as severe T heatwaves by the operational system whilst approximately a quarter (25 to 32%) of severe T heatwaves were not detected as severe HI heatwaves. The significant alternate index miss-rate for both Darwin and Port Hedland detection of heatwave severity demonstrates tropical cities can be affected by unusually dry or moist heatwaves. High spatial variability within coherent heatwave severity patterns explains some of this variability.

The Darwin very humid ($EHF_{SEV(HI)}$) severe heatwave shown in Figure 31 shows a severe signal extending across Darwin's coastal location, whilst a larger dry ($EHF_{SEV(T)}$) severe heatwave signal is located further to the southwest. The overall footprint of the heatwave in either index is similar. Wind vector and sea level pressure anomalies (Figure 32) show a strong cyclonic anomaly over central Australia recirculating a dry hot airmass off-shore which feeds into strong anomalous westerly flow across the north of the continent. Wind convergence between the developing Northwest Monsoon and the recirculating hot continental airmass picks up sea surface moisture in the westerly flow that produced the severe humid heatwave at Darwin. Whilst the spatial severe heatwave signal in either sequence (T or HI) would have provided the basis for preparation, mitigation and response across the region, the severe humid heatwave signal that impacted the exposed coasts of the Northern Territory was under-shot by the $EHF_{SEV(T)}$ guidance. Expert interpretation of regional circulation would be required to prepare an adequate response in the absence of $EHF_{SEV(HI)}$ guidance.

Figure 33 shows an extensive very dry severe heatwave across the Top End of the Northern Territory and Cape York in northern Queensland, whilst the humid heatwave severity signal is weak and highly pixelated. Wind vector and sea level pressure anomalies (Figure 34) show a strong anti-cyclonic anomaly over southern Australia advecting a hot dry interior airstream across northern tropical coasts. This example illustrates an inherent weakness in the $EHF_{(HI)}$ system. Heat Index has a much higher temperature range in the presence of high humidity and temperature. Consequently, unusually hot and dry airmass temperatures may not register as significant heat and can struggle to register as a heatwave. Similar examples are included as supplementary figures, further illustrating pixilated internal heatwave severity structure and reduced spatial heatwave severity detection associated with the $EHF_{(HI)}$ index. These additional examples consistently demonstrate the influence of continental synoptic wind patterns that deliver very dry heatwaves over tropical coastal regions. Recirculation of very dry heat in long trajectories over adjoining tropical seas appears to acquire moisture before arriving on adjacent exposed tropical coasts to form very humid heatwaves.

4. Conclusions

Four heat exposure variables (T, AT, WBGT, HI) were calculated at hourly intervals from 12 km resolution Bureau of Meteorology high resolution Regional Reanalysis for Australia (BARRA) data set. Climatological characteristics of three-day averaged maximum and minimum values were then examined for suitability within a temperature percentile-based heatwave severity index. T and HI daily temperatures were selected as the best candidates for calculation and comparison of dry and humid versions of the Excess Heat Factor (EHF), a percentile-based heatwave severity index.

We studied populated locations across Australia's climate zones and found $EHF_{(T)}$ and $EHF_{(HI)}$ provided comparable warning advice for six of Australia's seven Capital cities across 5 of Australia's 6 climate zones. Both $EHF_{(T)}$ and $EHF_{(HI)}$ occasionally failed to provide consistent severe heatwave guidance for Darwin, Capital city for the North Territory in Australia's wet and humid tropical climate zone. Cairns and Port Hedland were also examined to further explore EHF warning characteristics across a wider span of Australia's tropical climate zone. Port Hedland exhibited a similar rate of warning failures, with failures much less frequent for Cairns.

Our study examined spatial case studies for the Darwin and Port Hedland where $EHF_{(T)}$ or $EHF_{(HI)}$ failed to warn for a severe heatwave to understand the broader mechanisms prevailing on those occasions.

Case studies developed for Darwin and Port Hedland warning failures revealed occasions when tropical regions were impacted by sustained advection of anomalously hot and very dry continental airmasses or sustained recirculation of these same airmasses over tropical seas before returning to tropical coasts. On other occasions warning failures appeared as artifacts of pixilation variability within broadly similar heatwave footprints which may be explained by differences in boundary layer depth of very dry and very humid heatwaves. The boundary layer depth of very dry continental heatwaves is usually in excess of 3000m whilst the very humid maritime boundary layers are generally below 1000m. Further investigations into how boundary layer depth changes and mixes within severe heatwave circulations may explain the pixilation of very humid heatwaves.

Persistent circulation patterns required to create unusually humid severe heatwaves at Cairns did not appear during the analysis period. Impacted sectors would benefit from further research focused on the drivers of unusual humidity in severe tropical heatwaves.

Our investigation demonstrates Australia's current operational temperature-only percentile-based heatwave severity service provides effective heatwave warning guidance for 5 of Australia's 6 diverse climate zones. However, very dry or very humid heatwaves in the tropics require both dry bulb temperature and Heat Index versions of Excess Heat Factor (EHF) severity index to provide more complete operational heatwave warning guidance. While this result supports the ongoing use of $EHF_{(T)}$ for epidemiological impact studies and seamless temporal heatwave services for most of Australia (five of six climate zones), our analysis identifies the need for a humidity-based metric (Heat Index in this case) for impact assessments in tropical locations.

Our analysis also found that the operational heatwave services would benefit from next-neighbour analysis schemes to overcome possible grid point variability or variable boundary layer mixing effects within very humid marine layers.

Epidemiological heatwave impact studies should consider a combined use of $EHF_{(T)}$ and $EHF_{(HI)}$ exposure indices in tropical climate zones in order to avoid significant failure of heatwave detection and therefore its impacts.

Acknowledgments.

The authors have sourced Bureau of Meteorology high-resolution atmospheric reanalysis for Australia (BARRA) data for this study. The Bureau's Data Catalogue http://www.bom.gov.au/metadata/catalogue/view/ANZCW0503900566.shtml?template=full contains the license under which this data has been used.

Data Availability Statement.

The supplementary data file Australian Cities.csv (4.8Mb) contains daily EHF severity data (T, AT, HI) for the cities examined in this study.

TABLES

City	Latitude (°N)	Longitude (°E)
Darwin (Humpty Doo)	-12.57	131.10
Cairns (White Rock)	-16.98	145.74
Port Hedland (inland)	-20.44	118.62
Brisbane (City)	-27.47	153.02
Sydney (Strathfield)	-33.87	151.09
Adelaide (City)	-34.97	138.61
Melbourne (Essendon)	-37.76	144.92
Perth (City)	-31.95	115.86
Hobart (Claremont)	-42.79	147.25

Table 1. Grid point sample locations.

	HW INTENSITY	EHF_{SEV} = 1 (EHF_{85})	EHF_{SEV} = 3 (3 X EHF_{85})	MAX EHF
MELBOURNE	EHF_T	30	90	>150
	EHF_{HI}	28	84	150
BRISBANE	EHF_T	7	22	40
	EHF_{HI}	11	33	60
DARWIN	EHF_T	0.6	1.7	3
	EHF_{HI}	3	9	25

Table 2. EHF intensity for EHF severity = 1, 3 and max for Melbourne, Brisbane and Darwin in Figure 23.

START DATE	HUMID LENGTH (DAY)		START DATE	DRY LENGTH (DAY)
19900302	2		20011101	2@
19901117	4		20041026	3
19920207	3#-		20041114	3
19980104	4#-		20050309	3
19980225	2#-		20081010	2@
20070202	3#		20081019	3@
20111126	2		20081202	3@
20130123	3		20121204	3+
20141214	3-		20140106	2-
20150217	2#+		20160228	2-
20160313	2#-			
20181210	3			

Table 3. Darwin: start date and length of very humid and very dry severe heatwaves. Positive and negative Indian Ocean Dipole annotated by + or -. El Niño or La Niña annotated by # or @.

START DATE	LENGTH (HUMID)		START DATE	LENGTH (DRY)
19990117	5@-		19921229	2#-
20010120	3@-		19931201	2#
20090221	2@		19940205	2#+
20101226	2@-		19961226	2-
20110106	2		20020109	2#
20121221	3+		20050224	2
20130107	2		20060216	2#+
20130220	2		20141205	3-
20160301	3-			
20161221	3-			
20180103	2@			
20180119	4@			

Table 4. Port Hedland: start date and length of very humid and very dry severe heatwaves. Positive and negative Indian Ocean Dipole annotated by + or -. El Niño or La Niña annotated by # or @.

FIGURES

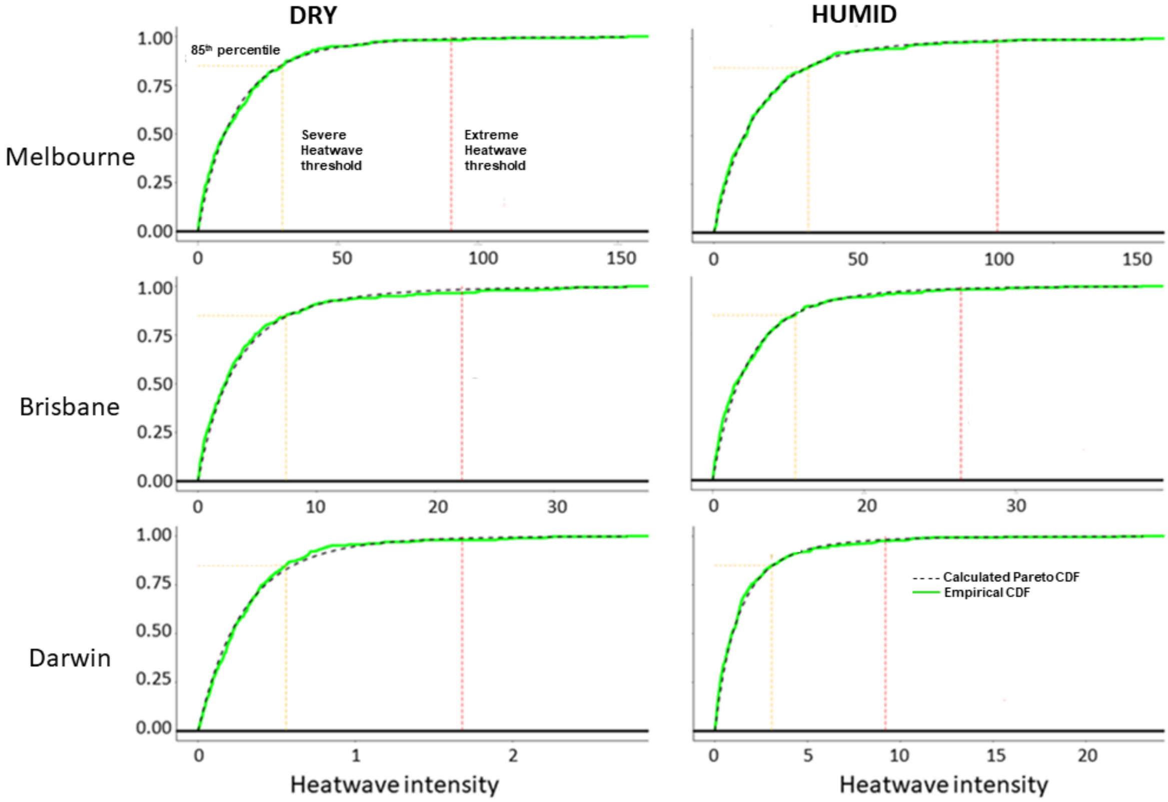


Figure 23. Dry and Humid Excess Heat Factor (°$\mathbf{K^2}$) empirical cumulative distribution functions (green lines) derived from BARRA dry bulb (left) and Heat Index (right) for Melbourne, Brisbane and Darwin. Calculated Pareto Distribution Function overlaid (dashed).

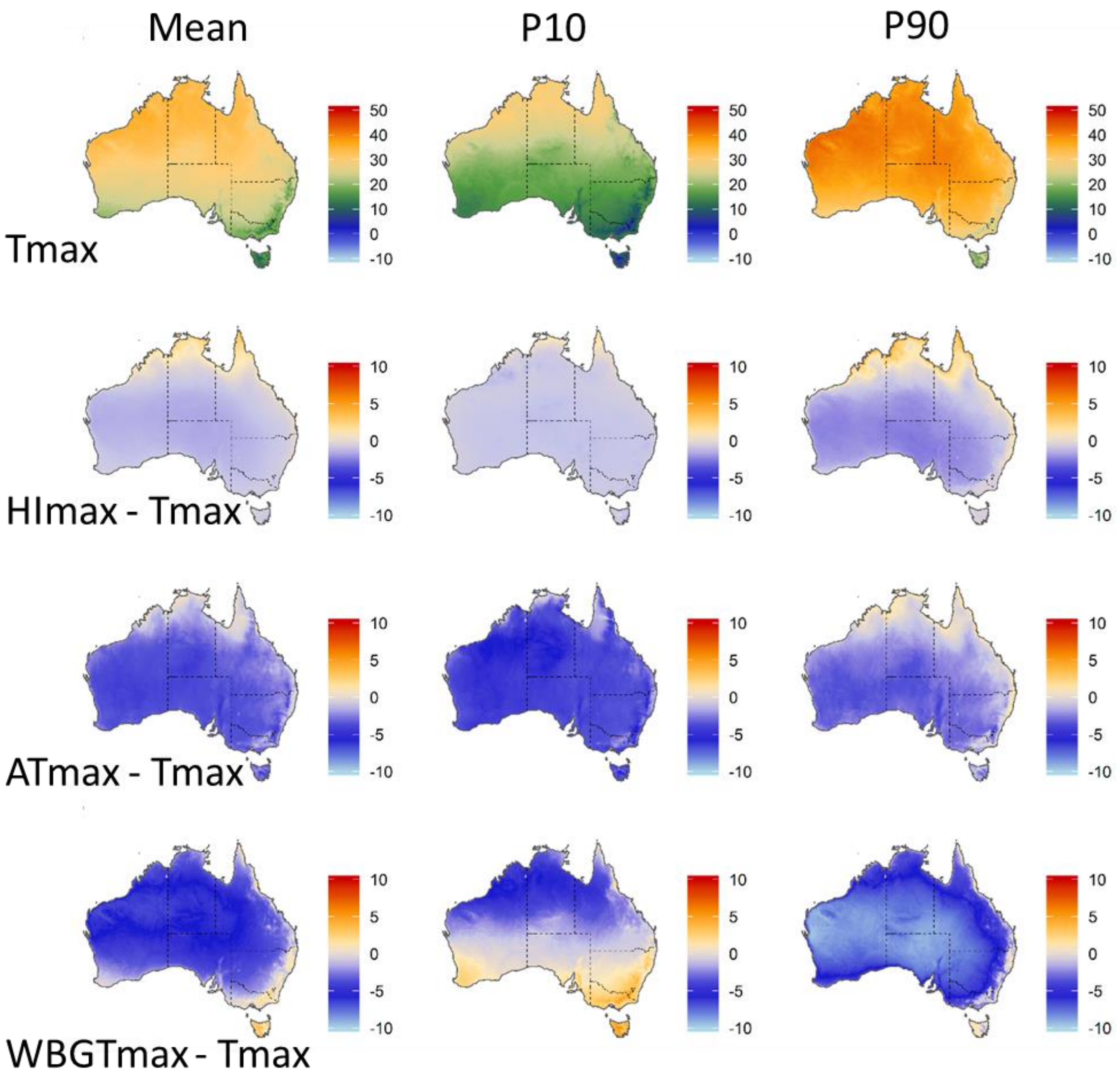


Figure 24. Mean, 10th and 90th percentile maps of three-day average maximums for Temperature (T, top row), Heat Index anomaly (HImax-Tmax, second row), Apparent Temperature anomaly (ATmax-Tmax, third row), and Wet Bulb Globe Temperature anomaly (WGBTmax-Tmax, fourth row), calculated from 12km BARRA data (1990-2018). The unit on all figures are in [°C].

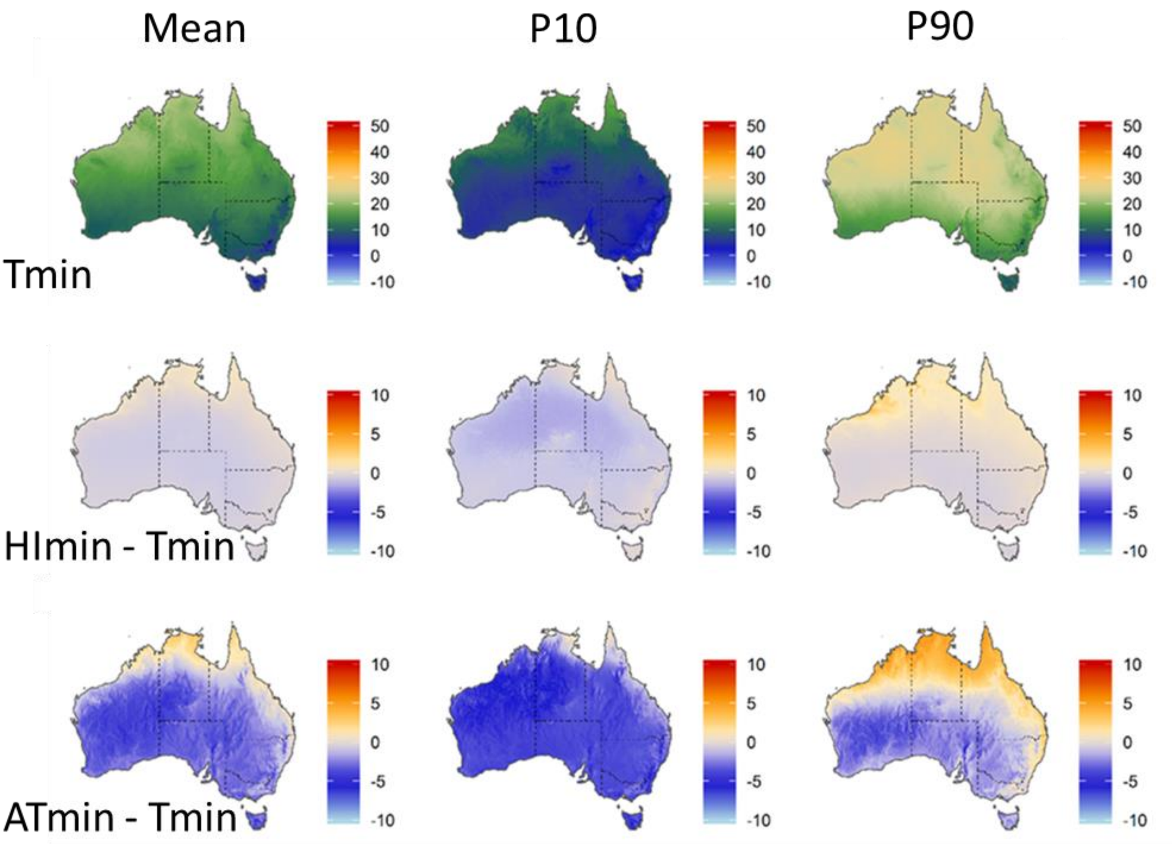


Figure 25. Mean, 10th and 90th percentile maps of three-day average minimums for Temperature (T, top row), Heat Index anomaly (HImin-Tmin, second row), Apparent Temperature anomaly (ATmin-Tmin, third row), calculated from 12km BARRA data (1990-2018). The unit on all figures are in [°C].

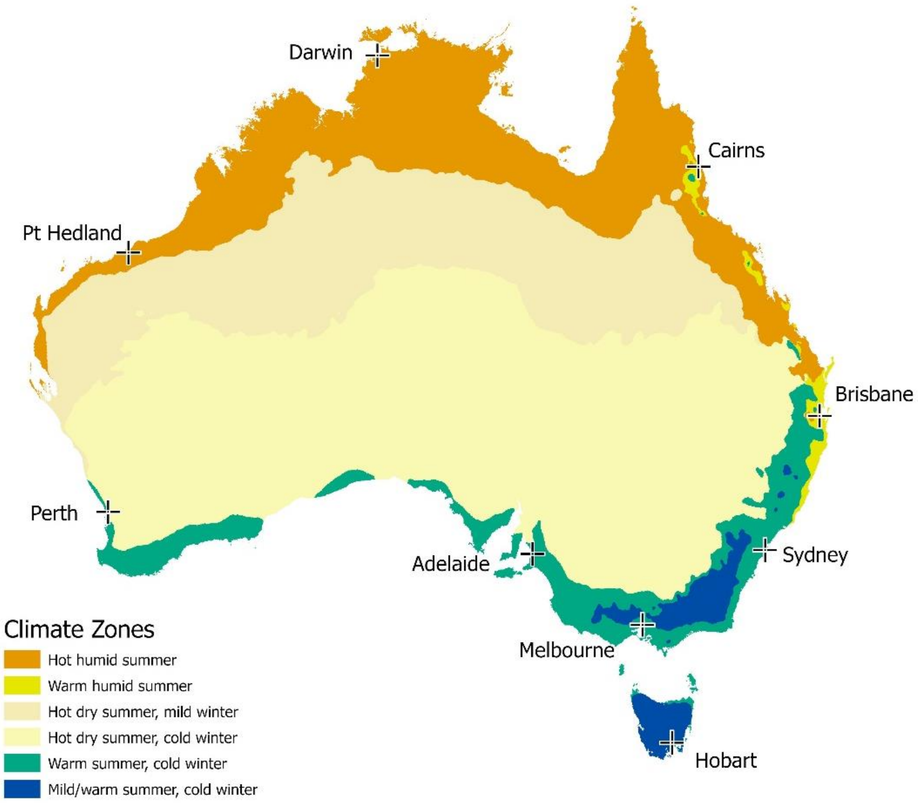


Figure 26. Australian Climate zones based on temperature and humidity. Bureau of Meteorology.

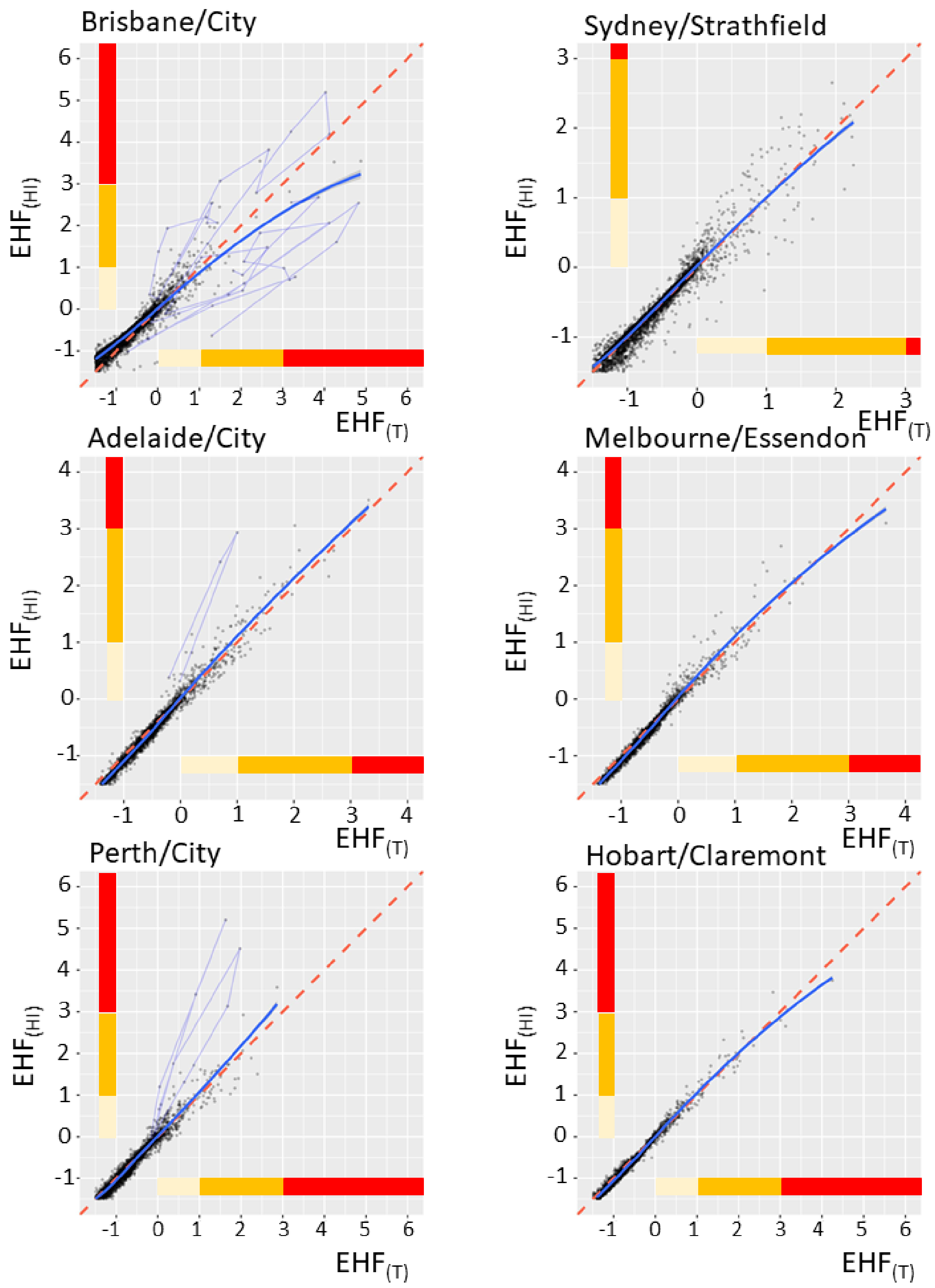


Figure 27. Scatter plot of T and HI based EHF severity indices on severe heatwave days for Brisbane, Sydney, Adelaide, Melbourne, Perth and Hobart. The coloured bars represent the heatwave severity categories (‘low’, ’severe’ and ‘extreme’). Thin blue lines indicate heatwave sequences where $|EHF_{SEV(H)} – EHF_{SEV(T)}| > 1$. Bold coloured lines indicate heatwaves where either $EHF_{(T)}$ or $EHF_{(HI)}$ does not generate a heatwave warning. LOESS regression in solid blue. Red dashed line has a slope of 1:1 for reference.

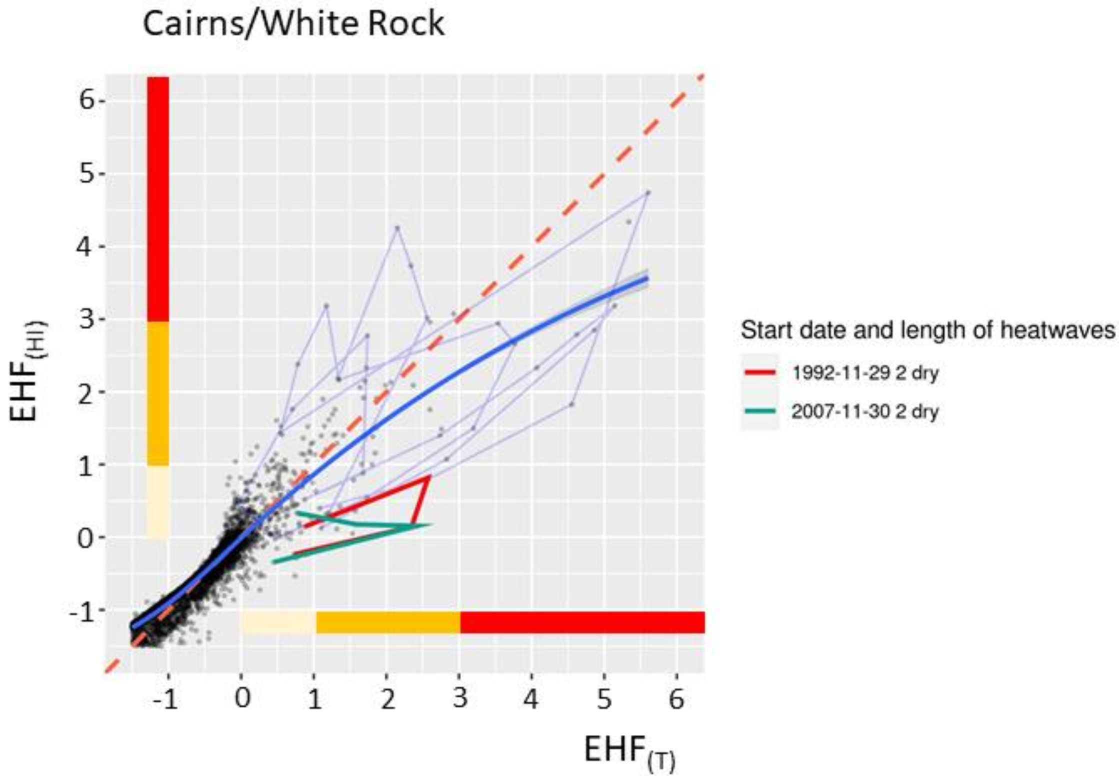


Figure 28. Scatter plot of T and HI based EHF severity indices on severe heatwave days for Cairns. The coloured bars represent the heatwave severity categories (‘low’, ’severe’ and ‘extreme’). Thin blue lines indicate heatwave sequences where $|EHF_{SEV(H)} – EHF_{SEV(T)}| > 1$. Bold coloured lines indicate heatwaves where either $EHF_{(T)}$ or $EHF_{(HI)}$ does not generate a heatwave warning. LOESS regression in solid blue. Red dashed line has a slope of 1:1 for reference.

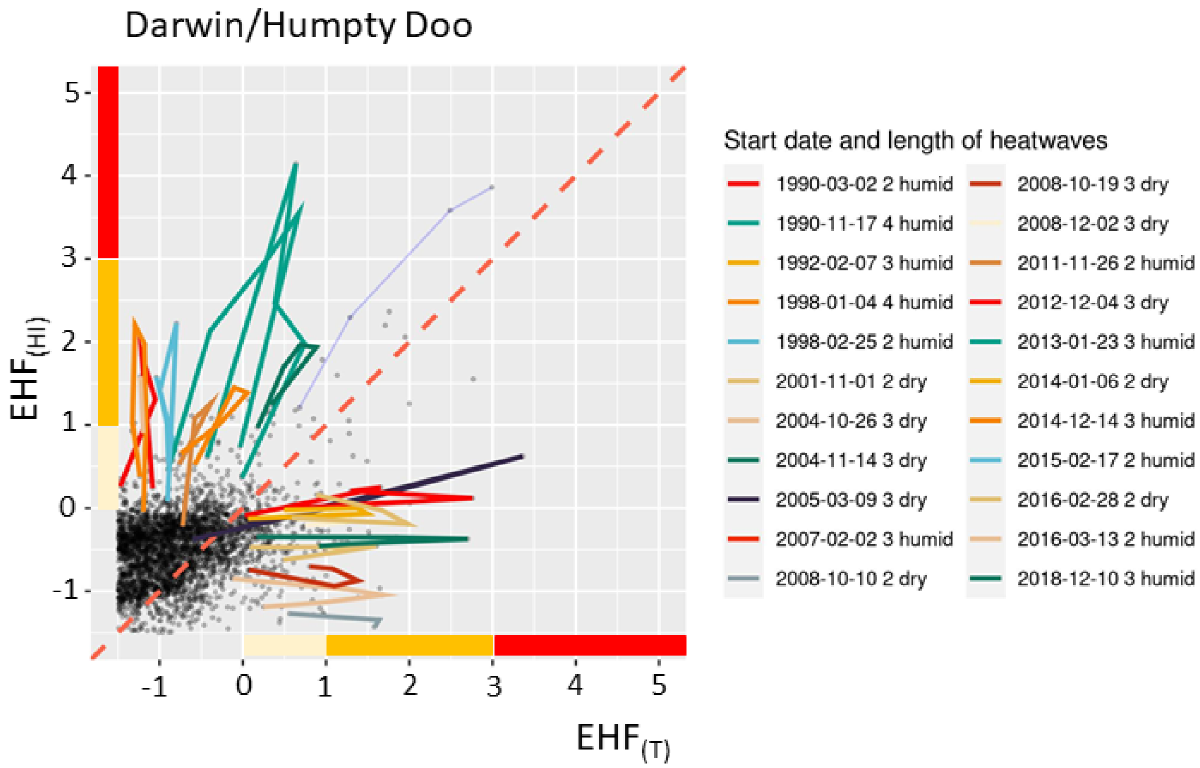


Figure 29. Scatter plot of T and HI based EHF severity indices on severe heatwave days for Darwin. The coloured bars represent the heatwave severity categories ('low', 'severe' and 'extreme'). Thin blue lines indicate heatwave sequences where $|EHF_{SEV(H)} - EHF_{SEV(T)}| > 1$. Bold coloured lines indicate heatwaves where either $EHF_{(T)}$ or $EHF_{(HI)}$ does not generate a heatwave warning. LOESS regression in solid blue. Red dashed line has a slope of 1:1 for reference.

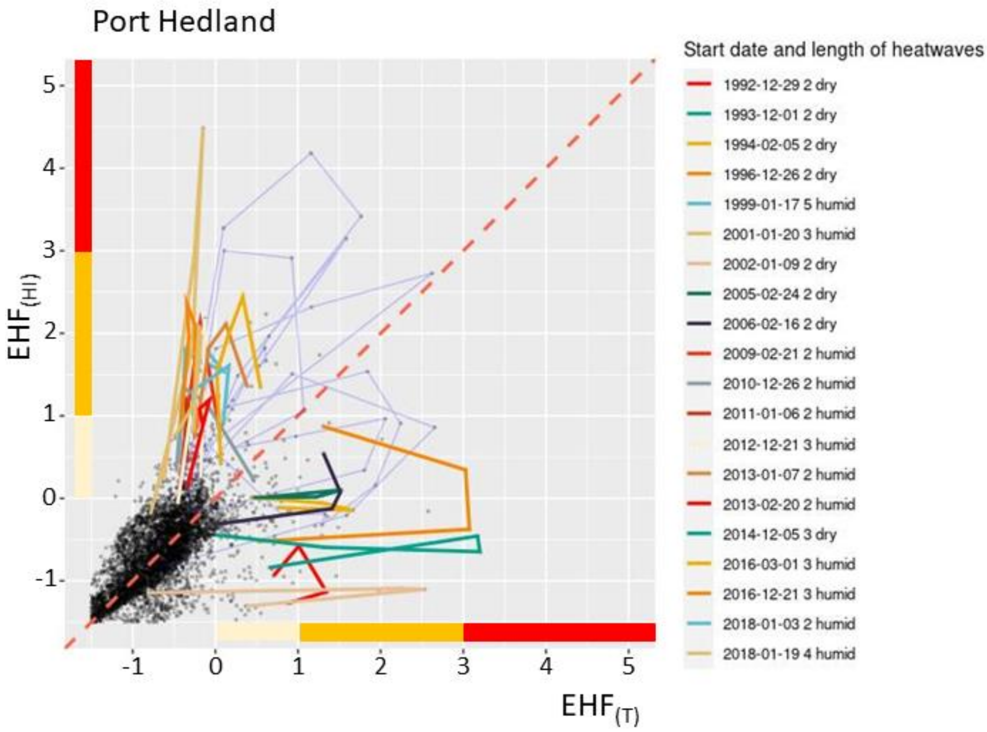


Figure 30. Scatter plot of T and HI based EHF severity indices on severe heatwave days for Port Hedland. The coloured bars represent the heatwave severity categories (‘low’, ’severe’ and ‘extreme’). Thin blue lines indicate heatwave sequences where $|EHF_{SEV(H)} – EHF_{SEV(T)}|$ >1. Bold coloured lines indicate heatwaves where either $EHF_{(T)}$ or $EHF_{(HI)}$ does not generate a heatwave warning. LOESS regression in solid blue. Red dashed line has a slope of 1:1 for reference.

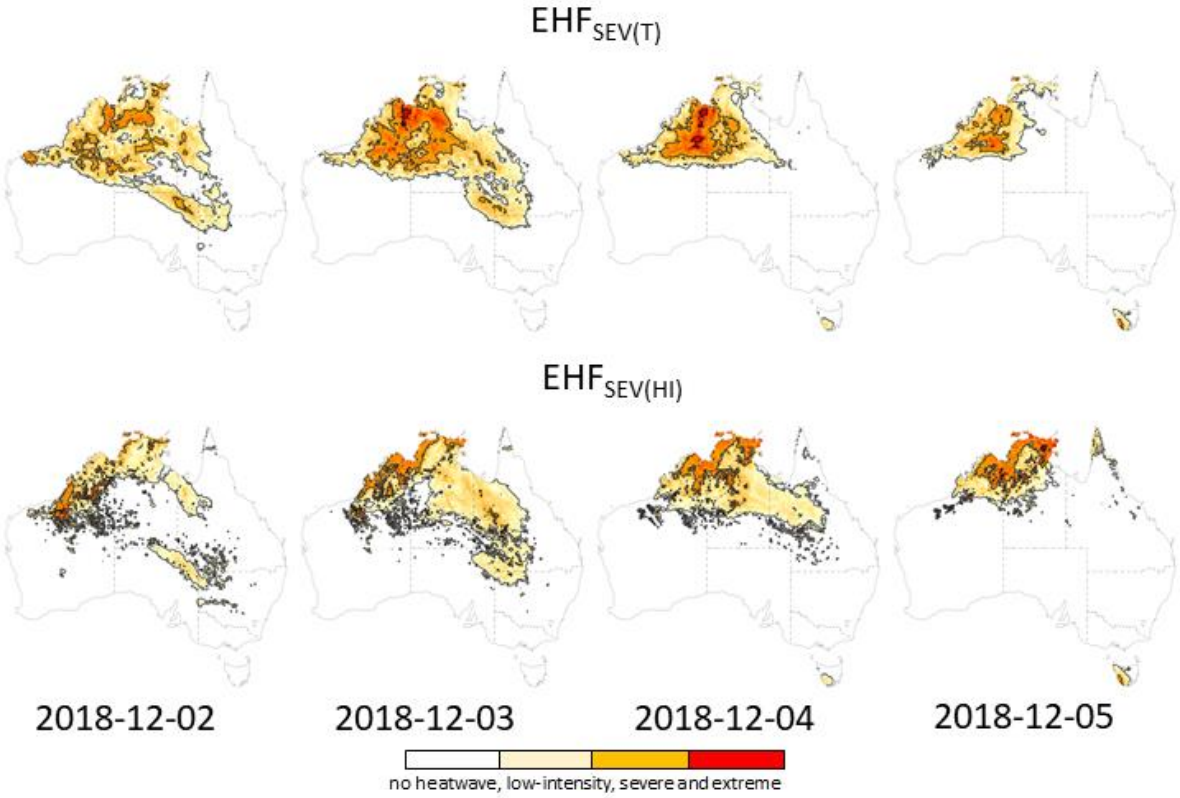


Figure 31. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ very humid heatwave sequences in December 2018. Refer Figure 26 for location of Darwin.

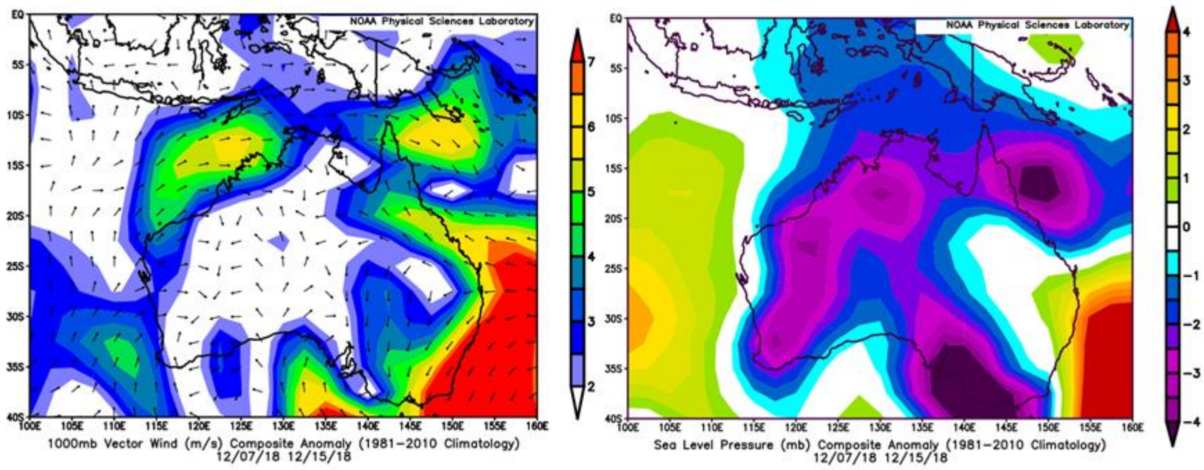


Figure 32. Surface wind vector 9- day anomaly (left) and sea level pressure 9-day anomaly (right) for very humid severe Darwin heatwave (December 2018). Refer Figure 26 for location of Darwin.

Anomaly is with respect to (1980-2010) base period. Source: https://psl.noaa.gov/data/composites/day/

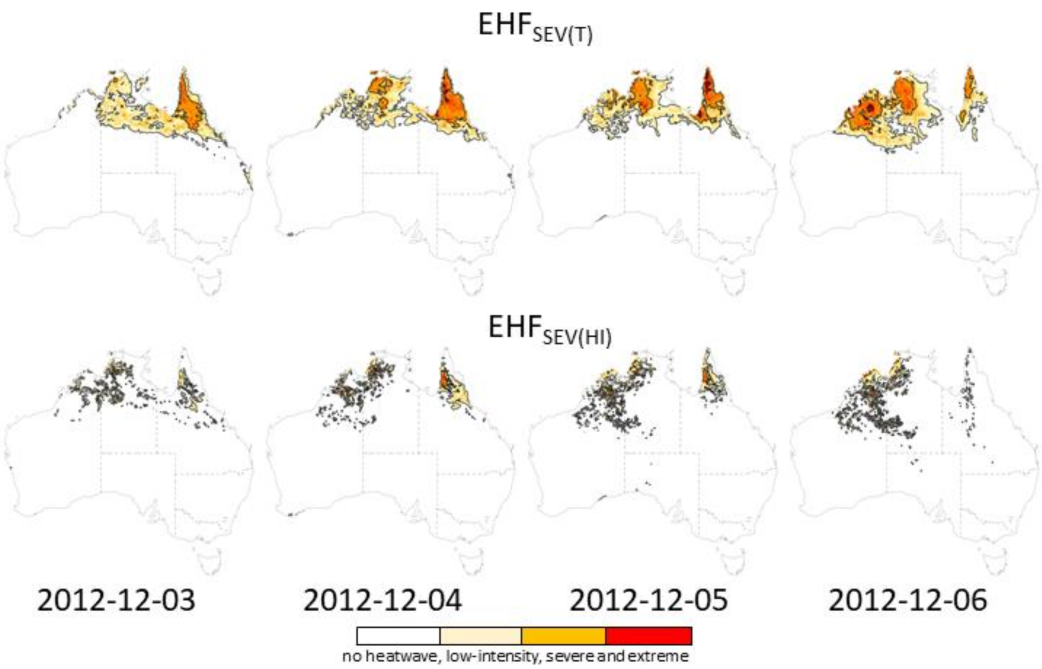


Figure 33. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ Very dry heatwave sequences in December 2012. Refer Figure 26 for location of Darwin.

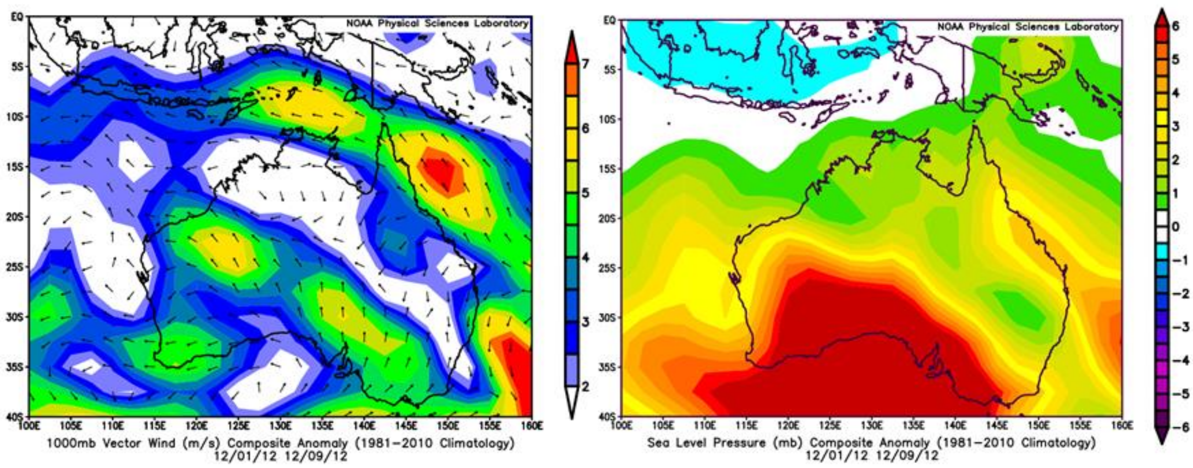


Figure 34. Surface wind vector 9- day anomaly (left) and sea level pressure 9-day anomaly (right) for very dry severe Darwin heatwave (December 2012). Refer Figure 26 for location of Darwin. Anomaly is with respect to (1980-2010) base period. Source: https://psl.noaa.gov/data/composites/day/

Supplementary Section

Darwin severe heatwaves

Detected by $EHF_{(HI)}$

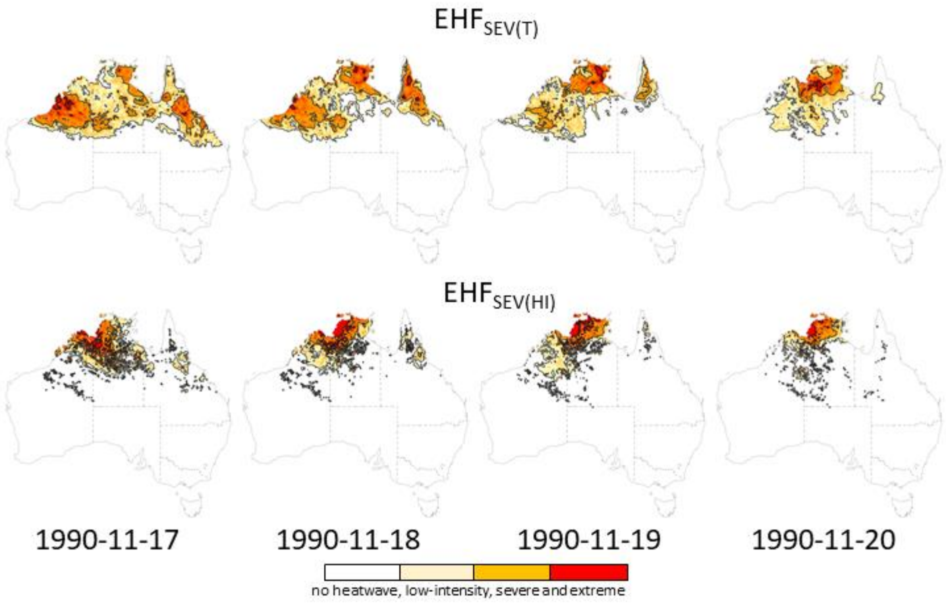


Figure 35S. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ more humid heatwave sequence in November 1990. Refer Figure 26 for location of Darwin.

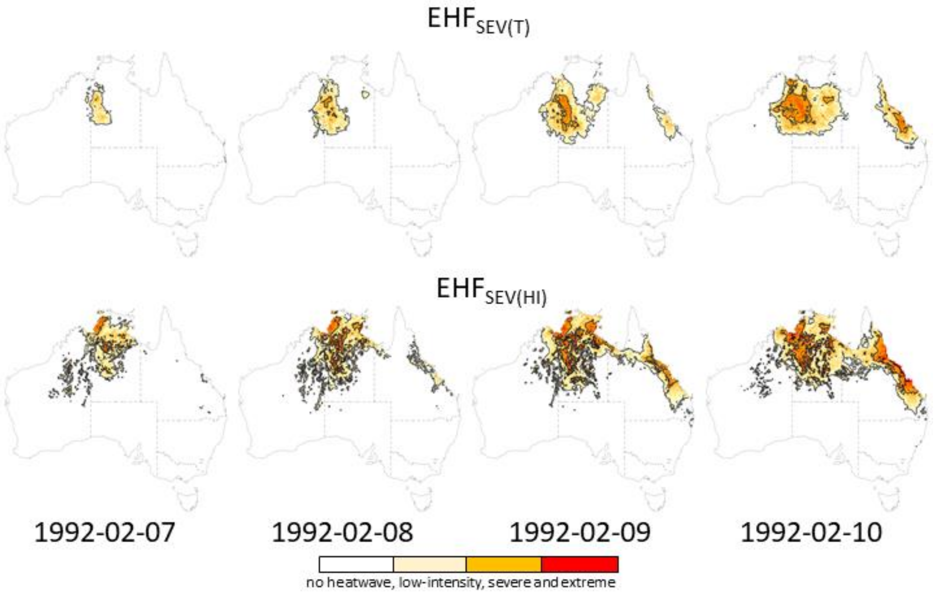


Figure 36S. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ more humid heatwave sequences in February 1992. Refer Figure 26 for location of Darwin.

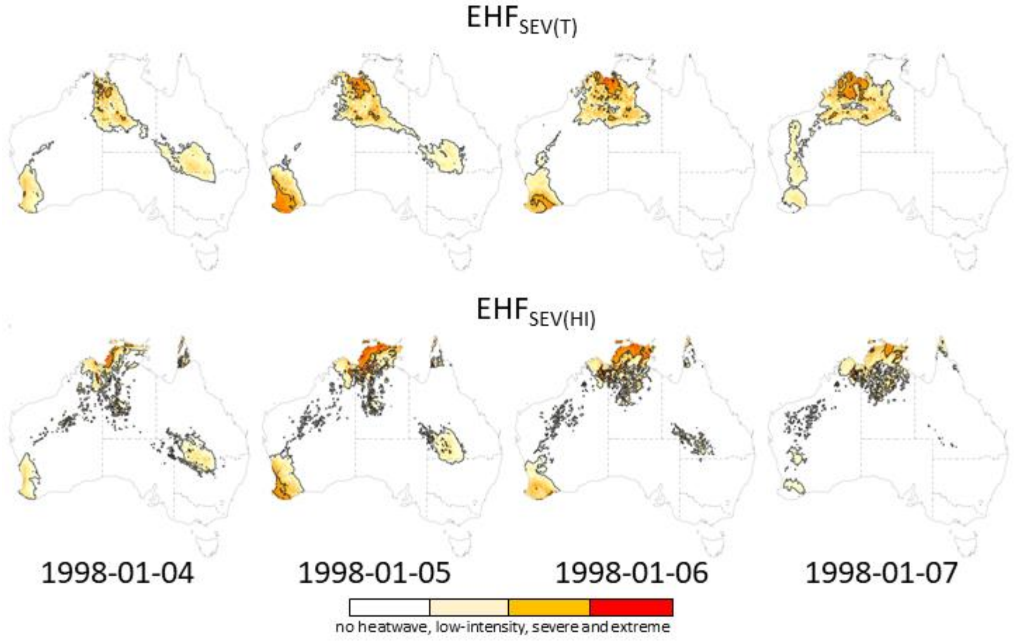


Figure 37S. Darwin EHFSEV(T) and EHFSEV(HI) more humid heatwave sequence in January 1998. Refer Figure 26 for location of Darwin.

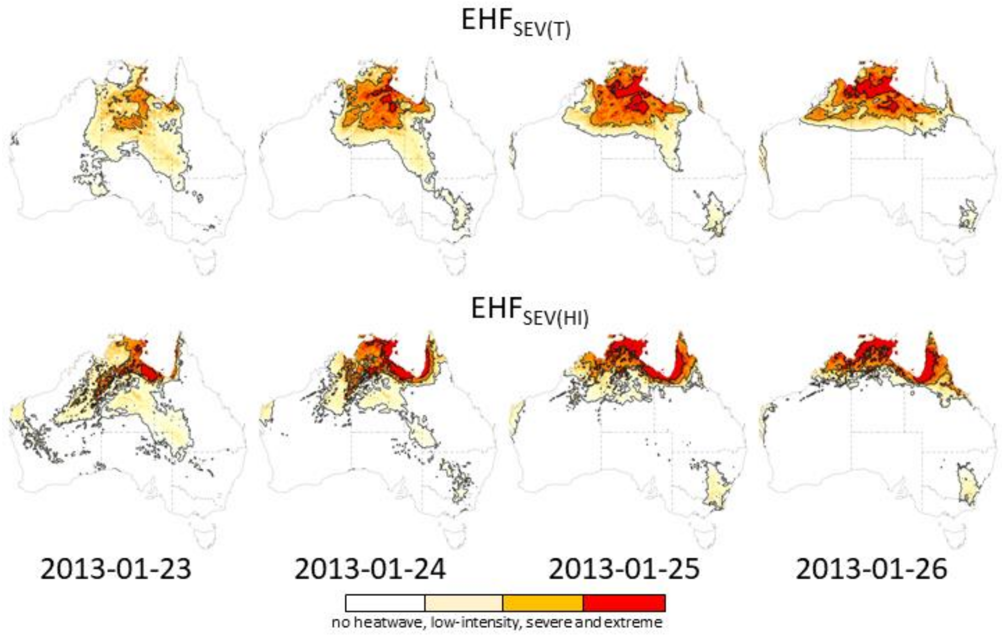


Figure 38S. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ more humid heatwave sequence in January 2013. Refer Figure 26 for location of Darwin.

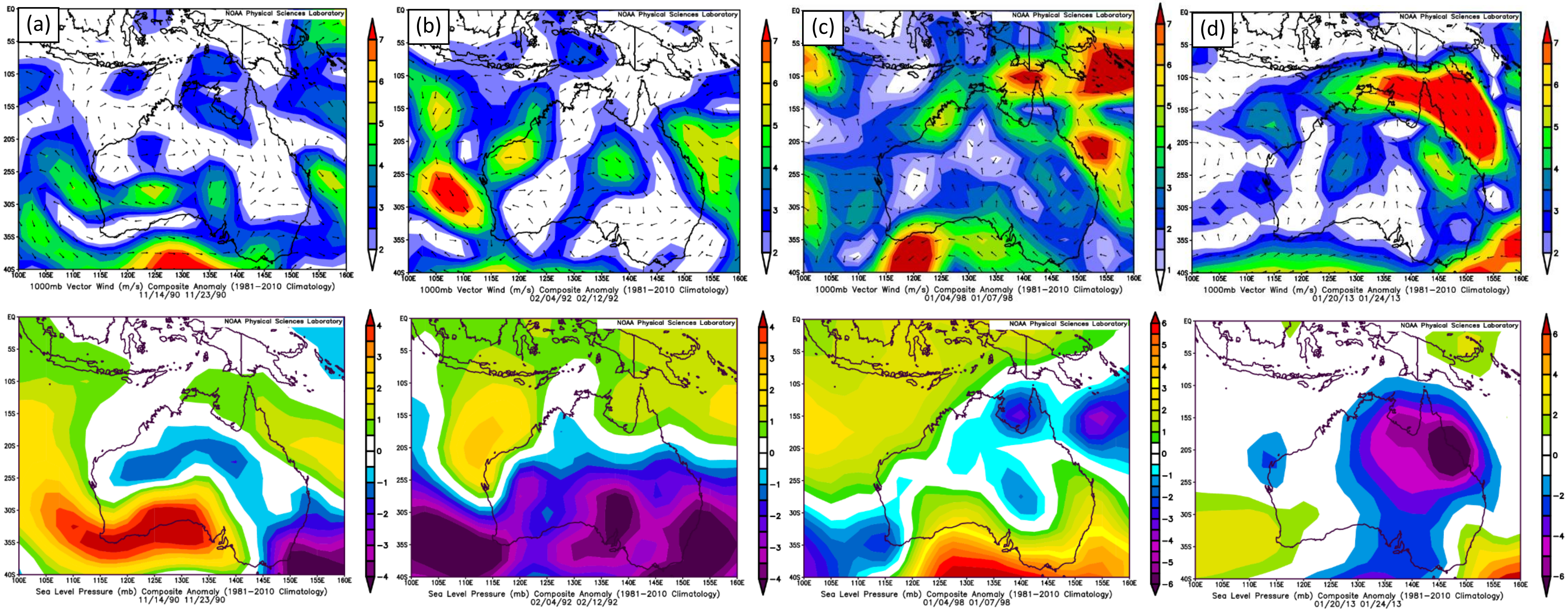


Figure 39S. Surface wind vector (top row) and sea level pressure (bottom row) Australian multi-day anomalies for Darwin *humid severe heatwaves* (a) November 1990, (b) February 1992, (c) January 1998 and (d) January 2013. Anomalies are calculated against the (1980-2010) baseline. Refer Figure 26 for location of Darwin. Source: https://psl.noaa.gov/data/composites/day/

Detected by $EHF_{(T)}$

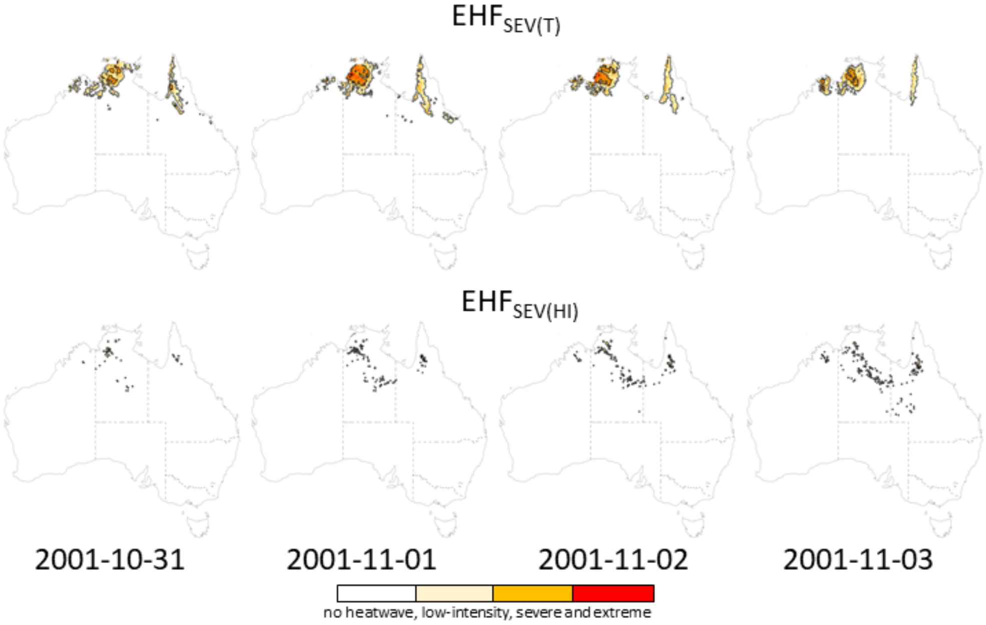


Figure 40S. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in November 2001. Refer Figure 26 for location of Darwin.

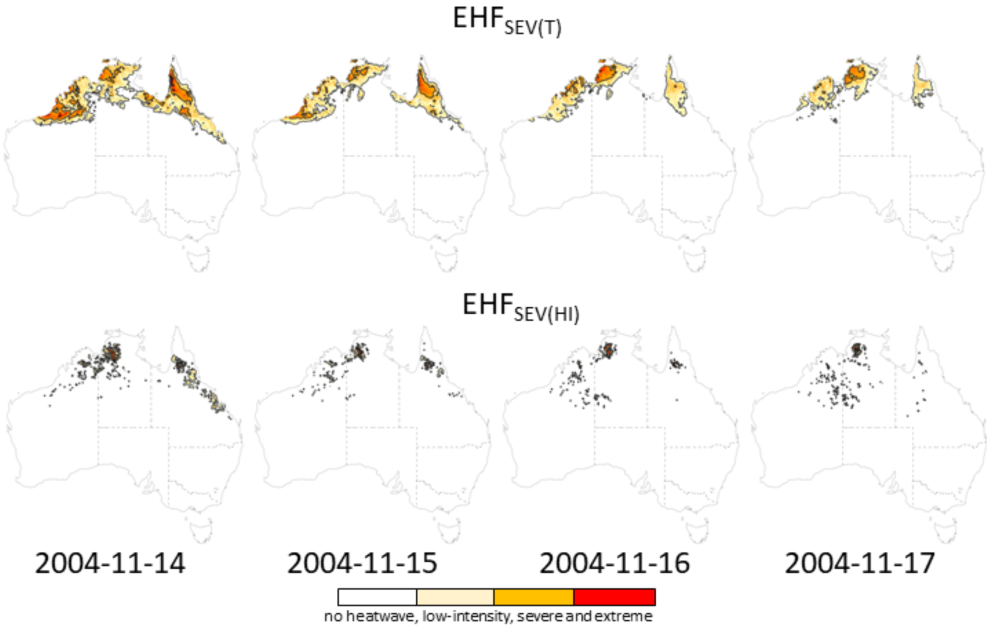


Figure 41S. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in November 2004. Refer Figure 26 for location of Darwin.

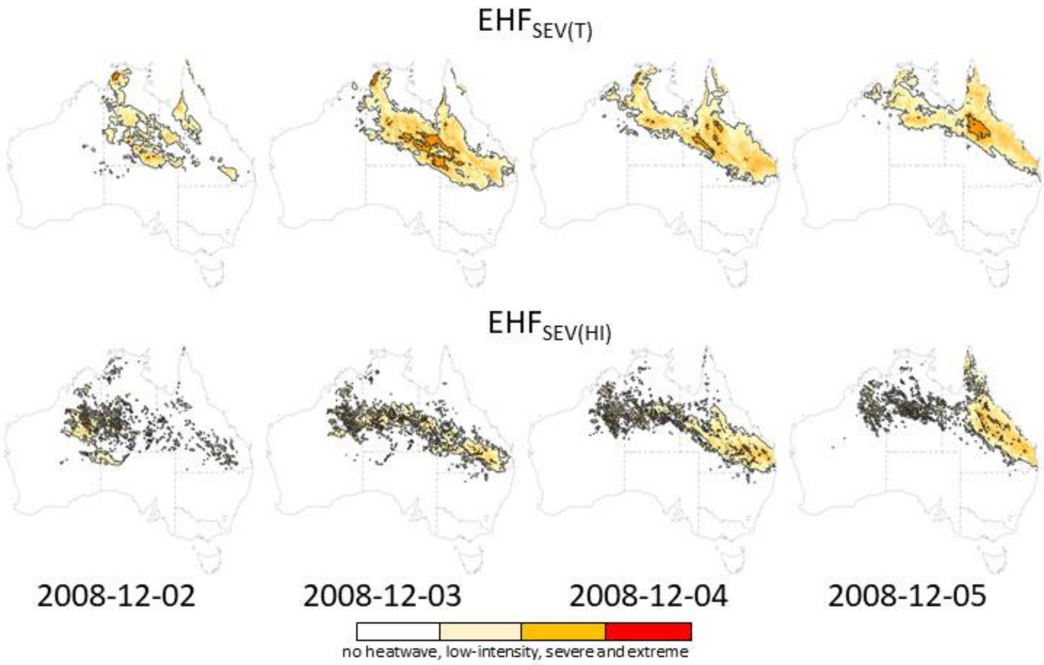


Figure 42S. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in December 2008. Refer Figure 26 for location of Darwin.

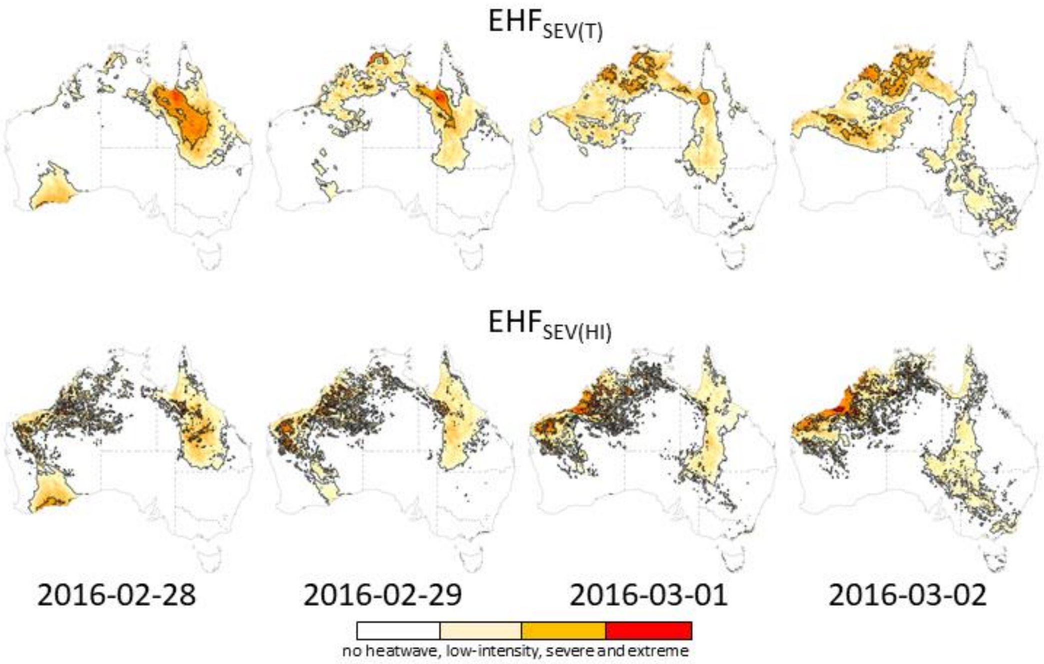


Figure 43S. Darwin $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in February 2016. Refer Figure 26 for location of Darwin.

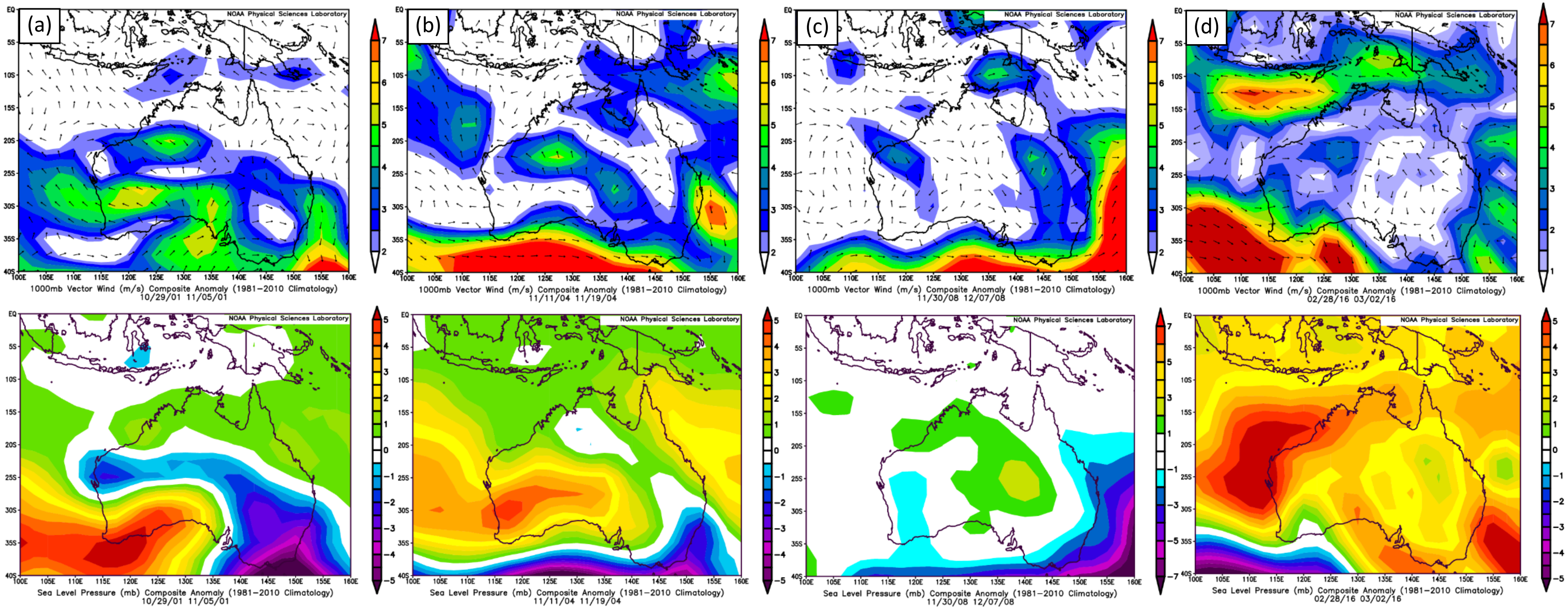


Figure 44S. Surface wind vector (left) and sea level pressure (right) Australian multi-day anomalies for Darwin *dry severe heatwaves* (a) November 2001, (b) November 2004, (c) December 2008 and (d) March 2016. Anomalies are calculated against the (1980-2010) baseline. Refer Figure 26 for location of Darwin. Source: https://psl.noaa.gov/data/composites/day/

Port Hedland Severe heatwaves

Detected by EHF(HI)

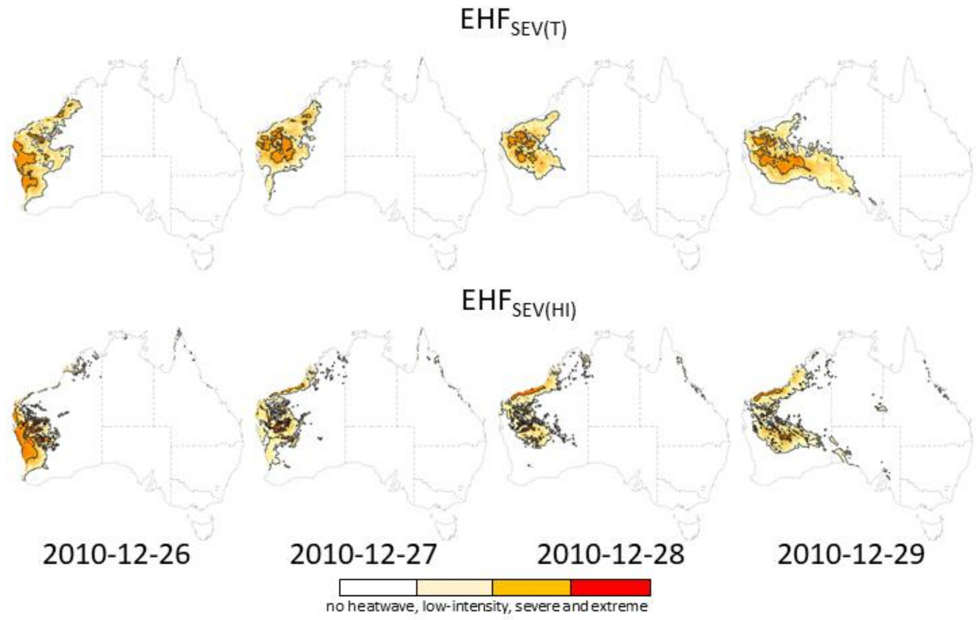


Figure 45S. Port Hedland EHFSEV(T) and EHFSEV(HI) more humid heatwave sequence in December 2010. Refer Figure 26 for location of Port Hedland.

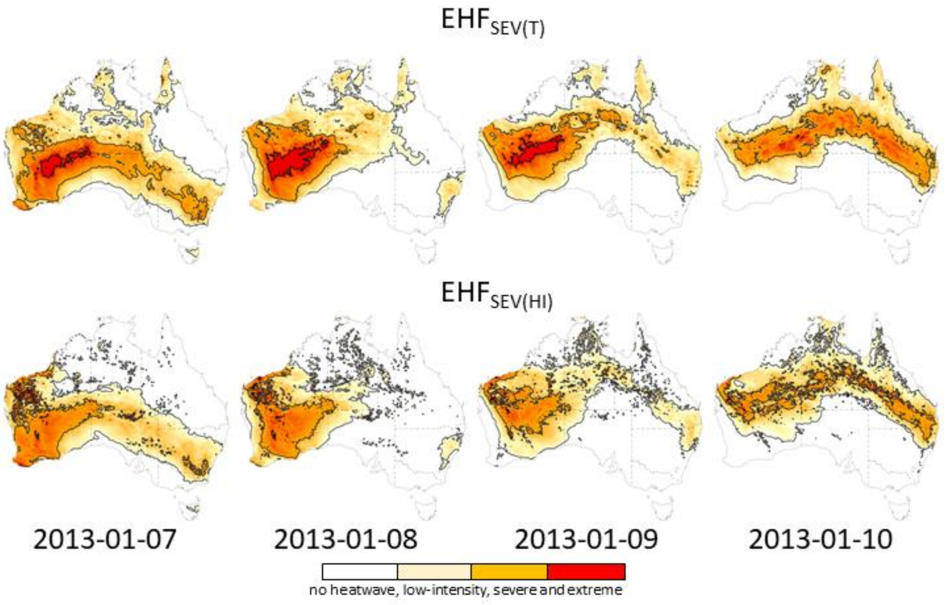


Figure 46S. Port Hedland $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ more humid heatwave sequence in January 2011. Refer Figure 26 for location of Port Hedland.

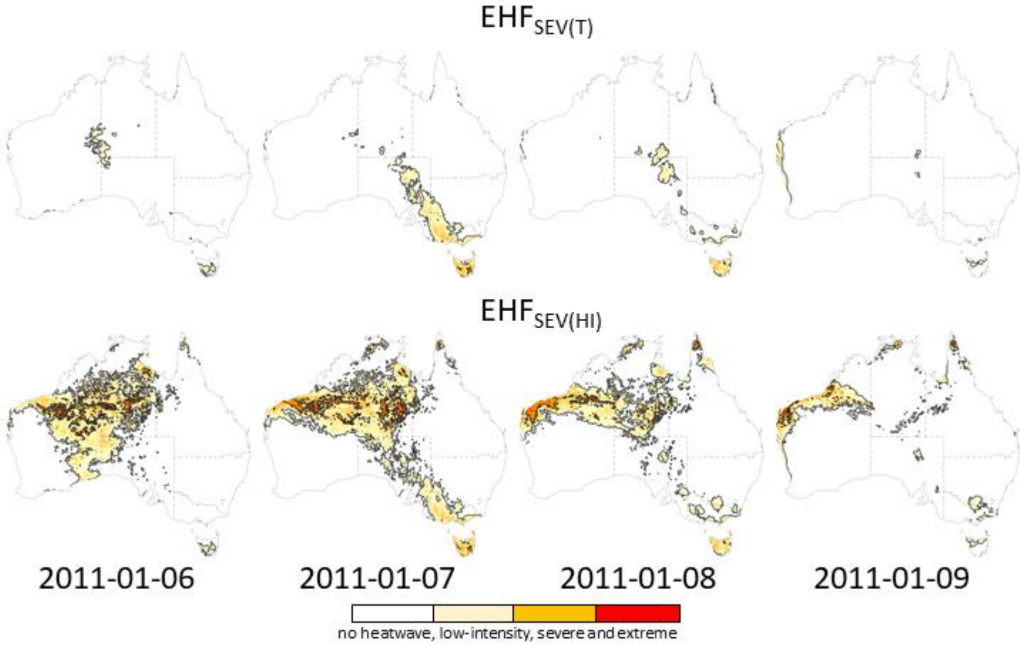


Figure 47S. Port Hedland $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ more humid heatwave sequence in January 2013. Refer Figure 26 for location of Port Hedland.

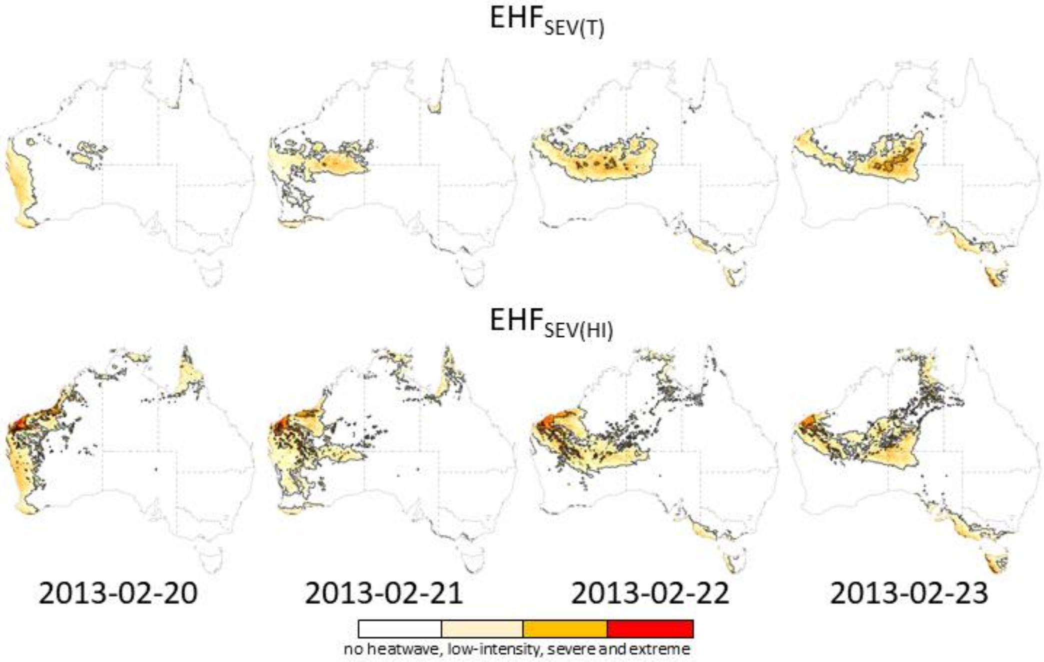


Figure 48S. Port Hedland $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ more humid heatwave sequence in February 2013. Refer Figure 26 for location of Port Hedland.

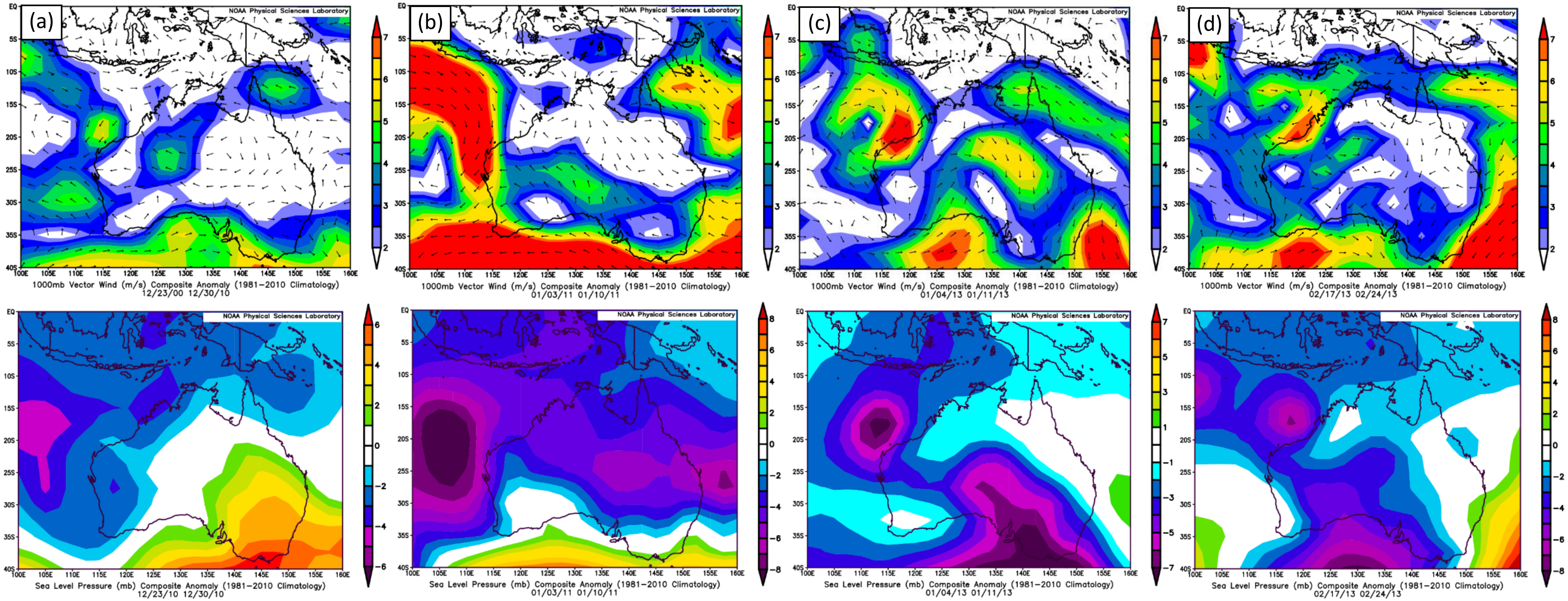


Figure 49S. Surface wind vector (left) and sea level pressure (right) Australian multi-day anomalies for Port Hedland humid severe heatwaves (a) December 2010, (b) January 2011, January 2013 and February 2013. Anomalies are calculated against the (1980-2010) baseline. Refer Figure 26 for location of Port Hedland. Source: https://psl.noaa.gov/data/composites/day/

Detected by $EHF_{(T)}$

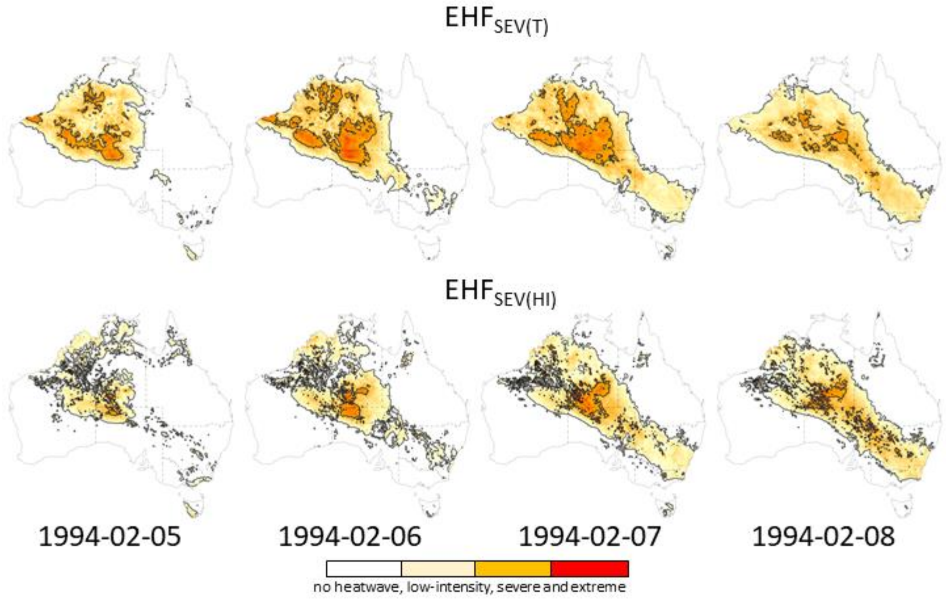


Figure 50S. Port Hedland $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in February 1994. Refer Figure 26 for location of Port Hedland.

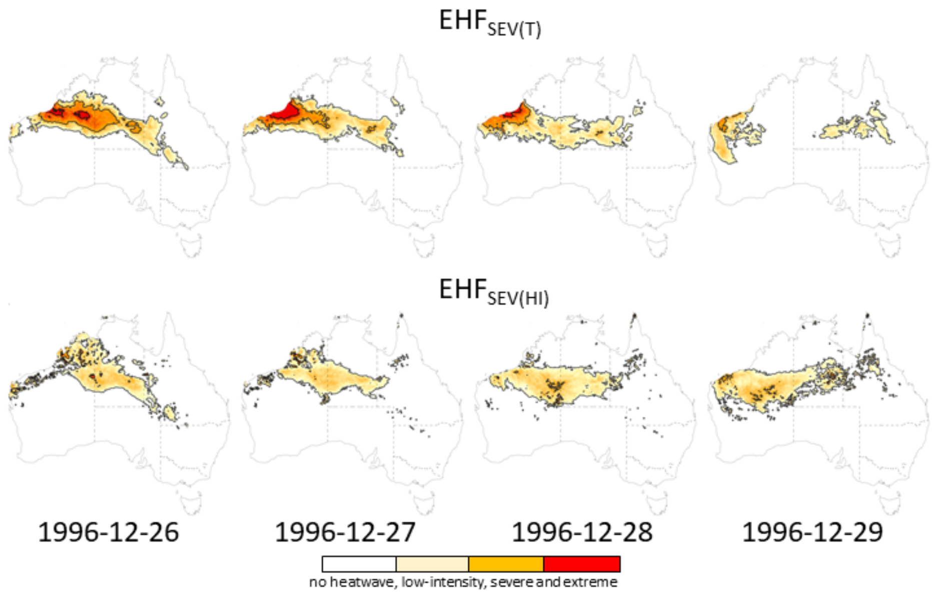


Figure 51S. Port Hedland $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in December 1996. Refer Figure 26 for location of Port Hedland.

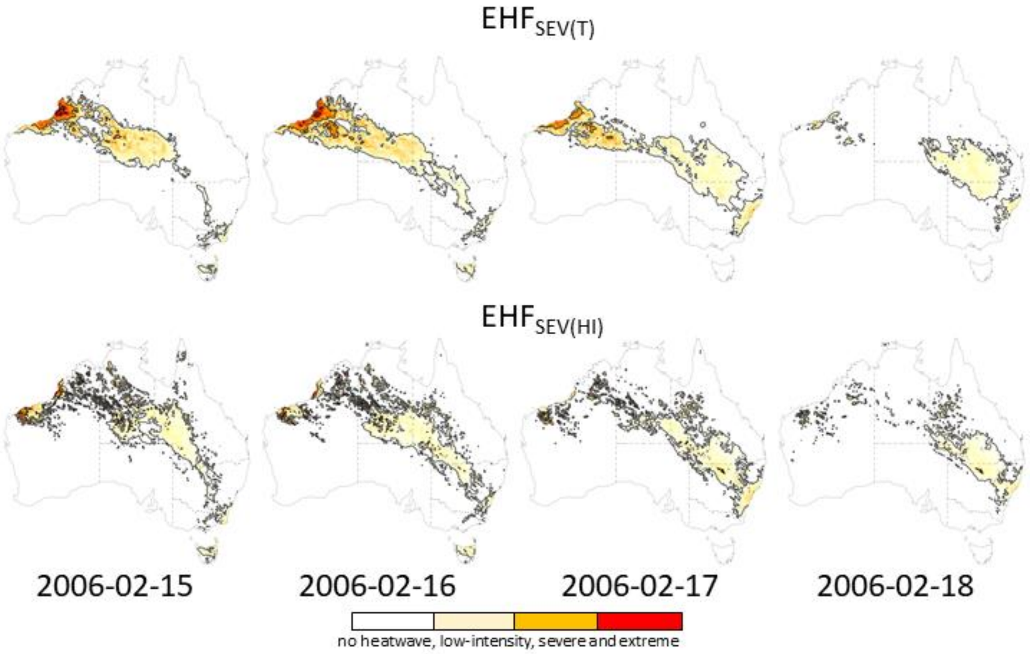


Figure 52S. Port Hedland $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in February 2006. Refer Figure 26 for location of Port Hedland.

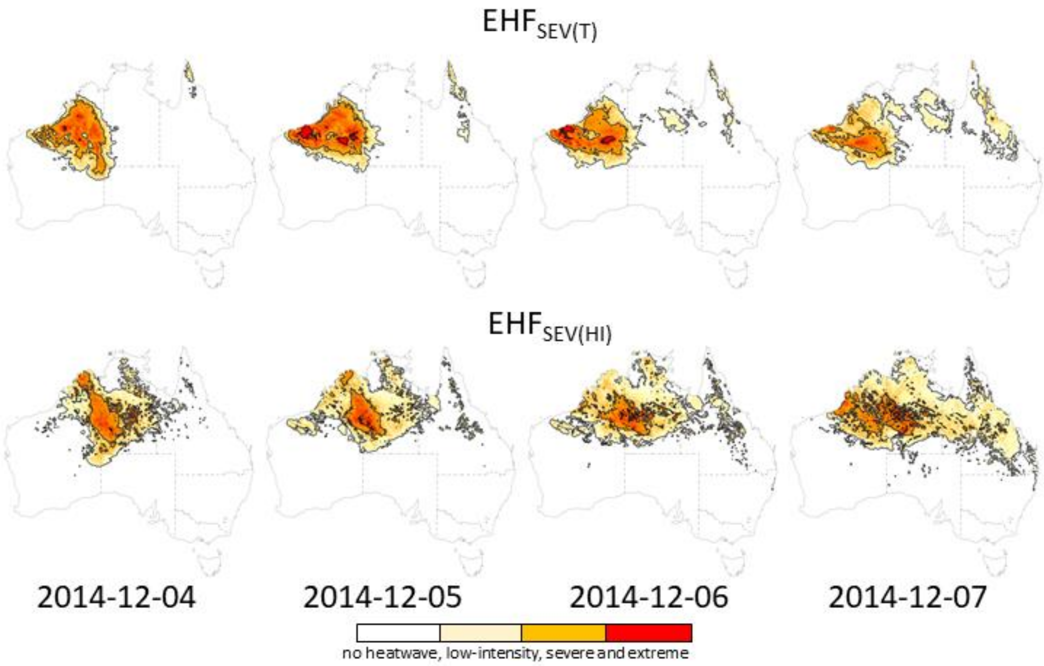


Figure 53S. Port Hedland $EHF_{SEV(T)}$ and $EHF_{SEV(HI)}$ drier heatwave sequence in December 2014. Refer Figure 26 for location of Port Hedland.

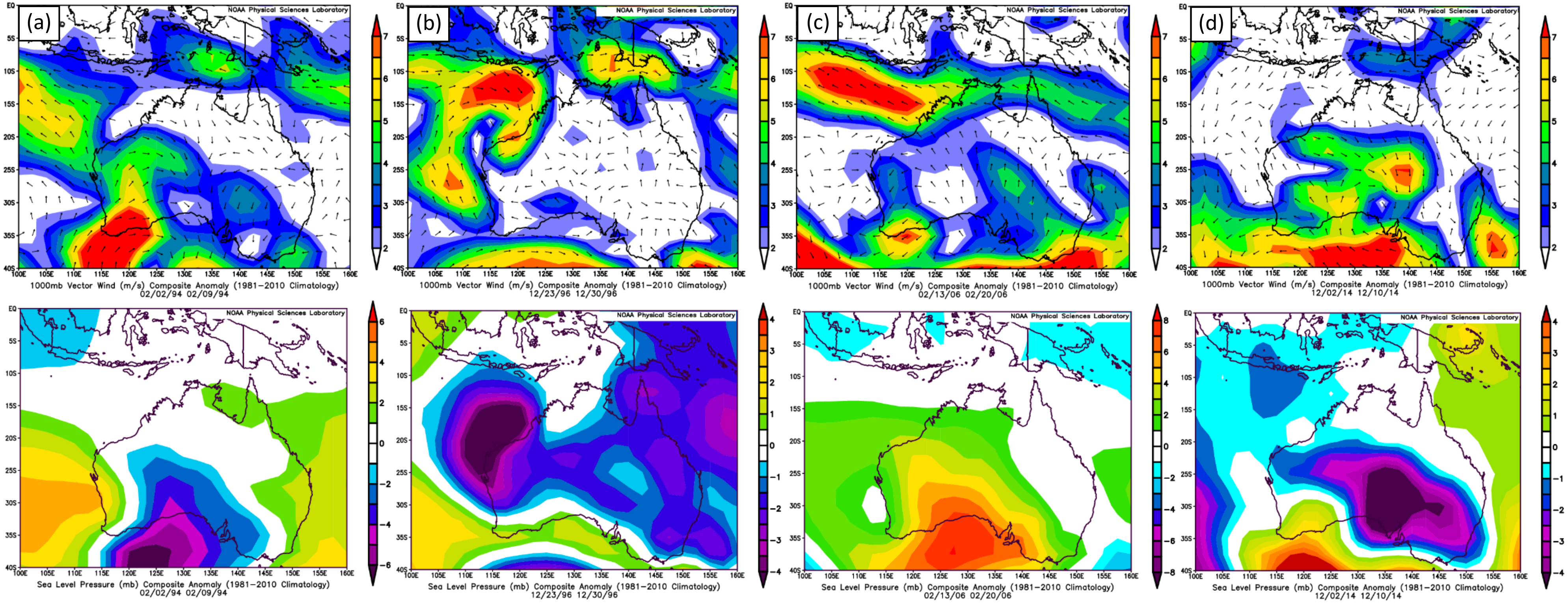


Figure 54S. Surface wind vector (left) and sea level pressure (right) Australian multi-day anomalies for Port Hedland dry severe heatwaves (a) February 1994, December 1996, February 2006 and December 2014. Anomalies are calculated against the (1980-2010) baseline. Refer Figure 26 for location of Port Hedland. Source: https://psl.noaa.gov/data/composites/day/

Chapter 3. Seamless Climate Data, Forecasts and Climate Projections

Creation of a robust heatwave climate analysis tool resulted in adoption of EHF as the Bureau of Meteorology's official heatwave definition. Adoption spurred immediate interest in heatwave forecast services leading to the launch of a public 7-day forecast pilot heatwave service on the Bureau of Meteorology's web site [117], coincident with an outbreak of extreme heatwaves across Australia [54].

Discussions on advances in subseasonal-to-seasonal (S2S), or seamless prediction skill [145], [146] provided an additional test for the effectiveness of a new heatwave service. Customers now expected forecast and warning services to convey their experience of hazard impact in seamless guidance across climate and prediction time scales.

This chapter demonstrates the utility of a heatwave definition which spatially forecasts heatwave severity, and analyses heatwave severity climate trends, a pre-condition for a seamless index that enables extension into S2S and climate projection services.

Chapter 3 contains two peer-reviewed publications.

These were delivered to Australia's emergency management sector to demonstrate how heatwaves could be forecast and monitored in the course of a summer (publication 3), and how the heatwave climate of a region (State of Queensland) can be diagnosed and trends examined under the influence of climate change (publication 4).

Through exposure of this work with colleagues within the Bureau of Meteorology, research colleagues developed seasonal forecast products for customers [96], providing a S2S capability heatwave using the Excess Heat Factor (EHF), demonstrating utility of a percentile-based, temperature-only heatwave index.

Concurrently, colleagues within the UK Met Office incorporated the EHF heatwave (Excess Cold Factor, coldwave) index within their Global Hazard Map [147], producing 7-day probability of severe heatwaves (coldwaves) across the globe. Adoption of EHF within the UKMO global Numerical Weather Prediction ensemble forecast system tested the utility of EHF beyond the Australian continent.

Extension of EHF prediction beyond S2S prediction range was undertaken under a Copernicus project developed by the Swedish Meteorological and Hydrological Institute (SMHI). Australia's contribution to the GLORIOUS project [148] developed future heatwave climate scenarios that Australian health authorities could incorporate into their strategic planning process. The global data set created under this project provides a policy planning asset available for health authorities across the globe.

Successful seamless deployment of a single heatwave index across historical, multi-day, S2S and climate projection prediction scales is attributed to the temperature-only, percentile-based construction of EHF. This attribute is a key enabler for effective community communication, data-sharing with impact data custodians and adoption by heatwave warning partners, covered in Chapters 4 and 5.

Title of Paper	The Heatwaves of the 2013/14 Australian Summer [54]
Publication Status	Published
Publication Details	*Conference Proceedings. AFAC/BNHCRC Conference 20/10/2014, Available* *https://www.bnhcrc.com.au/sites/default/files/managed/downloads/fawcett.pdf*

Principal Author

Name of Principle Author	R J B Fawcett		
Contribution to the Paper	Both authors revised the technique and designed the gridded data system. Fawcett implemented the methodology within the Bureau of Meteorology's gridded climate and NWP forecast data. Fawcett was responsible for generating the national forecast accuracy plots. Fawcett drafted the manuscript, which was revised by both authors. Both authors read and approved the final manuscript		
Overall percentage (%)	50%		
Signature		Date	7 Nov 2021

Co-Author Contributions

Name of Co-Author (Candidate)	John Nairn		
Contribution to the Paper	Nairn developed original idea for the heatwave intensity and severity methodology, developing the concept using site data. Both authors revised the technique and designed the gridded data system. Manuscript revised by both authors. Both authors read and approved the final manuscript		
Overall percentage (%)	50%		
Certification	This paper reports on original research to operations, published as a daily national public web site product. These results arise from research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that w [illegible] is. I am the primary author of this paper.		
Signature		Date	8/11/2021

Extended abstract, presented at AFAC/BNHCRC Conference 20/10/2014
https://www.bnhcrc.com.au/sites/default/files/managed/downloads/fawcett.pdf

Paper 3: **The heatwaves of the 2013/2014 Australian summer**

Robert J B Fawcett[1,2] and John R Nairn[3]

Affiliations:

1. CAWCR, Docklands, Victoria, Australia
2. Bushfire Cooperative Research Centre, Melbourne, Victoria, Australia
3. South Australian Regional Office, Bureau of Meteorology, Adelaide, South Australia, Australia

Abstract: Heatwaves represent a significant natural hazard in Australia, arguably more hazardous to life than bushfires, tropical cyclones and floods. In the 2008/2009 summer, for example, many more lives were lost to heatwaves than to that summer's bushfires which were among the worst in the history of the Australian nation. Yet for many years, these other forms of natural disaster have received much greater public attention than heatwaves. This might be changing in Australia however, as health and emergency services increasingly use weather forecast information to become proactive in providing advice to the community on how to mitigate the effects of heatwaves. Significant community engagement took place during the 2013/2014 Australian summer, a summer which generated some significant heatwaves, comparable to those of 2009, 2004, 1939 and 1908.

In January 2014, the Australian Bureau of Meteorology introduced a pilot national heatwave forecasting service, to issue forecasts of forthcoming non-severe, severe and extreme heatwaves. The service is based on the excess heat factor (EHF) or heatwave intensity concept, which quantifies the extent of the temperature elevation during a heatwave in a manner relevant to the expected impact of the heatwave on human health. The forecasting system makes use of both daily maximum and minimum temperatures, the latter providing implicit information about average humidity levels, without humidity being included explicitly in the calculation.

This paper will document the heatwaves of the 2013/2014 Australian summer, in terms of the EHF metric, and will describe how well they were forecast by the new service.

1. Introduction

Heatwaves represent a significant natural hazard in Australia, arguably more hazardous to life than bushfires, tropical cyclones and floods. In the 2008/2009 summer, for example, many more lives were lost to heatwaves (374 excess deaths in Victoria alone, [94]; an additional 50 to 150 deaths in South Australia have been estimated, Reeves et al. 2010 [149]) than to that summer's bushfires (173 deaths [27]) which were among the worst in the history of the Australian nation. Yet for many years, these other forms of natural disaster have received much greater public attention than heatwaves. This might be changing in Australia however, as health and emergency services increasingly use weather forecast information to become proactive in providing advice to the community on how to mitigate the effects of heatwaves. Significant community engagement took place during the 2013/2014 Australian summer, a summer which generated some significant heatwaves, comparable to those of 2009, 2004, 1939 and 1908.

In January 2014, the Australian Bureau of Meteorology introduced a pilot national heatwave forecasting service, to issue forecasts of forthcoming non-severe, severe and extreme heatwaves. The service is based on the excess heat factor (EHF) or heatwave intensity concept [74], which quantifies the extent of the temperature elevation during a heatwave in a manner relevant to the expected impact of the heatwave on human health. The forecasting system makes use of both daily maximum and minimum temperatures, the latter providing implicit information about average humidity levels, without humidity being included explicitly in the calculation.

This paper will document the heatwaves of the 2013/2014 Australian summer, in terms of the EHF metric, and will describe how well they were forecast by the new service. We also compare the 2014 Melbourne heatwave with earlier heatwaves in its history.

2. Methodology and data

The EHF is a new measure of heatwave intensity, incorporating two ingredients. The first ingredient is a measure of how hot a three-day period (TDP) is with respect to an annual temperature threshold at the particular location. If the daily mean temperature (DMT) averaged over the TDP is higher than the climatological 95th percentile for DMT (denoted T_{95} in what follows), then the TDP and each day within in it are deemed to be in heatwave conditions. [This calculation uses the period 1971-2000.] On average, around 18 days per year will have a DMT exceeding T_{95}, but it is necessary to have three high DMTs in succession in order to form a heatwave according to this characterisation. The second ingredient is a measure of how hot the TDP is with respect to the recent past (specifically the previous 30 days). This takes into account the idea that people acclimatise (at least to some extent) to their local climate, with respect to the 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.

The heatwave intensity (i.e., the EHF) is a combination of these two ingredients, and larger values of each ingredient result in a larger EHF (see Nairn and Fawcett 2013 [74] for a detailed explanation of the calculation and the climatology periods adopted). The heatwaves across the period 1958-2011 are assessed, and the severity threshold at each location set to be the 85th percentile of EHF values. This implies that 15 per cent of the TDPs in heatwave at a particular location will be severe. The extreme heatwave threshold is then set at a multiple (three) of the severity threshold. The units of EHF are $(°C)^2$, or perhaps more conveniently K^2, as the EHF is a modified product of the two ingredients described above.

EHF values may be calculated using site daily temperature data (as in Figure 56 below) or using gridded analyses of daily temperature such as the Bureau of Meteorology's operational analyses (the choice of 1958 as the start year for the climatology period arises from data availability considerations in these operational analyses [89]). Forecasts of DMT, and subsequently of

EHF, have been prepared using the modified Gridded Objective Consensus Forecast (GOCF) system described in Fawcett and Hume (2010, [98]). This GOCF system allows forecasts of DMT for seven consecutive days, and consequently forecasts of EHF for five consecutive overlapping TDPs to be made once each day. While these EHF forecasts were only issued to the Australian public from 8 January 2014 onwards, the Bureau of Meteorology was generating these forecasts internally before their public release, and accordingly we present forecast verification results for the period November 2013 to March 2014 inclusive.

The heatwave forecasts issued to the public took the form of maps (an example is shown in Figure 55) showing areas forecast to be in extreme, severe and non-severe heatwave, or not in heatwave at all, together with supporting commentary. Underlying these maps were gridded forecasts, but these were not made available to the public during the 2013/2014 summer.

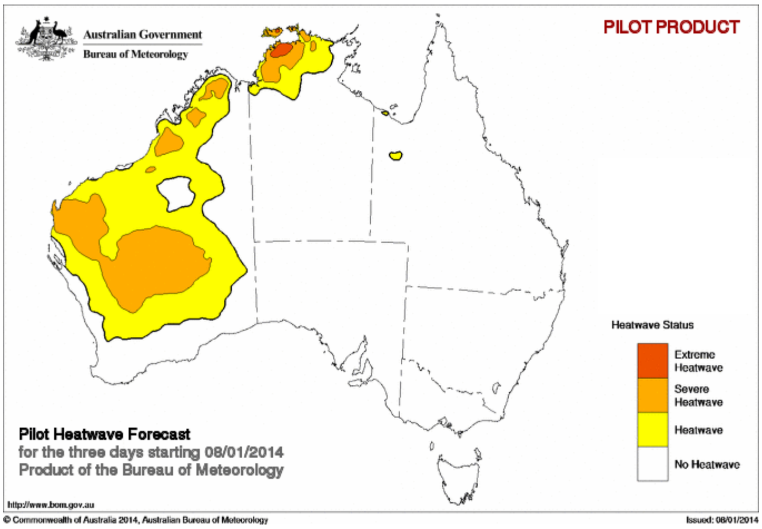


Figure 55: Heatwave forecast map for the TDP 08/10 January 2014, prepared in the morning on 8 January 2014. The coloured shades denote regions with heatwave, severe heatwave and extreme heatwave forecasted.

3. Results

Figure 56 compares the heatwaves of 1908, 1939, 2009 and 2014, as they appear in the daily temperature data from the Bureau of Meteorology's Melbourne Regional Office site (Station number 086071), using the base periods described in the previous section. These daily temperature data are quality-controlled, but not homogenised. To put these four years in context, a pre-federation heatwave in mid-January 1875 saw three consecutive days with maximum temperatures above 41°C in Melbourne, with a peak EHF of 140 K^2 (more than five times the severity threshold). The cool temperatures in the weeks preceding this event were a notable contributing factor to the very high EHF. Thirty years later, an event in mid-January 1905 saw three consecutive days above 40°C and a peak EHF of 94 K^2 (more than three times the severity threshold).

The 1908 heatwave (Figure 56a) peaked (at 82 K^2) just into the extreme range at Melbourne, with the city experiencing five consecutive days with maximum temperatures of 40°C or above, and six consecutive days of 39.9°C or above, setting consecutive-day records which still stand.

While the peak intensity of this event was less than that of the 1905 event, the longer duration of the 1908 event made it much more significant in terms of cumulative heat load. 246 fatalities across southern Australia have been reported for this heatwave.

The 1939 heatwave (Figure 56b) was weakly represented in the Melbourne data, with its strongest presence in southwest New South Wales. Melbourne experienced some very hot days during the heatwave (43.1°C on the 8th, 44.7°C on the 10th, 45.6°C on the 13th and Melbourne's then hottest day on record broken only in 2009), but they were not consecutive and were interspersed with much cooler days with 438 fatalities reported [149], 300 being in country NSW.

The 2009 Melbourne heatwave (Figure 56c) in late January was extreme, with 9 consecutive days of heatwave and six consecutive days of severe heatwave. The peak intensity (132 K^2) was nearly five times the severity threshold. There were three consecutive days with maximum temperatures above 43°C, a new three-day record. An analogous two-day record was also set during the event: both still stand. A week after the heatwave, on 7 February, a new daily record (46.4°C) was set, breaking the previous 45.6°C record of 13 January 1939, both days of catastrophic bushfires [150].

The 2014 Melbourne heatwave (Figure 56d) in mid-January was even more extreme than the 2009 heatwave, with a peak intensity (147 K^2) more than five times the severity threshold. There were seven consecutive days of heatwave and six consecutive days of severe heatwave. There were four consecutive days with maximum temperatures above 41°C (from the 14th to the 17th), a new four-day record. In summary, the 2014 heatwave in Melbourne was comparable with the worst previously experienced in the instrumental record (which extends back to 1856).

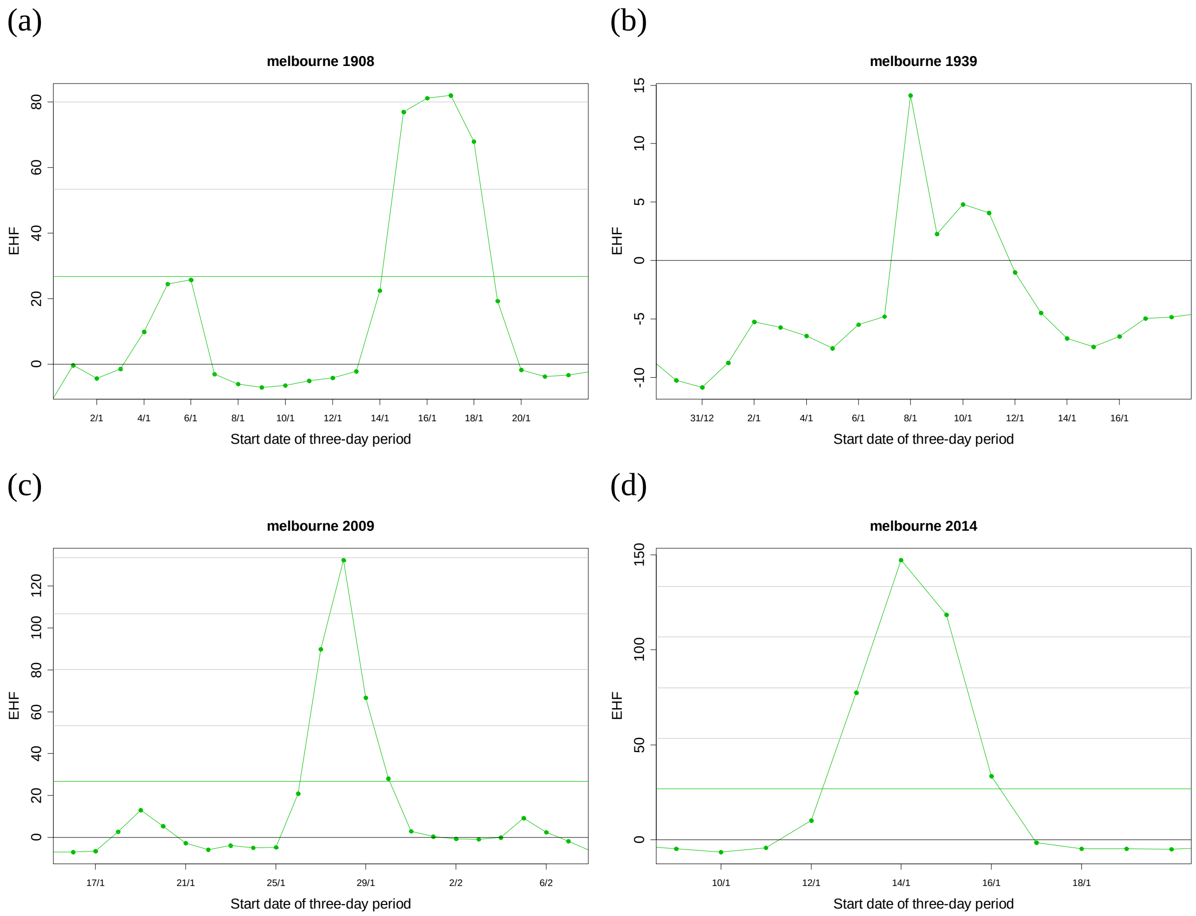


Figure 56: Four heatwaves in Melbourne, Victoria: (a) January 1908, (b) January 1939, (c) January/February 2009, and (d) January 2014. The horizontal green line represents the EHF severity threshold EHF85, with the horizontal grey lines multiples thereof. The calculation based on site data. At this site, T95 is 24.9°C.

Figure 57 shows the percentage area of Australia (as calculated using continental Australia and the main island of Tasmania) in heatwave for each TDP from November 2013 to March 2014, with Figure 58 and Figure 59 showing the analogous results for severe and extreme heatwaves, respectively. At the peak summer extent, more than half the country was simultaneously in heatwave, and more than 30 per cent simultaneously in severe heatwave. At one point (not shown) all of Victoria was in severe heatwave, and most of it actually in extreme heatwave.

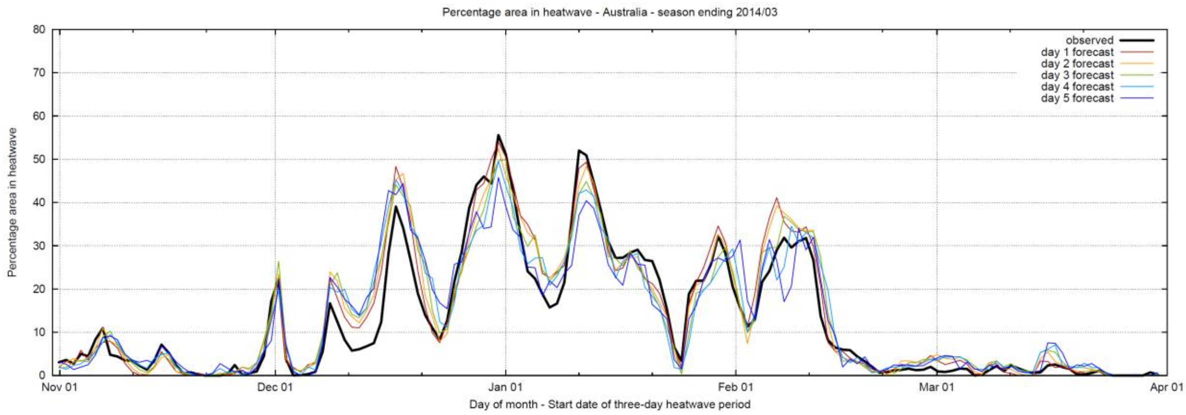


Figure 57: Percentage area of Australia in heatwave (black line) for the period November 2013 to March 2014, together with the percentage area forecast to be in heatwave at short (red, yellow) to long (blue, purple) lead times.

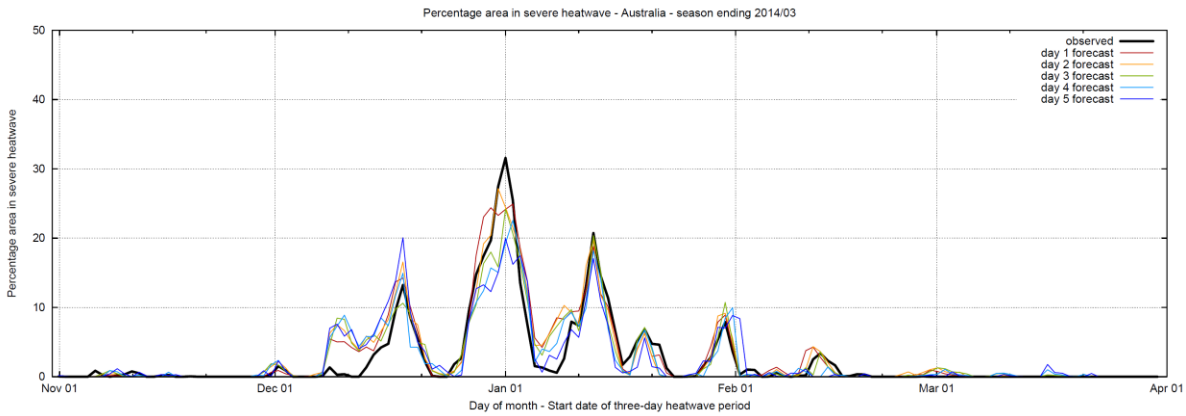


Figure 58: As per Figure 57 but for severe heatwaves.

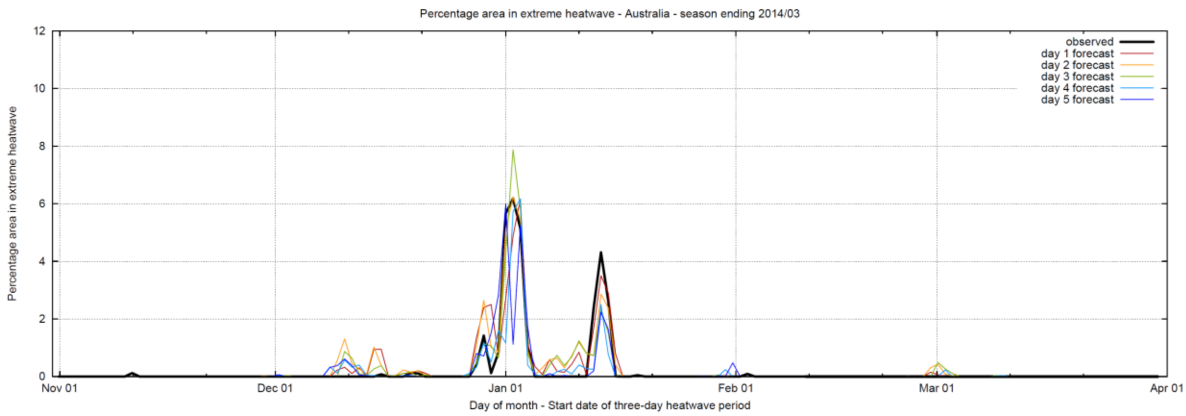


Figure 59: As per Figure 57 but for extreme heatwaves.

Six significant bursts of heatwave activity during the 2013/2014 summer may be identified in Figure 57. These will now be described using the gridded EHF data. In each case a representative location will be chosen to present a time series of EHF interpolated from the grids, together with a map integrating the positive EHF values within the nominated period to characterise the spatial pattern of the episode. The interpolated data are representative of a larger area (the analysis grid cells are ~ 20 to 25 km across) than would be the case for site data at the same location.

3.1 Late November/Early December

Although one fifth of the country was simultaneously in heatwave conditions, this was a mild event in terms of intensity. It covered much of inland Australia (Figure 60) and extended far into the southeast, but reached severe levels only in central and northwest Western Australia. It did not impact upon major population centres.

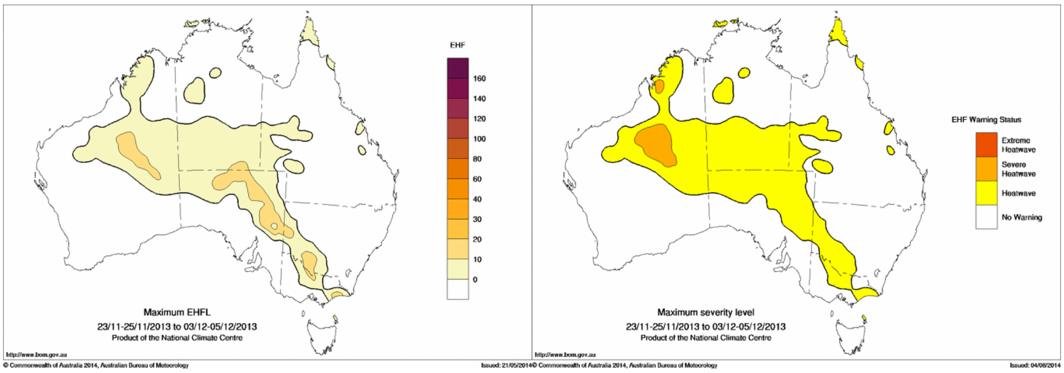


Figure 60: Maximum EHF attained during the first heatwave episode of the 2013/2014 Australian summer, expressed in terms of EHF values (left) and severity level (right).

3.2 Mid-December

This episode covered much of southern Australia (Figure 61), although without the southeast coastal regions being much affected. Mildura (Victoria) went into severe heatwave (Figure 62, peaking on 18/20 December), as did Adelaide and Oodnadatta (South Australia, not shown). Kalgoorlie-Boulder (southwest Western Australia) also experienced severe heatwave conditions (not shown, peaking on 15/17 December), but a few days earlier.

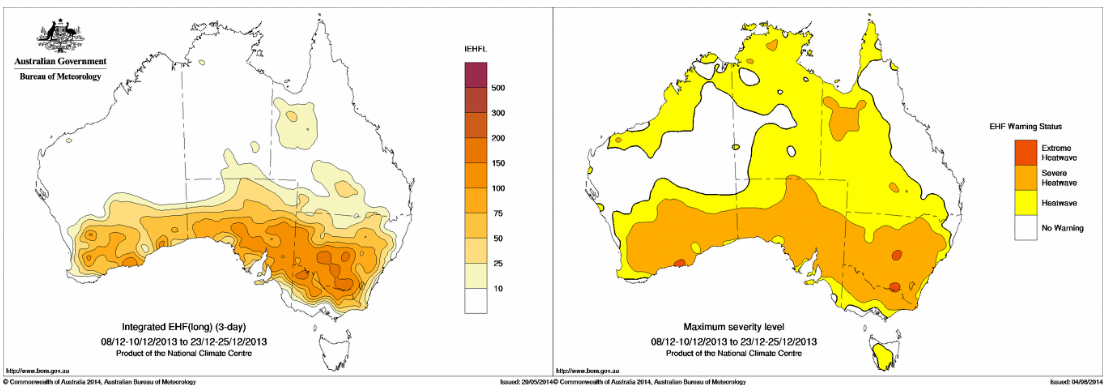


Figure 61: Integrated EHF across Australia for the period 08/10 to 23/25 December 2013 (left) and maximum EHF within that period expressed in terms of severity level (right).

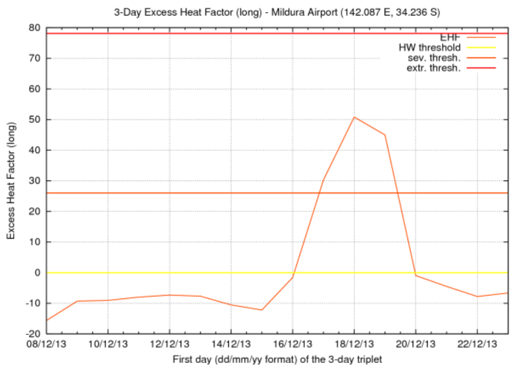


Figure 62: Time series of EHF (left) for Mildura (Victoria) for the period 08/10 to 23/25 December 2013. The peak intensity was 1.95 times the severity threshold (horizontal orange line). The yellow line denotes the non-severe heatwave threshold, and the red line the extreme heatwave threshold.

3.3 Late December/Early January

This episode was active across Queensland and the Northern Territory (Figure 63), although extending into South Australia and inland Western Australia. The peak intensity (19.8 K^2, on 03/05 January) at Brisbane (Figure 64) was more than 3.8 times the severity threshold, making this an extreme event there. Archerfield in suburban Brisbane reached 43.5°C on the 4th, its hottest day on record. This was also an extreme event further inland at locations such as Dalby (not shown).

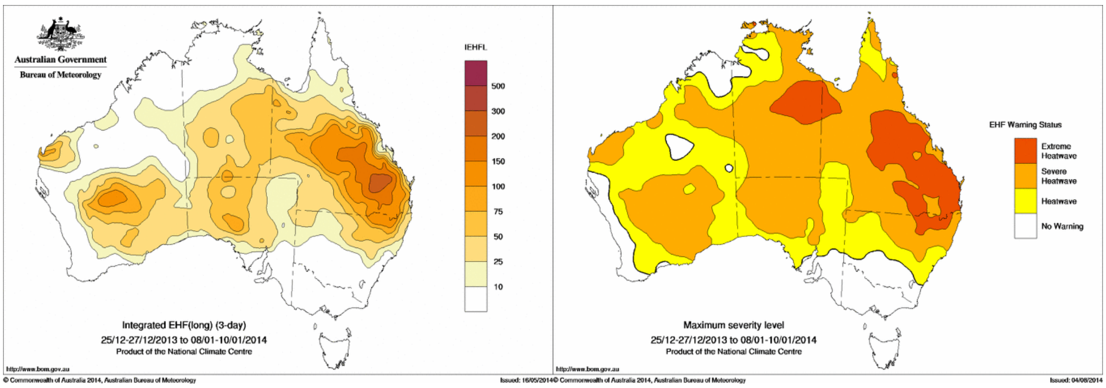


Figure 63: As per Figure 61 but for the period 25/27 December 2013 to 08/10 January 2014.

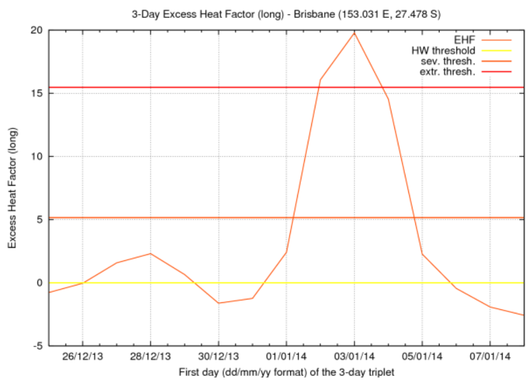


Figure 64: As per Figure 62 but for Brisbane (Queensland) for the period 25/27 December 2013 to 08/10 January 2014. The peak intensity was 3.8 times the severity threshold.

3.4 Mid-January

This episode was in many respects a typical southeast Australian heatwave, although a particularly intense one. Peak intensities were across Victoria and adjacent parts of South Australia (Figure 65). Early assessments suggested that this heatwave resulted in at least 100 excess deaths in Victoria (ABC 2014, [151]). For Melbourne, the peak intensity was 5.5 times the severity threshold (Figure 66), for Adelaide 3.5 times (implying that it was slightly less intense than the 2009 event there).

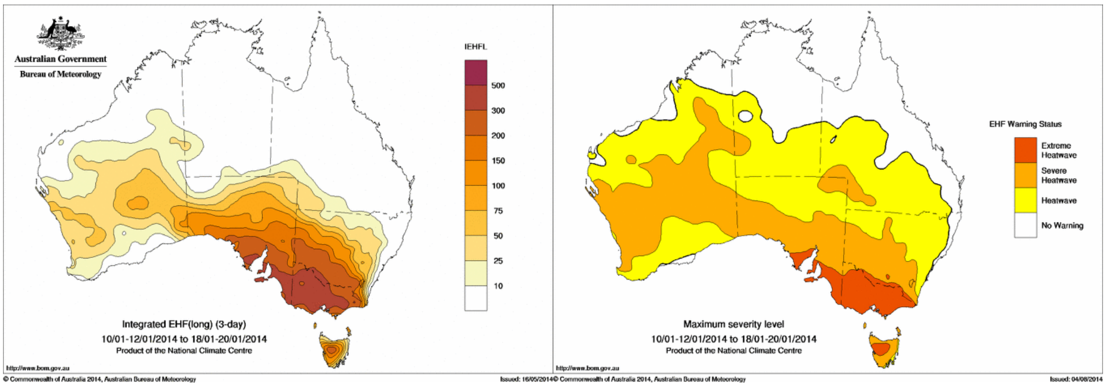


Figure 65: As per Figure 61 but for the period 10/12 to 18/20 January 2014.

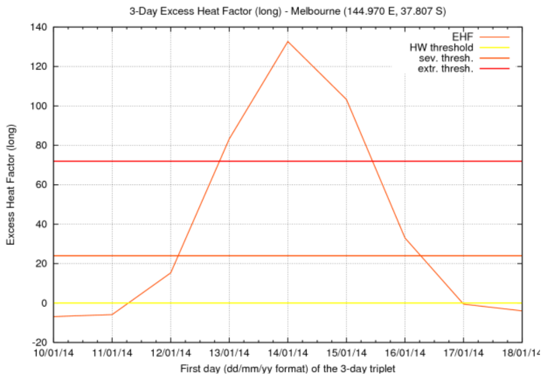


Figure 66: As per Figure 62 but for Melbourne (Victoria) for the period 10/12 to 18/20 January 2014. The peak intensity was 5.5 times the severity threshold.

3.5 Late January

This episode, while affecting much the same area as the previously described episode, had a reduced impact along the Victorian coast (Figure 67). Accordingly, Mildura is chosen as the representative location (Figure 68) for this episode. With peak intensity 2.2 times the severity threshold, this event was well into the severe category at Mildura. The event was also severe at Adelaide (not shown, 1.3 times the severity threshold).

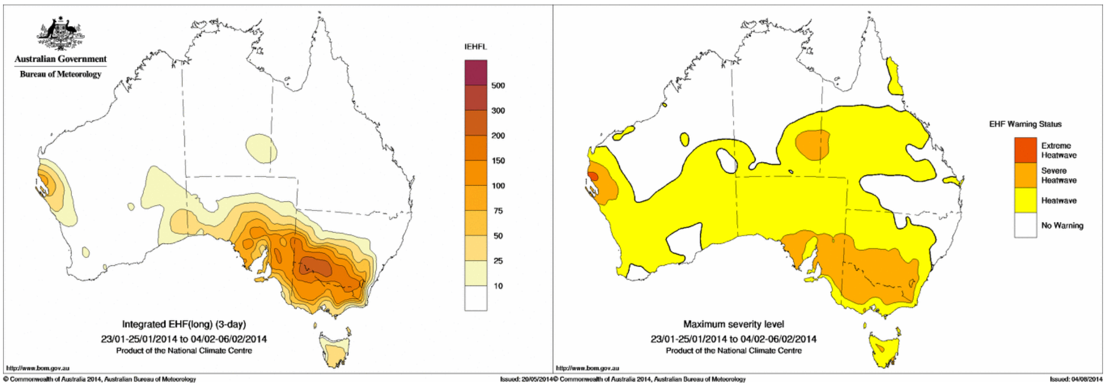


Figure 67: As per Figure 61 but for the period 23/25 January to 04/06 February 2014.

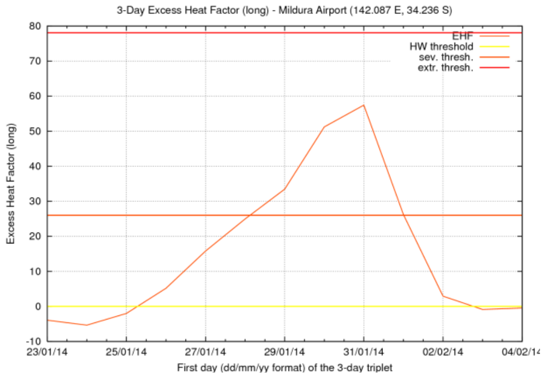


Figure 68: As per Figure 62 but for Mildura (Victoria) for the period 23/25 January to 04/06 February 2014. The peak intensity was 2.2 times the severity threshold.

3.6 Early February

This last episode of the summer mainly affected inland parts of southeast Queensland and the southeast States (Figure 69). Peak EHF severity levels were attained along the Queensland-New South Wales border and around Carnarvon in Western Australia, at twice the local severity threshold. Moree (New South Wales) is chosen in Figure 70 as a representative location. During the period represented in Figure 69, nearly all the southern half of the country experienced non-severe heatwave conditions at some point.

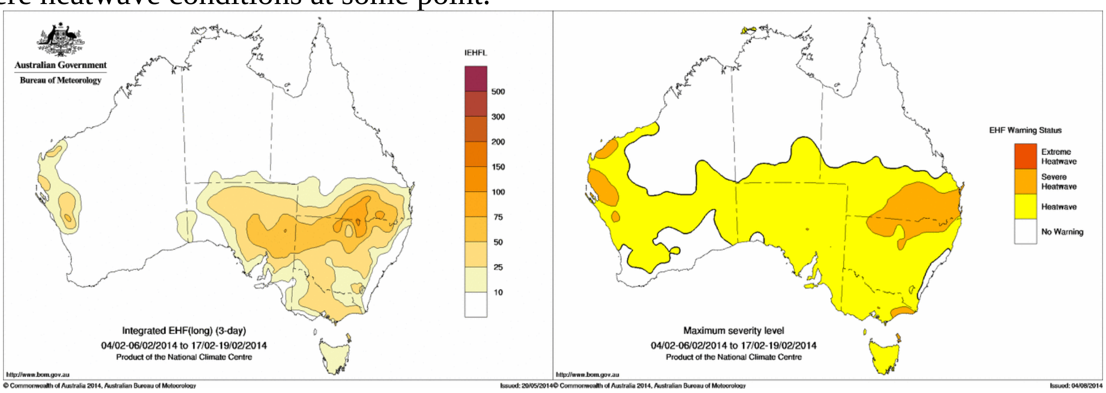


Figure 69: As per Figure 61 but for the period 04/06 to 17/19 February 2014.

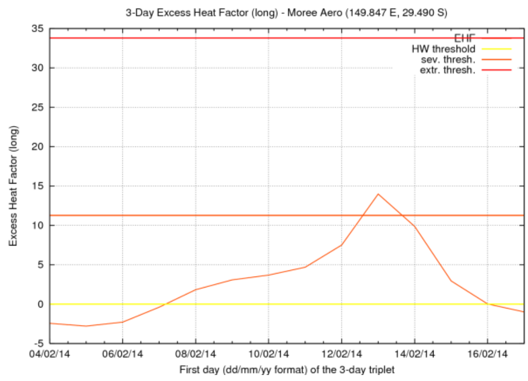


Figure 70: As per Figure 62 but for Moree (New South Wales) for the period 04/06 to 17/19 February 2014.

4. Discussion

The 2013/2014 Australian summer saw some very significant heatwaves, comparable to the worst previously seen in the historical record. For Melbourne, this meant a lapse of just five years since the previous event of a comparable magnitude. It should be noted that the site data used to generate the results shown in Figure 56 are quality-controlled but not homogenised and that lack of homogenisation may have some bearing on the interpretation of the results. Across the period represented by the results (1875 to 2014) the observing site (086071) has moved once (January 1908), with a possible change in the screen used to house the thermometers. Ashcroft (2013 [152]) found statistical evidence for a minor inhomogeneity in minimum temperature around the time of the site move, but none for maximum temperature, so its impact on the EHF would likely not be large. In recent decades the site has seen significant building construction nearby, and so a significant urban heat island (UHI) effect may be present in the minimum temperatures. On the other hand, the UHI is thought to be more noticeable on cool, clear nights which would not normally be associated with spikes in the EHF at this site. In the preparation of homogenised temperature time series, the removal of non-climatic signals such as those caused by site moves, changes in observing practices (including instrumentation and instrument housing) and changes in site surroundings is required. This normally motivates an avoidance of city sites affected by the UHI effect, although for some purposes the UHI effect is only significant (and therefore to be removed) if it *changes* across the duration of the time series. In the heatwave context, while most of the above noted non-climatic signals should be removed in a temperature homogenisation process, we would recommend the retention of the UHI effect in the temperature data contributing to the EHF calculation because of its direct relevance to the human experience of heatwave.

Figure 57 indicates that there is considerable skill in forecasting the national percentage area in heatwave, even at long lead-times (e.g., four days), although the percentage area may sometimes be over-forecast or under-forecast. None of the major severe heatwave events (Figure 58) or extreme heatwave events (Figure 59) were missed, although there were some false alarms (i.e., events forecast which did not subsequently occur). It should be noted that the ability to forecast EHF essentially arises from the ability to forecast daily maximum and minimum temperatures. At short range, daily maximum and minimum temperatures are well forecast, although forecast skill does typically degrade with increasing lead time, and the consequences of this can be seen to some extent in Figure 57 and Figure 58. The ability to forecast the extreme events (Figure 59) is not as good as that achieved for severe events (Figure 58). This is not an unreasonable result when considering the infrequency of extreme heatwaves in comparison to severe heatwaves.

The pilot heatwave forecast service product consists of an image graphic supported by limited text. As such this service is not integrated with the Bureau's official digital forecasts and warnings system. The Bureau's Next Generation Forecast Warning System (NexGenFWS) is responsible for the generation and distribution of Australia's official forecasts and warnings, which is held in the Bureau's Australian Digital Forecast Database. The Bureau is investigating community interest in the generation of a national heatwave warning system within the NexGenFWS, which would enable multiple formats and delivery channels for the delivery of heatwave forecasts and warnings.

Title of Paper	Heatwaves in Queensland [55]
Publication Status	Published
Publication Details	Aust. J. Emerg. Mana., vol. 32, no. 1, 2017, [online]. Available: https://ajem.infoservices.com.au/items/AJEM-32-01-11.AJEM

Principal Author

Name of Principal Author (Candidate)	John Nairn		
Contribution to the Paper	Nairn developed the concept of diagnosing the incidence of heatwaves in Queensland. Nairn drafted the manuscript. Both authors read, reviewed and approved the final manuscript		
Overall percentage (%)	70%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in th [illegible] per.		
Signature		ate	8/11/2021

Co-Author Contributions

Name of Co-Author	R J B Fawcett		
Contribution to the Paper	Fawcett created figures in the paper. Both authors read, reviewed and approved the final manuscript		
Overall percentage (%)	30%		
Signature		Date	7Nov 2021

Paper 4: Heatwaves in Queensland

Presented at AFAC/BNHCRC 2016 - Published AJEM Available:
https://ajem.infoservices.com.au/items/AJEM-32-01-11.AJEM [55]

John Nairn[1] and Dr Robert Fawcett[2]
1. Bureau of Meteorology, Adelaide, South Australia.
2. Bureau of Meteorology, Melbourne, Victoria.
Submitted: 1 July 2016. Accepted: 2 September 2016.

Abstract
The Bureau of Meteorology has used the excess heat factor (EHF) metric of heatwave intensity over three warm seasons (November to March in years 2013-16) for the preparation of its heatwave severity forecasts. The EHF is a relatively recent metric, derived from two excess heat indices (EHIs). The first EHI (significance) characterises whether the three-day period under consideration is hot with respect to the historical record. The second EHI (acclimatisation) characterises whether the three-day period is warm with respect to the immediate past, specifically the preceding 30 days. Both aspects contribute to heat-health impacts on the population. This paper describes the performance of the Bureau of Meteorology's heatwave forecasting service. A heatwave climatology for Queensland in terms of the EHF is presented across a 1958-2011 year-base period that was used in the construction of the EHF dataset. This climatology is compared with a recent period, 1986-2015, revealing higher rates of heatwave occurrence and severity in the later period. This shift in heatwave climatology correlates with an increase in demand for heatwave services over the last decade. This has culminated in the release of the Heatwave Response Plan by Queensland Health (since overwritten [142]) that uses the Bureau of Meteorology Heatwave Service.

Article

Introduction

The Bureau of Meteorology (Bureau) has experienced a rising demand for heatwave services in Queensland. The Bureau was first approached for a heatwave service following extreme conditions in February 2004 in which 75 known excess deaths[1] occurred in southeast Queensland [79]. In January 2014, the Bureau introduced a pilot heatwave forecasting service of national scope using the EHF metric of heatwave intensity. The heatwave forecasting service is an extension of the Bureau's routine forecasting of daily maximum and minimum temperatures. The service has been used over the two warm seasons from November to March 2014-2016.

Forecasts are issued every day and comprise a set of seven maps of heatwave severity, each one valid for a three-day period. The first two maps cover periods that are partially in the past

[1] Excess deaths relate to the number of deaths in excess of the average number expected for the time of year and the region, based on data from other years.

at the time of issue i.e. {the day before yesterday + yesterday + today} and {yesterday + today + tomorrow}. The last five maps comprise the actual forecasts i.e. {today + tomorrow + the next day}, {tomorrow + the next day + the day after} and so on.

The EHF is derived from two EHIs [56], [74]. The significance EHI characterises whether the three-day period under consideration is hot with respect to the typical annual cycle of temperatures at the location, while the acclimatisation EHI characterises whether the three-day period is warm with respect to the immediate past, specifically the preceding 30 days. EHF has been shown to have superior sensitivity [153] to human heat-health response. The EHIs are calculated from daily temperature (DT), which is the average of the maximum and minimum temperatures in a 9am-to-9am 24-hour period; the maximum temperature typically occurring in the afternoon and the minimum temperature in the following morning. Specifically:

$$EHI_{sig} = DT_{3\text{-day}} - DT_{95}$$

$$EHI_{accl} = DT_{3\text{-day}} - DT_{30\text{-day}}$$

$DT_{3\text{-day}}$ denotes the average daily temperature across three consecutive days while $DT_{30\text{-day}}$ denotes the average daily temperature across the 30 days preceding the nominal three-day period. DT_{95} denotes the 95th percentile of daily temperature across a long reference period. Lastly:

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

The units of EHI_{sig} and EHI_{accl} are degrees Celsius (°C), alternatively Kelvin (K), while the units of EHF are $°C^2$, alternatively K^2.

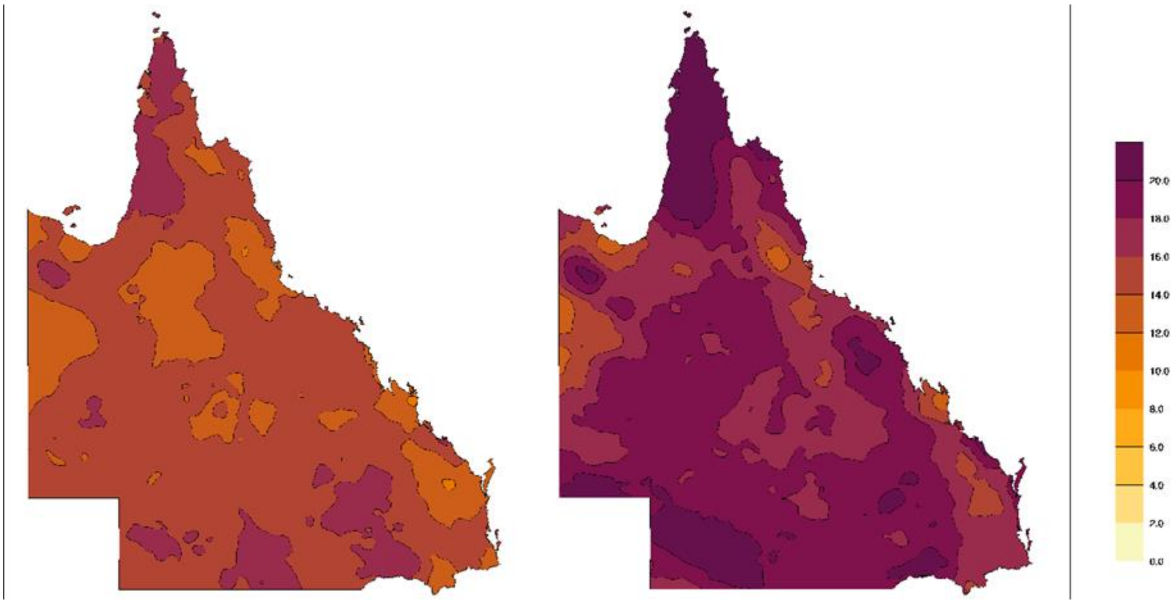
Positive values of the EHF are associated with the presence of heatwave conditions; negative values with their absence. As a single EHF value is associated with a single three-day period, a positive EHF value is taken to indicate heatwave conditions across all three days. By construction, a positive EHF value only occurs when the significance EHI is also positive, with the implication that the three-day period *is* hot with respect to the typical annual cycle of temperature at the location. Thus, heatwaves defined in this way predominantly occur in the November to March period in the southern hemisphere. In order to characterise the severity of heatwaves, the 85th percentile (EHF_{85}) is taken of the EHF values associated with heatwave conditions as the threshold for a severe heatwave, and three times that severity threshold as the criterion for an extreme heatwave. Hence EHF greater than EHF_{85} implies a severe heatwave for the three-day period, while EHF greater than three times the EHF_{85} implies an extreme heatwave. The EHF_{85} threshold is likewise calculated over a long reference period. The choice of these reference periods are, in part, influenced by data availability considerations.

This paper presents a heatwave climatology for Queensland using a 54-year reference period 1958-2011. This is used in the construction of the Bureau's gridded historical EHF dataset and associated heatwave service. This is contrasted against the period 1986-2015 revealing increased rates of heatwave occurrence. Some significant Queensland heatwaves of recent decades are described followed by an assessment of the performance of three warm season's heatwave forecasts (November to March in 2013-16).

A Queensland heatwave climatology

The dataset used is derived from the Bureau's current operational low-resolution (0.25°×0.25°) daily temperature analyses [89]. The description is based on calculations of the average number of heatwaves, severe heatwaves and extreme heatwaves per year. The comparison shows an increased occurrence of heatwaves and severe heatwaves across Queensland in the later period, compared with the earlier period. This change in the heatwave climatology correlates with an increase in demand for heatwave services experienced over the last decade. This has culminated in the release of the Heatwave Response Plan by Queensland Health[2], which uses the Bureau's heatwave service.

Figure 71. Average annual number of three-day periods with positive EHF (left 1958-2011, right 1986-2015).

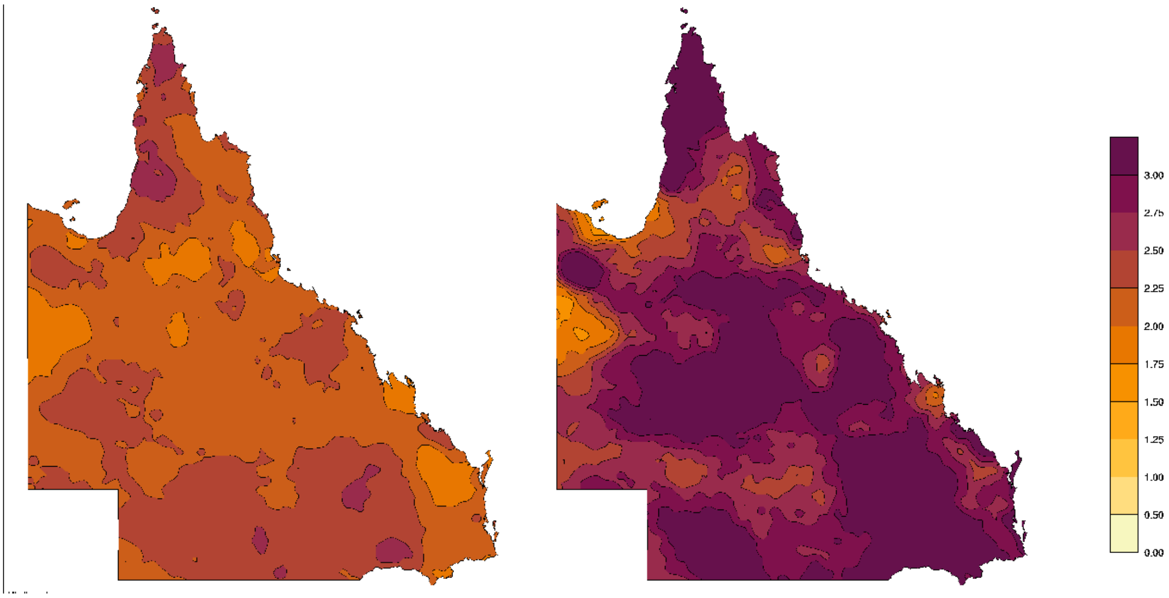


Source: Bureau of Meteorology

Figure 71 shows the average annual number of heatwaves (i.e. three-day periods with positive EHF) across Queensland for the two study periods. The numbers are first calculated for each individual calendar year and then the annual results are averaged. In counting the number of three-day periods, overlapping periods are counted separately. For example, a heatwave extending over four days is counted as two three-day periods, three three-day periods for a five-day heatwave and so on. In the first period, the average number of heatwaves was 14.8 per year averaged across Queensland, while in the second period it was 18.5. The spatial pattern remains fairly similar with higher numbers in the south and on Cape York Peninsula and lower numbers in between.

[2] Queensland Heath 2015, Heatwave Response Plan: an annex of the Queensland Health Disaster Plan. At: www.health.qld.gov.au/__data/assets/pdf_file/0032/628268/heatwave-response-plan.pdf

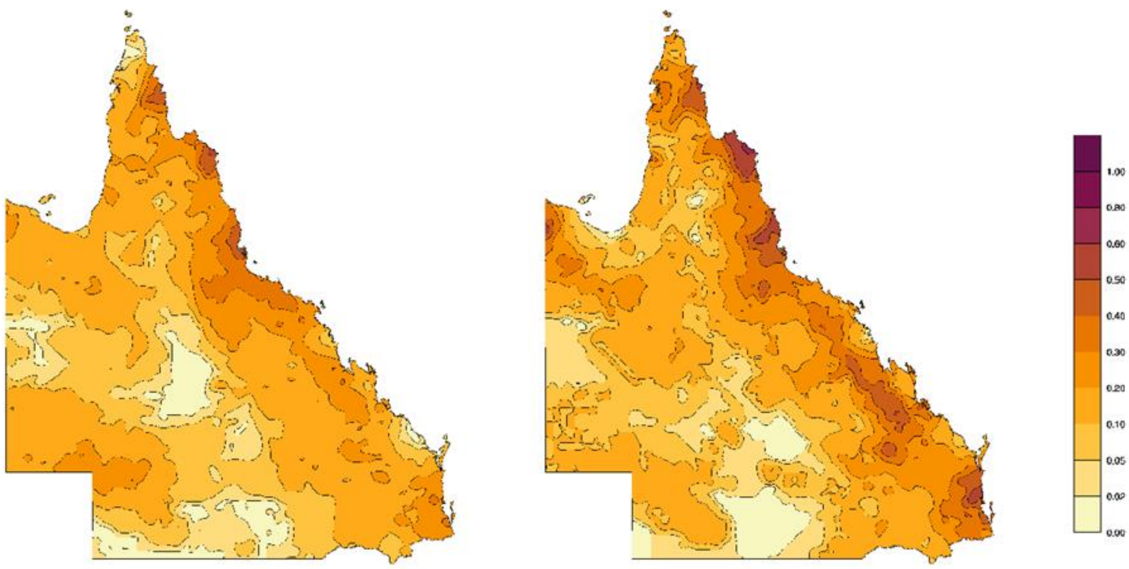
Figure 72. Average annual number of three-day periods with EHF greater than EHF85 (left 1958-2011, right 1986-2015).



Source: Bureau of Meteorology

Figure 72 shows the average annual number of severe heatwaves across Queensland for the two study periods. The counting of severe heatwaves is done in the same overlapping way as for all heatwaves. In the first period, the average number of severe heatwaves was 2.2 per year, averaged across Queensland, while in the second period it was 2.9. Over the 30 years 1986 to 2015, a substantial fraction of the state has experienced three such events per year on average.

Figure 73. Average annual number of three-day periods with EHF greater than 3 EHF85 (left 1958-2011, right 1986-2015).



Source: Bureau of Meteorology

Figure 73 shows the corresponding numbers for extreme heatwaves. Some of the highest frequencies of extreme heatwaves occur along the east coast of Queensland. In the earlier period, the average annual rate across Queensland is 0.13 events per year, with 0.16 events per year in the later period.

Some significant Queensland heatwaves

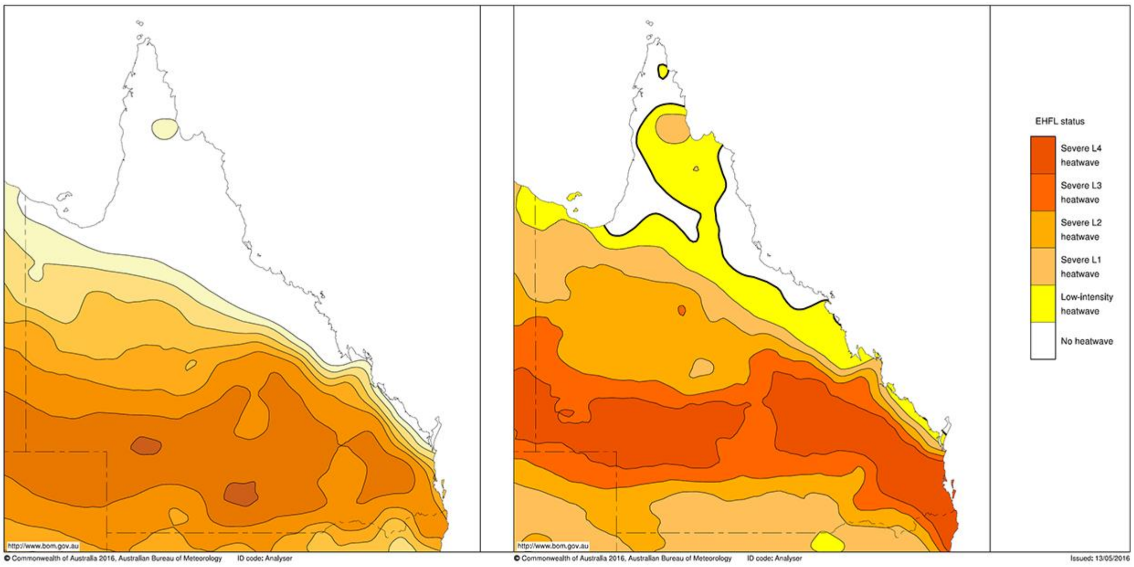
Results from three types of calculations help identify heatwave trends.

- The integrated positive EHF (e.g. Figure 74, left) involves summing the positive EHF values associated with each three-day period within the nominated month (or like period) and ignoring the negative EHF values.
- The highest EHF value for any three-day period within the nominated month is obtained and scaled with respect to EHF_{85} to compute a graded heatwave severity map (e.g. Figure 74, right). White shades indicate no heatwave activity within the nominated period. Yellow shades indicate that some heatwave activity was analysed but it did not reach severe levels. Lighter orange shades (i.e. L1 and L2) indicate that some severe heatwave activity was analysed but it did not reach extreme levels. Dark orange shades (i.e. severe L3 and L4 as indicated in the figure key) indicate that some extreme heatwave activity was analysed.
- Time series are extracted for representative locations (e.g. Figure 75, left) by interpolating the gridded data. In these graphs, the horizontal yellow line represents the threshold for a low-intensity heatwave, the horizontal light-orange line is the threshold for a severe heatwave, and the horizontal dark-orange line is the threshold for an extreme heatwave.

Heatwave December 1972

December 1972 saw extreme heatwave activity across the southern half of Queensland at the end of a major El Niño event. A band stretching from the Queensland, Northern Territory and South Australia borders across to the coast and down towards Brisbane and the far northeast of New South Wales showed peak heatwave intensities exceeding four times the EHF severe threshold. This qualified as an extreme heatwave (Figure 74).

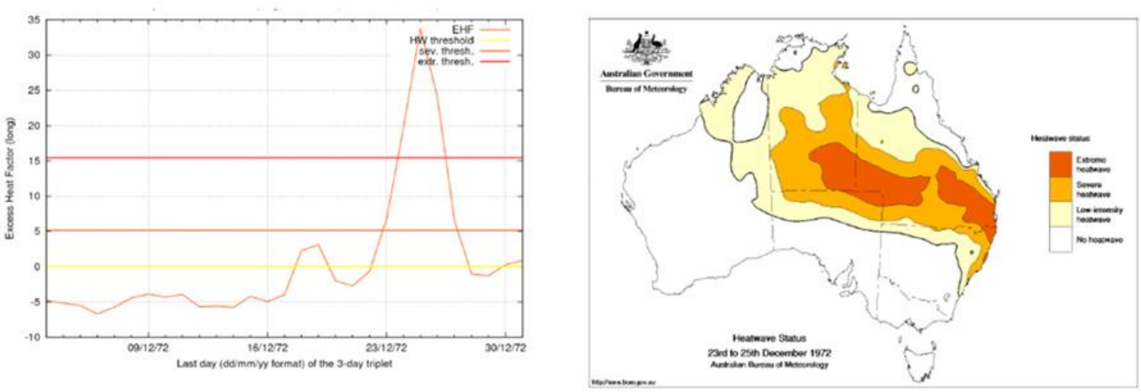
Figure 74. Integrated positive EHF (left) and maximum heatwave severity level (right) for December 1972.



Source: Bureau of Meteorology

Extreme heatwaves in Australia normally affect multiple states and territories. Ninety-nine excess deaths were estimated across South Australia, New South Wales and Queensland [154]. Figure 75 shows the progression of the heatwave in Brisbane together with the national heatwave severity map at the time of the peak heatwave intensity. The heatwave exceeded the local severe heatwave threshold by a factor of six.

Figure 75. Time series of EHF values at the Brisbane Regional Office, for the three-day periods 1-3 to 29-31 December 1972 (left) and the heatwave severity map for 23-25 December 1972 (right), the three-day period that represents the heatwave peak at Brisbane.

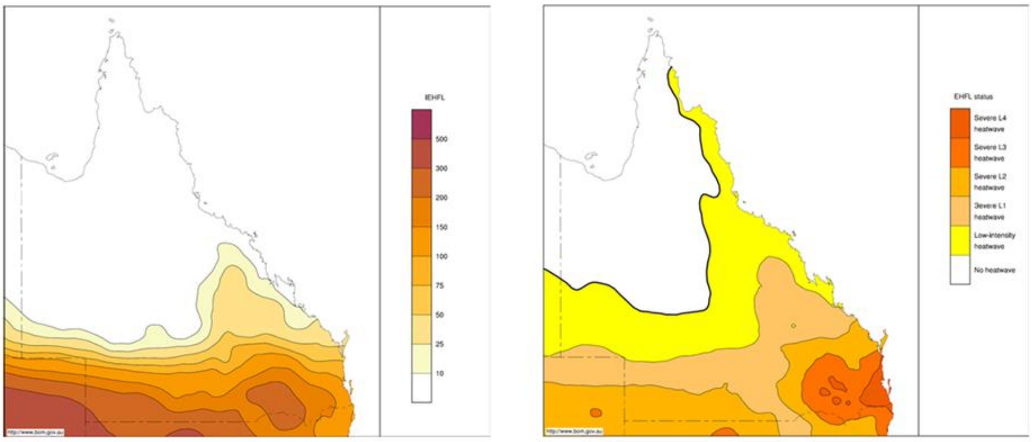


Source: Bureau of Meteorology

Heatwave February 2004

The peak signal of the heatwave of February 2004 was further south than that of December 1972, particularly in terms of the integrated EHF where higher values were recorded in South Australia and New South Wales (Figure 76). Even so, extreme heatwave intensities were analysed over southeast Queensland, particularly in the vicinity of Brisbane.

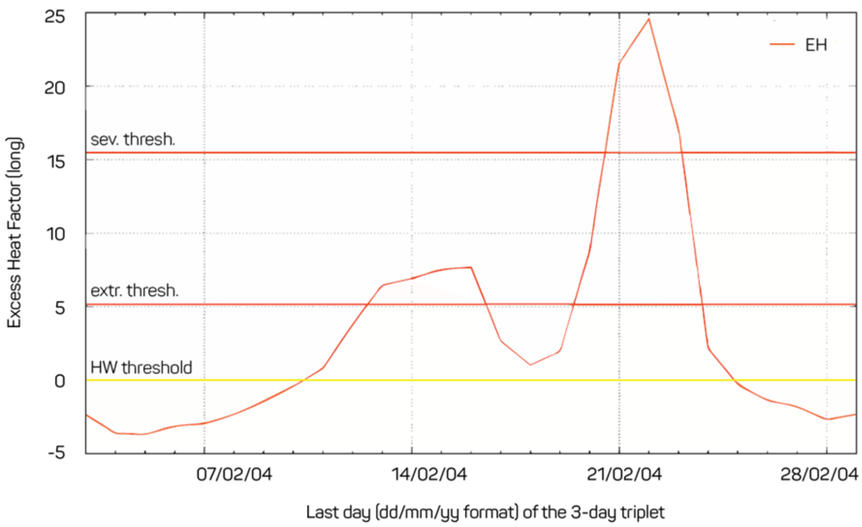
Figure 76. Integrated positive EHF (left) and maximum heatwave severity level (right) for February 2004.



Source: Bureau of Meteorology

Modelling mortality rates due to heat stress estimated 116 excess deaths during 7-26 February 2004 in Brisbane [79] corresponding to the location of highest heatwave severity shown in Figure 77. At Brisbane, three consecutive three-day periods (amounting to five days in total) were in the extreme range with EHF values rising to nearly five times the local severe heatwave threshold.

Figure 77. Time series of EHF values at the Brisbane Regional Office for the three-day periods 1-3 to 27-29 February 2004.

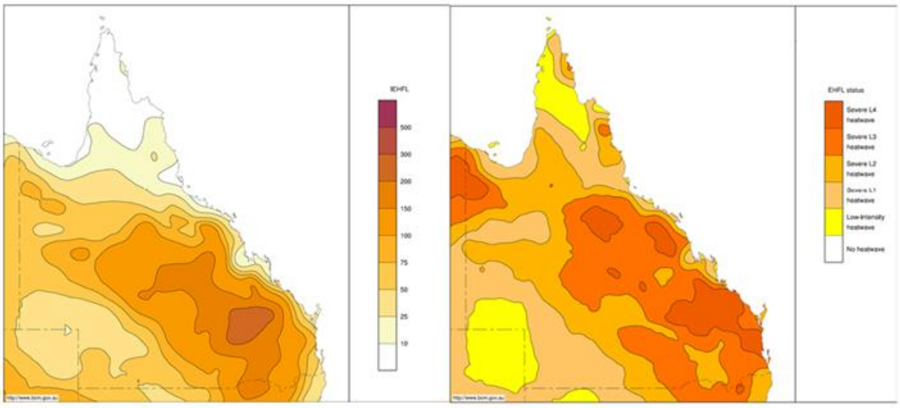


Source: Bureau of Meteorology

On Saturday 21 and Sunday 22 February 2004, the Queensland Ambulance Service experienced increases in calls of 28 per cent and 53 per cent respectively throughout the south-east of Queensland. This was its busiest day on record. The Ambulance Service reported on Monday 23 February that while ‘some cases were identified as specifically heat related, the bulk of calls were to people suffering from underlying medical conditions’ [155].

Heatwave New Year 2014

Figure 78. Integrated positive EHF (left) and maximum heatwave severity level (right) for late December 2013 to early January 2014.



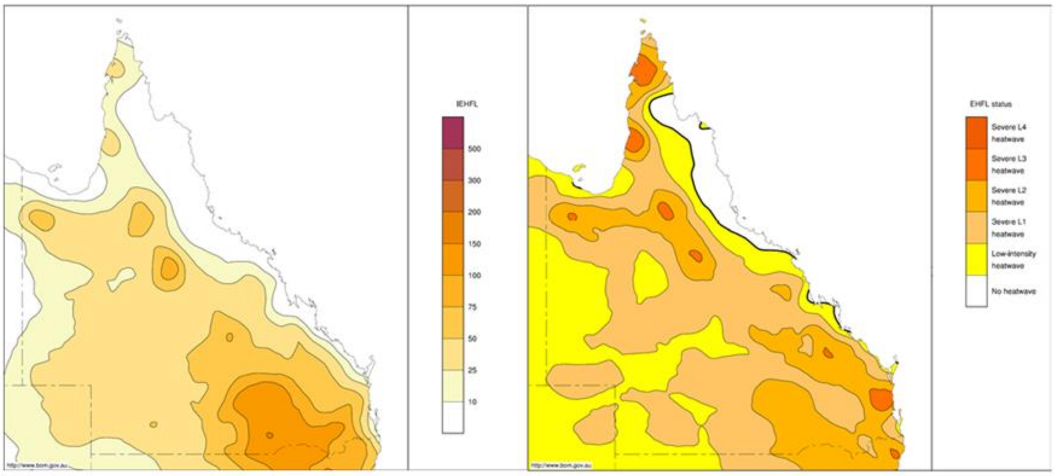
Source: Bureau of Meteorology

A heatwave peaking in the extreme range across parts of Queensland was recorded in late December 2013 to early January 2014 (Figure 78). While significant human health effects were recorded in southeast Australia in January 2014, there is little evidence of similar effects in Queensland. This could be attributed to effective messaging and warnings to the community over the threat posed [156] or the delay in the assessment of excess- and medically attributable heat effects. There were however, well documented impacts on colonies of flying fox in south east Queensland. An estimated 45,500 flying foxes died in 52 of the 162 colonies assessed [35]. This is a significant event when compared to studies by Welbergen *et al.* 2008 [157] that showed more than 30,000 flying foxes died in 19 such events in Australia between 1994 and 2008.

Heatwave November 2014

The heatwave of November 2014 had its peak integrated EHF in southern Queensland (Figure 79 left). In terms of peak severity, its impact was broadly spread across the state (Figure 79 right). This event, in the middle of the month, attracted international attention because of its proximity to the 2014 G20 Conference in Brisbane [158].

Figure 79. Integrated positive EHF (left) and maximum heatwave severity level (right) for November 2014.



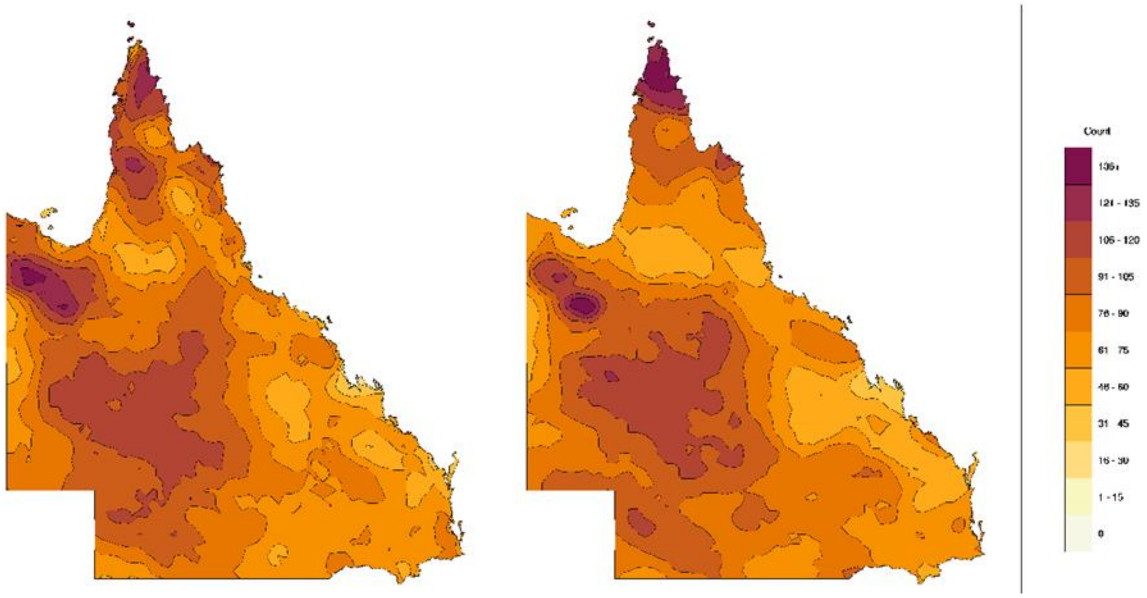
Source: Bureau of Meteorology

Similar to the January 2014 heatwave there has not been any public disclosure of the effects on the population other than the discomfort for G20 conference attendees [158].

Forecast performance

The Bureau began issuing national heatwave severity forecasts in a pilot service on 8 January 2014. As the forecast service had been running internally throughout the entire warm season (November 2013-March 2014), the entire warm season was used in calculations. The pilot service ran again during the warm season of 2014-2015. By the warm season of 2015-2016 the service was fully established. The forecast performance for this first warm season has been described at the national scale [54]. Here, the focus is on the forecast performance across Queensland for the three warm seasons of 2013-2014, 2014-2015 and 2015-2016. Figure 80 shows a comparison of the total number of heatwaves (i.e. three-day periods with positive EHF) forecast at 'lead time 1' and subsequently observed across the warm seasons of 2013-2014 to 2015-2016. Here, 'lead time 1' means the three-day period forecast issued today for {today + tomorrow + the next day}. The spatial pattern of the observed events is captured in the forecasts. Across the three seasons, the state-averaged forecasting rate at lead time 1 was 85.61 events (hence an average rate of 28.54 events per season) compared with 84.0 events observed.

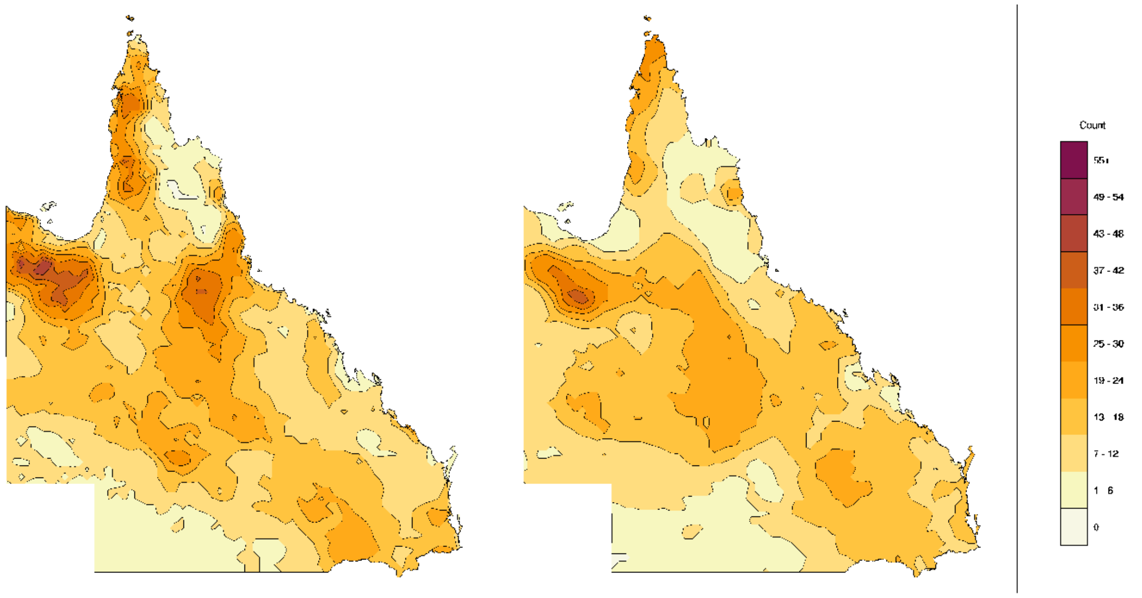
Figure 80. Number of heatwaves forecast at lead time 1 (left) and observed (right) in the warm seasons of 2013-2014 to 2015-2016. The heatwaves represent three-day periods with positive EHF and are not necessarily non-overlapping.



Source: Bureau of Meteorology

Figure 81 shows the corresponding comparison for the number of severe heatwaves. The state-averaged forecasted rate was 14.35 events compared with 12.75 events observed.

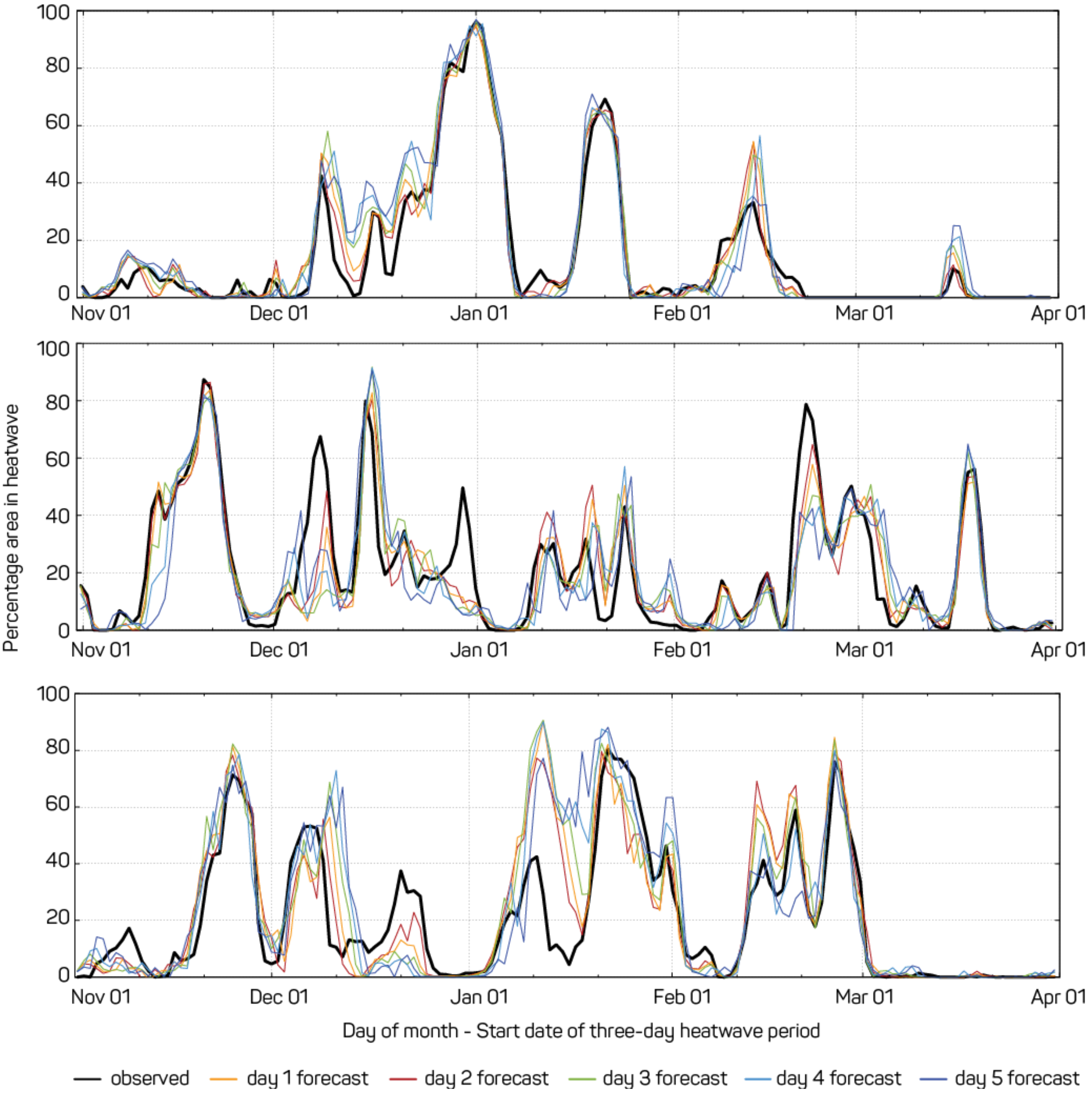
Figure 81. Number of severe heatwaves forecast at lead time 1 (left) and observed (right) in the warm seasons of 2013-2014 to 2015-2016.



Source: Bureau of Meteorology

Figure 82 shows the percentage area of Queensland in heatwave conditions for each three-day period throughout the three heatwave seasons. The percentage areas forecast to be in heatwave conditions are also shown (coloured lines). Heatwave activity across Queensland throughout the heatwave season is episodic in nature. There are periods where a large proportion of the state is in heatwave conditions over several consecutive days, interspersed with periods when almost none of the state is in heatwave conditions.

Figure 82. Time series of the percentage area of Queensland in heatwave for the 2013-2014 (top), 2014-2015 (centre) and 2015-2016 (bottom) heatwave seasons (November to March).

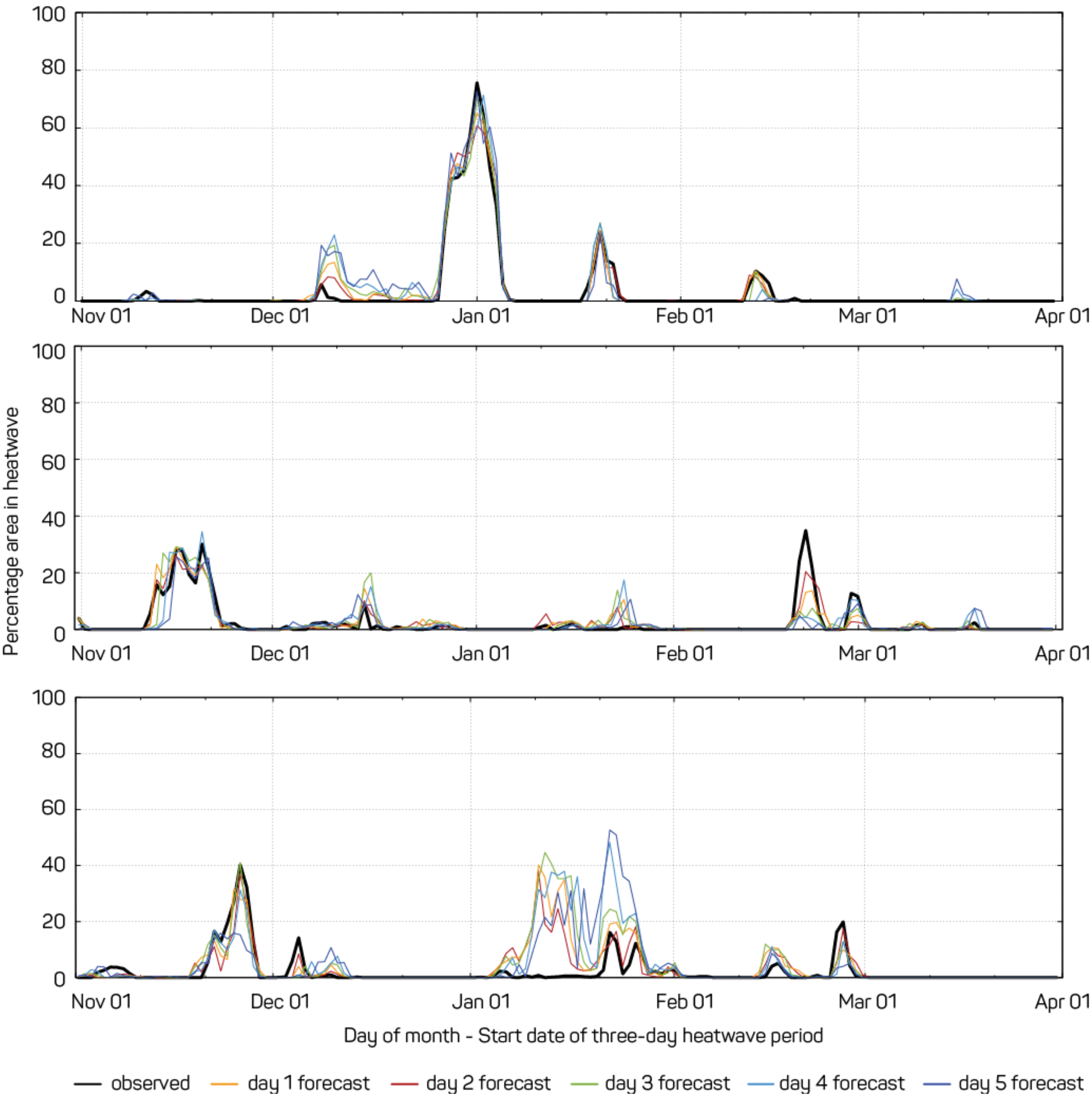


Source: Bureau of Meteorology

Each graph shows the percentage area observed (black lines) and corresponding forecasts (coloured lines; lead times 1 to 5). Red and orange colours denote shorter forecast lead times, blue colours longer forecast lead times.

The performance of the heatwave forecasting system in terms of the percentage area is variable. Sometimes the extent of the heatwave is forecast extremely well, as in the two largest events of the 2013-2014 season. On other occasions, substantial over forecasting (e.g. the first half of January 2016) or under forecasting (e.g. the onset of the major heatwave of November 2014) can be seen.

Figure 83. Time series of the percentage area of Queensland in severe heatwave for the 2013-2014 (top), 2014-2015 (centre) and 2015-2016 (bottom) heatwave seasons (November to March).



Source: Bureau of Meteorology

In terms of the percentage area of Queensland in severe heatwave, the performance of the forecast system (Figure 83 is similar to that observed. The severe heatwave around New Year

2014 was forecasted well, as was the November 2014 heatwave, although with under forecasting of the onset. Conversely, the peak intensity of the February 2015 heatwave was not captured in the forecasts, while January 2016 saw substantial over forecasting of severe heatwave activity. The poor performance in January 2016 is noticeably worse than in other cases, both for low-intensity and severe heatwaves. Reasons for this are not clear and warrant future investigation. Still, no episode of severe heatwave activity was missed entirely by the forecasting system.

Future heatwave services

Collaborative health studies in Australia and overseas are being used to test EHF skill as a predictor of heatwave impact. In combination with the growing understanding of heatwave climatology and demonstrated forecast skill in the heatwave service the Bureau has engaged with the health, emergency services and media sectors across Australia to establish the level of support for a national heatwave warning system. Federal, state and territory representatives from these sectors were invited to a National Emergency Management Project-funded workshop in October 2016. Regional health impact studies from Western Australia, South Australia and New South Wales were presented that demonstrated EHF impact forecast skill and explored principles required within a national heatwave warning framework. Attendees agreed to augment an existing heatwave services reference group established by the Bureau to assist in the ongoing development of this framework. The work of this reference group will be reported to the Hazards Services Forum (HSF). The HSF will be the national arena for jurisdictions at the highest operational level to consider the options provided by the reference group for implementation and development. It will allow a standardised service taking into account the requirements of community and industry disciplines such as health, transport and energy sustainability.

This work will be reported to the National Review into Warnings and Information working group[3] to ensure that heatwaves information and warnings are developed within the evolving national multi-hazard environment.

Conclusion

This paper presented a climatology of heatwave severity across Queensland using the EHF metric for two periods; 1958-2011 being the period used to construct the associated gridded dataset and 1986-2015 representing the current climate. The latter period shows, on average, a higher incidence of heatwaves compared to the earlier period. Some significant recent

[3] National Review Review into Warnings and Information. At: www.emv.vic.gov.au/publications/national-review-of-warnings-and-information

Queensland heatwaves were described in terms of the EHF metric. Verification results were given for the performance of the Bureau's pilot heatwave forecasting service. Development of a national heatwave warning service has growing support across health, emergency services and media sectors. A proposed heatwave warning framework would seek national endorsement through the Hazards Service Forum. Once established the Bureau would engage partner agencies in creating a national heatwave warning service.

Chapter 4. Impacts of heatwaves

Multidisciplinary collaboration between Australian epidemiologists and climate scientists emerged with the seminal "Human health and climate change in Oceania: a risk assessment 2002" [21]. This publication noted the risk of increased heatwaves (amongst other natural hazards) attributable to global warming and evidence for human health impacts. Australia had been placed on notice for increased risk to human health arising from heatwaves.

Heatwaves have been labelled 'the silent killer' [116], [159]. Studies into health impact lack medical attribution codes for influence of heat, with death frequently attributed to pre-existing conditions in health records. Disparate heatwave definitions in epidemiological studies [43], [44], [104], [112], [128], [160], [161] ruled out generalised impact attribution to common heatwave characteristics. Different heatwave measures result in stand-alone studies which are valuable at each location but difficult to apply elsewhere. The inability to compare heatwave vulnerability around the world motivated the development of a heatwave intensity index where normalised severity categories are proportional to the scale of impact, irrespective of location.

Significant international heatwave events are scaled against normalised severity categories, demonstrating proportionate human health impact to heatwave severity irrespective of location. Severity peak and heat load was examined and presented as informative characteristics that can assist in an early warning system.

Performance of the South Australian heatwave warning system during the 2018/19 summer is examined. Mitigation activations in response to warnings are documented demonstrating risk reduction for the health, transport, environment and emergency services sectors. The benefits of a spatially activated heatwave service are noted based on heatwave severity forecasts.

Impacts arising during the 2019/20 heatwave season are compared to heatwave severity observations during Australia's Black Summer. The cascading, compounding influence of drought and intense heatwaves on the development of mega-fires and the subsequent loss of housing and infrastructure are discussed. Preliminary national heatwave vulnerability results are presented as an opportunity to provide tailored services for risk of heatwave health impact.

Title of Paper	Performance of Excess Heat Factor as a global heatwave health impact index. [138]
Publication Status	Published
Publication Details	International Journal of Environmental Research and Public Health, 15(11). https://doi.org/10.3390/ijerph15112494

Principal Author

Name of Principal Author (Candidate)	John Nairn		
Contribution to the Paper	Nairn conceived the idea of the study. Wrote the original paper.		
Overall percentage (%)	80%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or ,ould constrain its inclusion in r.		
Signature		te	8/11/2021

Co-Author Contributions

Name of Co-Author	Bertram Ostendorf		
Contribution to the Paper	Reviewed concept, reviewed writing, coded in R for generation of results.		
Overall percentage (%)	15%		
Signature		Date	4/11/2021

Name of Co-Author	Peng Bi		
Contribution to the Paper	Reviewed concept, reviewed writing, sourced funds for publication.		
Overall percentage (%)	5%		
Signature		Date	5/11/2021

International Journal of Environmental Research and Public Health, *15*(11).
https://doi.org/10.3390/ijerph15112494

Paper 5: **Performance of Excess Heat Factor severity as a global heatwave health impact index.**

John Nairn [1,2,*], Bertram Ostendorf [2] and Peng Bi [2]

[1] Australian Bureau of Meteorology; John.Nairn@bom.gov.au
[2] University of Adelaide; Bertram.Ostendorf@adelaide.edu.au, Peng.Bi@adelaide.edu.au
***** Correspondence: J.Nairn@bom.gov.au; Tel.: +61-438-873-412

Published: 2018

Abstract: Establishment of an effective policy response to rising heatwave impacts is most effective when the history of heatwaves, their current impacts and future risks are mapped by a common metric. In response meteorological agencies aim to develop seamless climate, forecast and warning heat impact services, spanning all temporal and spatial scales. The ability to diagnose heatwave severity using the Excess Heat Factor (EHF) has allowed the Australian Bureau of Meteorology (the Bureau) to publicly release 7-day heatwave severity maps since 2014. National meteorological agencies in the UK and the United States are evaluating global 7-day and multi-week EHF heatwave severity probability forecasts, whilst the Bureau contributes to a Copernicus project to supply the health sector with global EHF severity heatwave projection scenarios. In an evaluation of impact skill within global forecast systems, EHF intensity and severity is reviewed as a predictor of human health impact, and extended using climate observations and human health data for sites around the globe. Heatwave intensity determined by short and long-term temperature anomalies at each locality is normalized to permit spatial analysis and inter-site comparison. Dimensionless heatwave event moments of peak severity and accumulated severity are shown to correlate with noteworthy events around the globe offering new insights into current and future heatwave variability and vulnerability. The EHF severity metric permits comparison of international heatwave events and their impacts, and is readily implemented within international heatwave early warning systems.

Keywords: heatwave intensity; heatwave severity; heatwave impact; heatwave index; heatwave event moments, early warning system

---

1. Introduction

There is increasing need to refine policies to address climate change and future heatwave risks. Heatwave impacts to human health has been established as a global phenomenon [118]. Chronic heatwave impacts have been demonstrated in Australia where a 2002 study [21] estimated 1000 people per year over the age of 65 die from heat related deaths. Numerous extreme events have resulted in the deaths of hundreds of people, which has led to the conclusion that heatwaves are Australia's deadliest natural hazard [19]. Extreme heatwaves became internationally notorious following a 2003 European heatwave when France recorded 15,000 excess deaths [162]. Heatwaves extract a heavy toll upon vulnerable people and communities. Human health aspects of the very young, old aged, mental health, underlying disease and social disadvantage contribute to heatwave vulnerability. On rare occasions high intensity impacts spread to healthy people through failure of infrastructure, utilities and inadequate adaptation strategies [94], [162]–[164]. Heatwaves trends and projections exhibit an increase in frequency and intensity under a warming climate [10], [11], [13], [165]–[167], implying increased risks and the need for improved climatic extreme warning systems to reduce the risk of disasters [168], [169].

Recent investigations have focused on the need to measure heatwave intensity in a manner that is meaningful for each location, yet seamless over broad spatial scales. Percentiles-based heatwave metrics have been recommended to satisfy the locality criteria [43], where an example of an intensity calculation that is meaningful to any sector is the Heat Wave Magnitude Index (HWMI) and its daily derivative HWMId [12]. Similar to HWMI, the Excess Heat Factor (EHF) [56] measures heatwave intensity at each location with an additional component to account for adaptation. Whilst similar in principle to HWMI, EHF has distinctions worthy of note. Rather than use maximum temperature alone, daily temperature is considered important due to minimum temperature compounding extremes through modification of the diurnal heating cycle [170], [171].

Epidemiological studies [24], [120], [122], [123], [139], [153], [172] have demonstrated EHF severity dose/response skill for morbidity and mortality in Australia for both city and regional communities. These multidisciplinary studies have formed the basis for partnership discussions between health agencies, emergency services and the Bureau of Meteorology (the Bureau) for development of a national heatwave forecast and warning framework. International studies have also demonstrated EHF's skill for epidemiological response [173] and mortality modelling [110]. EHF severity has been shown to be useful as an exposure index that scales well against human health impact for and between exposed locations but there is a lack of comparative studies to evaluate efficacy across different climates and broad spatial scales.

From an applied perspective, agencies tasked with generating the necessary environmental assessments, forecasts and warnings must consider how policy makers across health, infrastructure, utilities and emergency services can prepare and adjust to future climate scenarios. Choice of heatwave indices suitable for use in these systems must satisfy the following criteria:

1. Extreme values match user experience,
2. Useful as indicator of impact,
3. Seamless interpretation across climate records, 7-day, multi-week, seasonal and climate projection forecasts,
4. Ease of interpretation, and common to both policy and operational users
5. Mapped to provide timely and locally specific guidance, and
6. Operate within a multi-hazard warnings framework

National meteorological agencies in Australia, the UK and United States have either put into operation or under evaluation the Excess Heat Factor [56] for global heatwave severity analysis and forecasts. The Bureau's heatwave service has published national 7-day heatwave severity maps on the internet since 2014 [97]. The UK Met Office is evaluating global 7-day probability maps of heatwave (and coldwave) severity within their Global Hazard Map (GHM) project [174] whilst the Bureau [96] and NOAA (personal communication, University of Maryland) have funded experimental multi-week heatwave severity probability forecasts. The Bureau is also contributing global EHF heatwave severity maps to the Copernicus project [175] for users to envisage meaningful heatwave climate change scenarios. In support of further development and adoption of EHF severity as an international heatwave impact metric, this study will assess its skill across different climates around the globe.

In this paper, we question how EHF severity is related to health impacts as a globally comparable, quantitative indicator. We are using extreme heatwave events for which impacts are well documented and locations for which long-term climate data are available with the aim to investigate their relationships with human health impacts using various health outcomes. The relationship between heatwave indicators and health impact is then compared between sites around the globe to understand if a common response to heatwave severity is detectable.

2. Materials and Methods

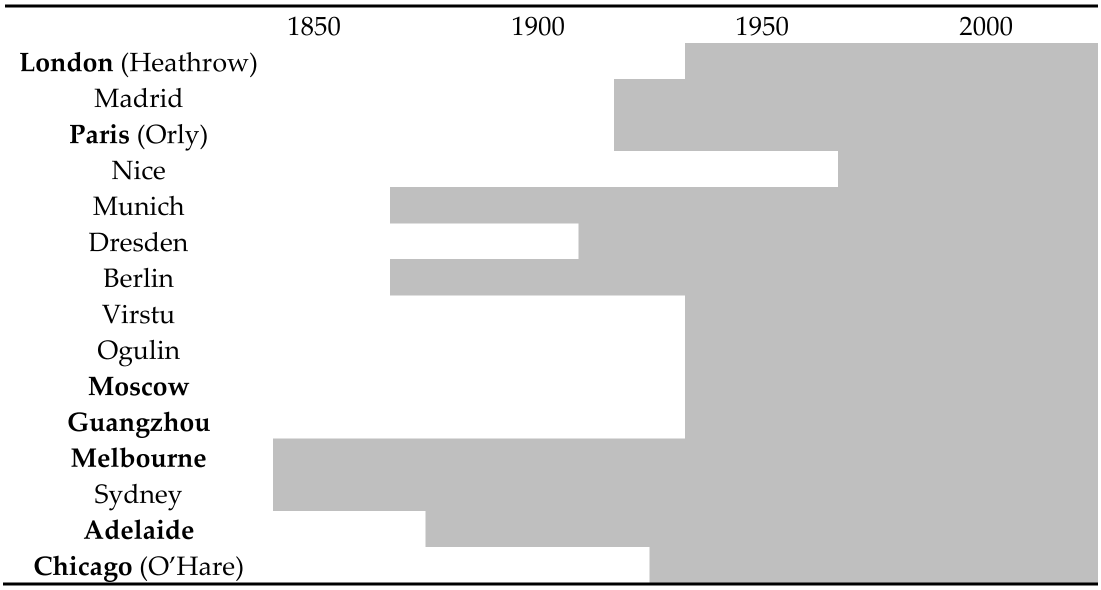
Meteorological data sites have been selected based on availability of impact data, geographical distribution across Europe, Asia, North America and Australia, and heatwave events that have been examined in the literature.

Maximum and minimum temperature data were accessed from the Australian Bureau of Meteorology, National Centers for Environmental Information (US, UK and Asia) and European Climate Assessment and Dataset [176]. Sites chosen are listed in

Table 5, showing the period for which data was available at each site. Time-series site data were examined and treated to remove data gaps, with subsequent ranked severity moments checked for false events due to data gaps.

Full EHF heatwave intensity and severity moment calculations for all stations listed below have been tabulated and are available as supplementary materials in a spreadsheet (NB. Refer article for spreadsheet, see article).

Table 5. EHF intensity and severity calculated for the observation period shown in grey bars for each site. Cities in bold are examined in detail in section 3.



Heatwave intensity and severity were calculated using the technique described by Nairn and Fawcett [56]. EHF's assembly (equation 1) from long (equation 2) and short-term (equation 3) daily mean temperature (DMT) anomalies creates a power-law time series that permits a novel normalization technique to build a dimensionless severity index (equation 4).

$$EHF = EHI_{sig} \cdot \max\left[1, EHI_{accl}\right] \quad (1)$$

$$EHI_{sig} = DMT_{3-day} - DMT_{95} \quad (2)$$

$$EHI_{accl} = DMT_{3-day} - DMT_{30-day} \quad (3)$$

$$Severity = EHF \div EHF_{85} \quad (4)$$

The principals and full derivation of this technique are reviewed in the Appendix supported by examples. EHI_{sig} denotes significance of heat events and EHI_{accl} quantifies heat events requiring an adaption or acclimatisation response, respectively. EHF has units of $°C^2_L$, with the non-SI unit subscript (L) used to indicate the locality constraint. As a percentile-based temperature anomaly heatwave intensity index, EHF values are unique for every location. For example, smaller anomalies are found in the tropics compared to the mid latitudes due to differences in climatic temperature range. As a measure of impact in exposure/response studies these intensity values are only meaningful at each location. In order to create an exposure/response index that can be used for both temporal and spatial studies EHF severity has been developed (equation 4, see Appendix for full description). Extreme value theory, (points over threshold) has been used to normalise EHF into a dimensionless severity index. In addition to the ability to compare heatwave impact spatial characteristics, impact thresholds have been successfully demonstrated for severity classes [24], [56], [123], [153]. This study will investigate whether these severity classes exhibit common impact thresholds.

Moments of average, mean, median and standard deviation (amongst others) are associated with statistical properties of populations, or samples of populations. Heatwave climate indices have been developed [62] and can be thought of as heatwave climate moments (HCM). The concept of heatwave event moments (HEM) is introduced here to help distinguish the utility of heatwave intensity and severity for examining heatwave event impact. Heatwave event moments of peak (highest value during the event), load (integrated values across the event), length (days) and mean load are investigated for their relationships with human health impacts using various health outcomes.

Heatwave event moments (HEM) are defined using the following equations:

$$Peak = \max_{event} Severity \tag{5}$$

$$Load = \sum_{start}^{finish} Severity \tag{6}$$

$$Length = \text{count(severity event)} \tag{7}$$

$$Mean = Load/Length \tag{8}$$

‘Peak’ denotes the highest heatwave severity recorded in a heatwave event and ‘Load’ is the integration of heatwave severity values for the duration of a heatwave event. Length is the number of days exceeding a severity threshold.

These heatwave event moments are initially discussed using mortality and morbidity data for the 2009 extreme heatwave that impacted Adelaide and Melbourne. The data are reproduced from a previous study [74] (p. 21, 22).

Daily London 1981 to 2016 mortality data have been sourced from MEDMI, through arrangements with the UK Met Office. Excess mortality was derived by averaging the mortality for a two-month period, centred on the heatwave event in the prior year or year earlier, depending upon the absence of heatwave conditions. Under this criteria, average mortality was calculated in 1982 for 1983; in 1988 for 1989; and in 1992 for 1994, 1995 and 1996.

Daily Chicago human health impact data have been sourced from publications [177]–[179] (p. 1516, Figure 1 and p. 1517, Figure 2; p. S159, Figure 1; and p. 174, Figure 1, respectively).

Daily Paris and Guangzhou human health impact data have been sourced from publications [180], (p.1486, Figure 1) and [181] (p.650 Figure 1).

A spreadsheet of all EHF severity moments for the cities listed in

Table 5 is included in Supplementary Materials (see, article). Results for cities in bold are presented in results and discussed.

3. Results

3.1. Adelaide and Melbourne heatwave event moments: peak, load, length and mean

Peak and load for both EHF intensity and severity are presented for Adelaide in

Table 6. In this table Peak (Intensity) and Peak (Severity) are both valid impact measures, although the intensity is only meaningful for Adelaide (see Appendix for explanation). Subsequent tables and discussion will only focus on the event severity moments as calculated in equations 5-8.

Table 6. Adelaide heatwave event peak, load, length and mean, using intensity and severity (1887 to 2018). Top 10 ranked for event peak. Peak and Load Intensity in units of °C^2. Peak, Load and Mean Severity are dimensionless [ ] and Length in days.

Heatwave Period	Peak(Int)	Peak(Sev)	Load(Int)	Load(Sev)	Length	Mean(Sev)
26 Jan - 6 Feb 2009	153	4.2	641.8	17.5	12	1.5
18-21 Jan 1875	121	3.3	418.6	11.4	7	1.6
11 - 17 Jan 2014	106.1	2.9	368.7	10.1	7	1.4
30 Dec 1899 - 2 Jan 1900	103.8	2.8	266.8	7.3	4	1.8
5 - 8 Jan 1930	94.9	2.6	173.7	4.7	4	1.2
25 - 29 Dec 1897	94.4	2.6	296.3	8.1	5	1.6
17 - 21 Jan 2006	93.7	2.6	209.4	5.7	5	1.1
17 - 23 Jan 1973	92.8	2.5	303.4	8.3	7	1.2
16 - 23 Jan 1982	90.5	2.5	367.7	10	8	1.3
8 - 13 Jan 1927	89.2	2.4	369.7	10.1	6	1.7

Adelaide's top peak and load moments range from 2.4 to 4.2 and 4.7 to 17.5 respectively in

Table 6. The 2009 event is top ranked for peak (4.2), load (17.5) and length (12). Mean (1.5) is strongly modulated by length and is not able to be interpreted in isolation from the other moments. As peak and load are considered to be superior moments, moments of length and mean are not always displayed in following tables but may be referenced in the Supplementary Materials spreadsheet.

A time-series of the 2009 event is shown in Figure 84, where heat related mortality lagged the rise and fall of severity by 2-days. As EHF under this formulation is designed as a lead indicator of heatwave impact the resultant lag suggests that the average heat accumulation over two or three days results in a scaled mortality response.

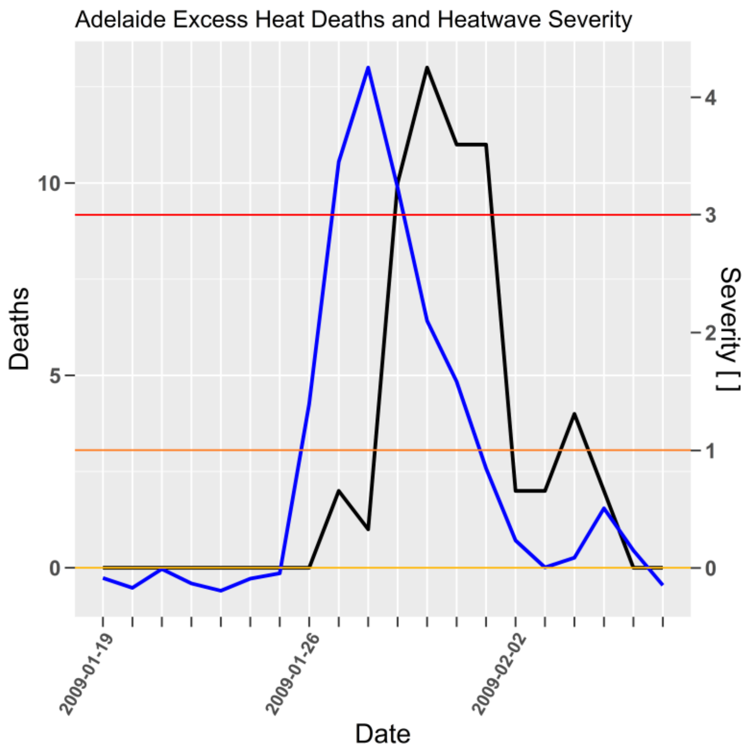


Figure 84. Heat related mortality (black line, left axis) and EHF severity (blue line, right axis) for Adelaide 2009 extreme heatwave [74] (p.21).

Melbourne's extreme peak and load moments range from 2.7 to 6.1 and 3.8 to 15.7 respectively in Table 7. The 2009 event is ranked third for peak (4.9), second for load (14.2) and first for length (12, Supplementary Materials). The mean (1.2, Supplementary Materials) demonstrates the dependence upon load and length.

Table 7. Heatwave event peak and load using severity for Melbourne (1855 to 2018). Top 10 ranked for event peak severity. Severity is dimensionless [ ] .

Heatwave Period	Peak	rank	Load	rank
12 - 17 Jan 2014	6.1	1	15.7	1
18-21 Jan 1875	5.2	2	13.2	4

26 Jan - 6 Feb 2009	4.9	3	14.2	2
15 - 19 Jan 1959	3.7	4	8.4	7
14 - 20 Jan 1908	3.2	5	13.8	3
9 - 13 Jan 1905	3	6	7.5	
22 - 24 Dec 1920	2.9	7	4.7	
9 - 11 Dec 1998	2.8	8	3.8	
29 Jan - 3 Feb 1912	2.7	9	8.3	8
18 - 22 Jan 2006	2.7	10	5.5	

Melbourne time-series for ambulance movements in Figure 85 responded to EHF severity in a similar manner to Adelaide's mortality under the influence of similar HEM values.

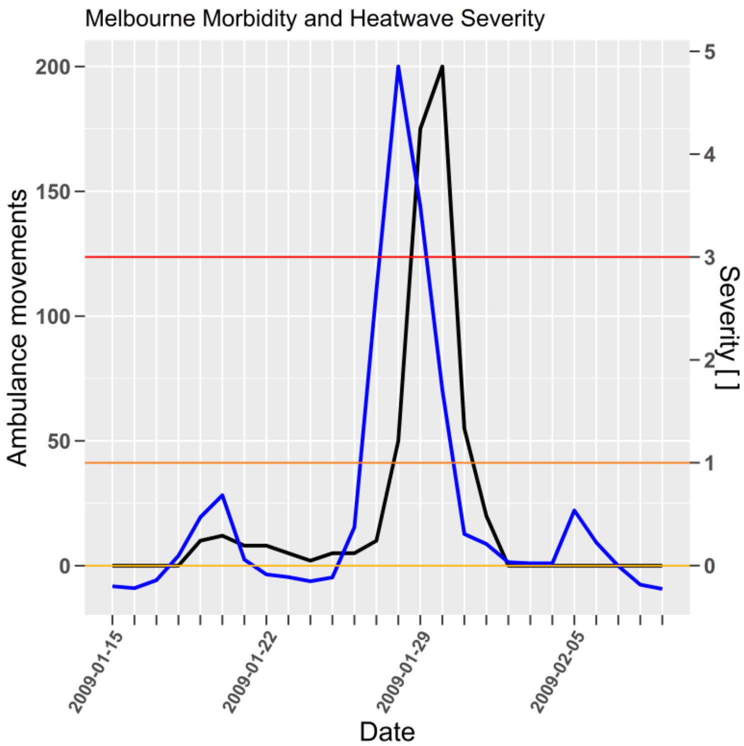


Figure 85. Heat related morbidity (ambulance movements, black line, left axis) and EHF severity (blue line, right axis) for Melbourne 2009 extreme heatwave [74] (p.22).

In this case Adelaide and Melbourne human health impacts are linked strongly to peak and load moments, whilst the time-series shows severity leads impact by two days.

Coates et al. [19] (p. 41) tabulate other occasions when these cities may have been impacted by high impact heatwaves. Listed by State, recorded fatalities as shown in Table 8 have reasonable correlation with the heatwave event moments (HEM).

Table 8. Heat Total Deaths for significant heat events in Australia, 1844-2011 [19] (p. 41) by State or City affected and heatwave event moments for affected city.

Date of event	State or city affected	Total deaths	heatwave event moments(city) Peak, Load, Mean, Length

			[ ], [ ], [ ], days
January-February 1879	NSW, Vic	22	
October 1895-January 1896	WA, SA, Vic, Qld, NSW	435	5.6, 13.0, 2.6 , 5 (Sydney)
January 1906	NSW, SA	28	
January 1908	Vic, SA, NSW	213	3.2, 13.8 ,2.0 ,7 (Melbourne)
January 1939	NSW, Vic, SA	420	2.4, 10.4, 1.5, 7 (Adelaide)
January-February 1959	Melbourne (Vic)	145	3.7 ,8.4, 1.7, 5
January-February 2009	Vic, SA	432	Tables 1 & 2

The spatial attributes of significant continental heatwave events may not affect Australia's coastal capital cities each time a heatwave occurs in that state. Inland exposures are likely however, to have casualties taken to local major cities.

3.2. London heatwave event moments: peak, load and mortality

Hajat et.al. [73] (p.370) heatwave study tabulated increases in deaths from 1976 to 1996. Table 9 includes these increases against HEM ranked by peak moment.

Table 9. Top ten ranked peak [ ] and load [ ] for London (Heathrow Airport, 1921 to 2018). Percentage change in deaths associated with heatwave period [73] (p. 370).

Heatwave Period	%Death	Peak	rank	Load	rank
22 Jun - 13 Jul 1976	30.7	5	1	34.6	1
28 Jul - 5 Aug 1990	16.8 (5.4)	3.5	2	10.2	8
3 - 14 Aug 2003	-	3.1	3	17.4	2
15 - 21 Jun 2017	-	2.5	4	9.4	12
17 - 24 Jun 2005	-	2.5	5	10.1	9
16 - 28 Jul 1989	11	2.4	6	9.9	10
24 Jul - 5 Aug 1995	7.1 to -0.3	2.4	7	9.5	11
5 - 8 Jun 1996	/	2.3	8	4.2	0
26 Jun - 2 Jul 1952	-	2.2	9	7.4	14
3 - 19 Jul 1983	11.3 to 4.5	2.1	10	16.6	3

The heatwaves in 1976 and 1990 are ranked 1 and 2 for peak, and ranked 1 and 8 for load respectively. The event in 1976 which is also shown as a time-series in Figure 86, is substantially more intense than 1990 by all measures; Year (1976 : 1990), %Death (30.7 : 16.8), peak (5 : 3.5), load (34.6 : 10.2) and mean (1.6 : 1.1, Supplementary Materials, see article). Whilst excess mortality data was unavailable for the 1976 heatwave, comparisons between Figure 86, Figure 87 and Figure 88 demonstrates the significance of this event. Only the 1990 event reached severity 3 compared to severity 5 in 1976 (site specific intensity is also shown in Figure 86).

Table 9 indicates 1976 excess mortality would have been about two times larger than the 1990 event, and three times larger than the 1989 and 1983 events. Assuming a consistent exposure/response relationship, peak excess mortality of between 120 and 180 is likely to have occurred with a two to four-day lag to severity in 1976.

The heatwaves in 1983 and 1989 have similar peaks and mortality, although the load (16.6 : 9.9) is substantially higher in 1983. Figure 87 (1) and (2) show the 1983 event persisted longer (17 : 13, Supplementary Materials, see article) with a higher mean (1.0 : 0.8, Supplementary Materials, see article). All of the time-series events in Figure 87 show severity peak leads the mortality peak, usually by between two and four days. In all cases, where the intensity lingers near the severe threshold (1) the mortality lags but appears to oscillate either side of the mean mortality, suggestive of a harvesting mechanism. Where the severity approaches and exceeds 2 there appears to be a strong, lagged pulse in excess mortality. In these cases, the recovery oscillation in mortality as the heatwave weakens does not appear to compensate for the mortality spike. The 1995 event recorded a temporary dip in excess mortality near severity 2, potentially indicative of interventions which were successfully protecting people. This appears to have been unsuccessful in subsequent days with excess mortality reestablishing a slightly delayed response to greater than severity 2.

In

Table 9 the 1996 heatwave is unmatched with mortality data from the Hajat et al. [73] study. The heatwave severity and mortality time-series in Figure 88 once again shows a robust lagged mortality response for a severity moment of 2. It is unknown why the 1996 heatwave was not documented in the Hajat et al. study. However, excess mortality preceding the 1996 heatwave was elevated in a manner that was inconsistent with the 1983, 1989, 1990 and 1995 events. This may be an indicator of a separate adverse health event affecting the population that impacted epidemiological heatwave impact analysis. The response of about 25 excess deaths to severity 1 and about 60 excess deaths to severity 2 and over, holds for all events except 1990 where excess deaths were approximately 5 lower for a higher severity heatwave. This is a remarkably consistent response over a 14 year period whilst the corresponding average daily mortality rate fell from approximately 184 to 168 per day between 1982 and 1997.

For this observational sample (1921 to 2018) there are five other heatwaves that rank in the top 10 London events in

Table 9. Notably, the 2003 event ranks second on load (17.4) and third on peak (3.1). The 2005 and 2017 events exhibit similar moment characteristics. More contemporary heatwaves (Supplementary Materials, see article) in 2006, 2013, 2015 and 2016 have each reached the same peak (1.8) with variable load (13.0, 11.5, 5.0, 5.7). There were two events in 2006 where the second event was more significant (13.0 load) and longer (15, Supplementary Materials, see article).

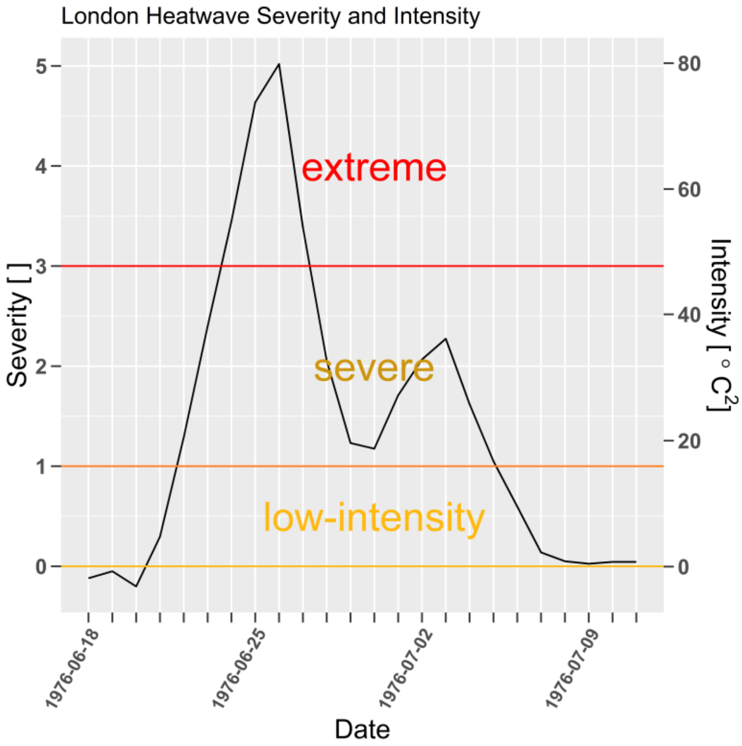


Figure 86. London (Heathrow) EHF severity and intensity for 1976 heatwave, calculated using site data. Dimensionless heatwave severity [ ] and intensity (EHF, [°C^2]) on left and right y-axes respectively.

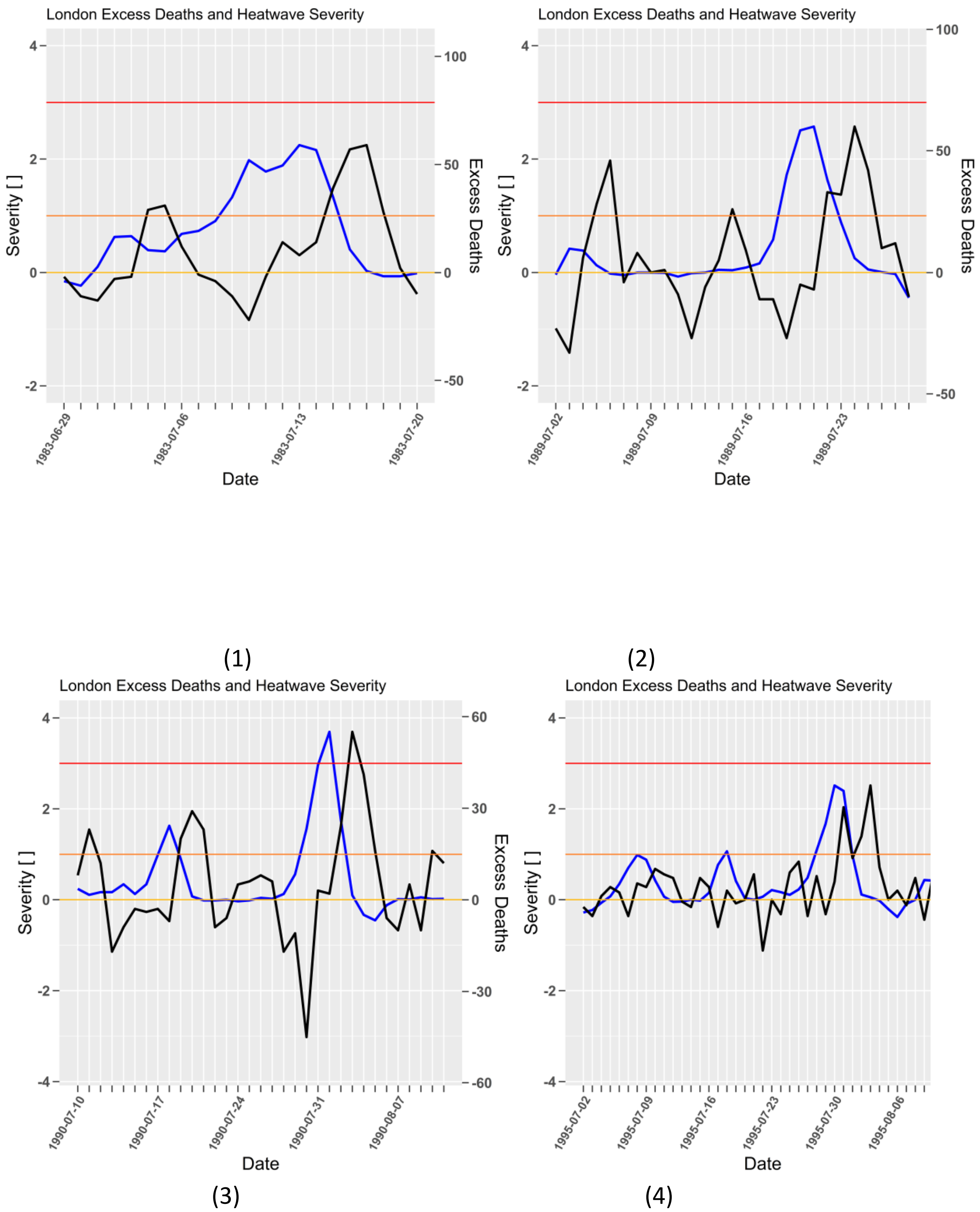


Figure 87. As per Figure 85. London (Heathrow) severity (blue) and mortality (black) for 1983 (1), 1989 (2), 1990 (3) and 1995 (4) heatwaves. Daily excess deaths and severity [dimensionless] on left and right y-axes respectively.

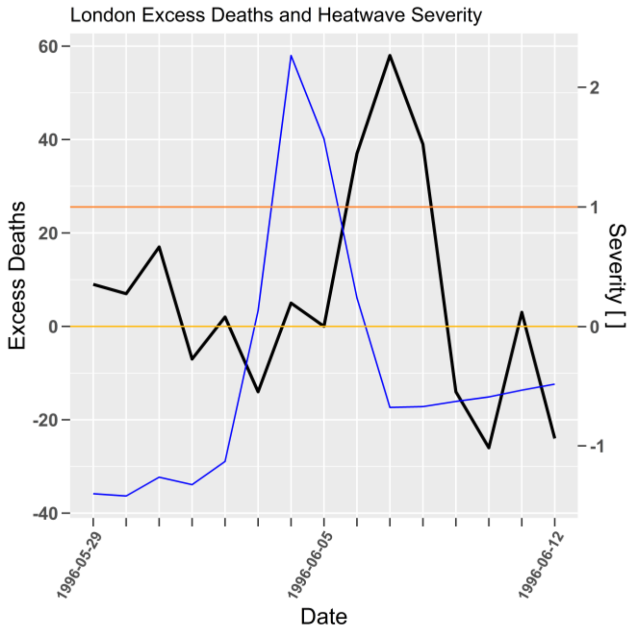


Figure 88. As per Figure 85. London (Heathrow) severity (blue) and mortality (black) for 1996 heatwave. Daily excess deaths and severity [dimensionless] on left and right y-axes respectively.

3.3. Chicago heatwave event moments: peak, load

Chicago's top four heatwaves rank peak and load in the same order (Table 6). The Chicago heatwave of 1995 is well documented as a devastating human health impact event [182]. The 1947 and 2012 events rank higher on both peak and load, however the 1995 length was shorter and returned a higher mean (Supplementary Materials, see article). An investigation into the nature of the 1999 [182] heatwave noted the reduction in heatwave impact was not due solely to meteorological factors. Whilst the 14th ranked 1999 heatwave was still an intense event (

Table 10) the lower peak of 2.2 and load of 5.1 shows it had significantly weaker meteorological heatwave severity moments than the 1995 heatwave.

Table 10. Heatwave event peak and load using severity for Chicago (O'Hare Airport, 1946 to 2018). Top 10 ranked for event peak severity. Rank 14 inserted. Severity is dimensionless [ ] .

Heatwave Period	Peak	rank	Load	rank
2 - 24 Aug 1947	6.1	1	35.3	1
28 Jun - 8 Jul 2012	4.1	2	16.9	2
11 - 17 Jul 1995	3.7	3	11.9	3
19 - 22 Jun 1988	2.7	4	6.4	4
3 - 7 Jul 1977	2.7	5	6.8	10
29 Jun - 2 Jul 1970	2.6	6	5.7	
28 Jul - 5 Aug 1988	2.6	7	9.3	4
14 - 19 Jun 1994	2.6	8	8.2	
25 Jul - 3 Aug 2006	2.4	9	8.3	7
22 - 26 Jun 2009	2.4	10	6	
2-6 Jul 1999	2.2	14	5.1	

The morbidity response for intensive care unit admissions shown in Figure 89 appears to be highly sensitive to severity due to the one-day lag. Mortality lag however, is consistent with prior examples at three to four-days. The three-day lag for excess all-cause, heat related and heat attributed deaths are coincident and show magnitudes consistent with each measure of mortality.

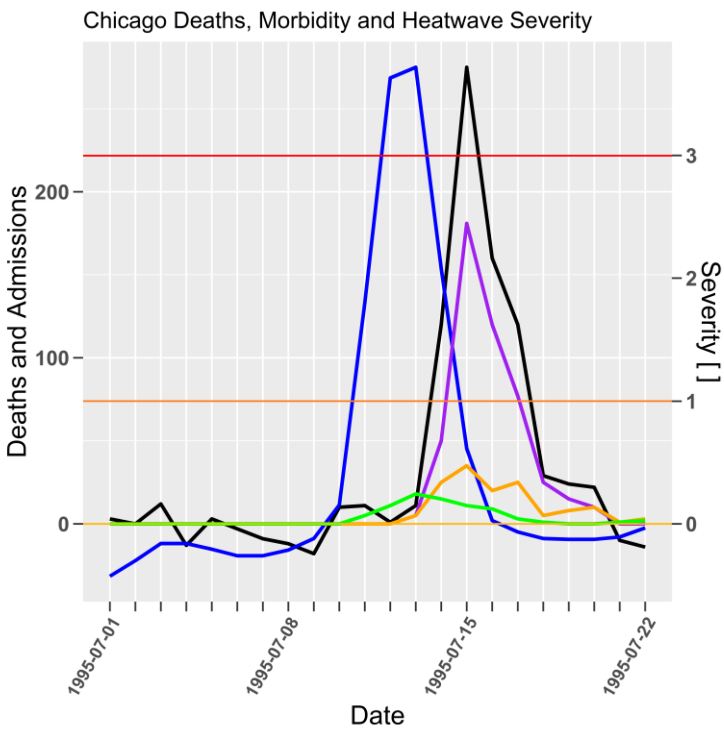


Figure 89. Chicago severity (blue), excess all cause deaths (black, Whitman et al.[177](p. 1517, Figure 2)), heat related mortality (purple, Whitman et al.[177](p. 1517, Figure 2)), heat deaths (gold, Kaiser et al.[178] (p.S159, Figure 1)), and intensive care admissions (green, Dematte et al.[179] (p.174, Figure 1)) for 1995 heatwave. Daily deaths and admissions, and severity [ ] on left and right y-axes respectively.

3.4. Paris heatwave event moments: peak, load

The top three Paris heatwaves (2003, 1976 and 1948) in Table 7 have similar moments (peak, 3.5 : 3.4 : 3.3, mean, 1.7 : 2.0 : 1.7, Supplementary Materials, see article), apart from the significantly lower load (31.2 : 35.2 : 11.9) in the 1948 event. The two top ranked heatwaves in 2003 and 1976 resulted in excess mortality across France of 15,000 and 6,000 people respectively [183]. The difference in excess mortality for these two events can be attributed to changes in the vulnerability profile of the population or magnitude of the heatwave outside of Paris. Spatial analysis using gridded heatwave data would permit an accurate assessment of the change in vulnerability.

A heatwave study which modelled the expected mortality from the 2006 heatwave found an impact reduction attributed to improved intervention measures [183]. The 2006 peak (1.5), length and mean (30 : 0.5, Supplementary Materials, see article) moments in Table 11 do not rank highly, although the load (15) ranks well (5). Any severity peak > 1 is considered to be a threat to vulnerable people and load was notable over the course of a lengthy heatwave. Each of these heatwave event moments may also assist in the assessment mortality model performance and assist in development of improved intervention measures.

Table 11. Heatwave event peak and load using severity for Paris (Orly Airport, 1921 to 2018). Top 10 ranked for event peak severity. 27th rank inserted. Severity is dimensionless [ ] .

Heatwave Period	Peak	rank	Load	rank
1 - 18 Aug 2003	3.5	1	31.2	2
22 Jun - 9 Jul 1976	3.4	2	35.2	1
26 Jul - 1 Aug 1948	3.3	3	11.9	9
27 Jul - 5 Aug 1990	3	4	11.5	11
22 - 30 Jul 1947	2.8	5	15.8	3
11 - 30 Apr 1921	2.8	6	15.4	4
25 - 28 Jun 1947	2.8	7	5.8	0
26 Jun - 6 Jul 2015	2.8	8	11.2	0
29 Jun - 7 Jul 1957	2.7	9	12.4	0
5 - 15 Jul 1923	2.7	10	11.6	10
8-28 Jul 2006	1.5	27	15.0	5

The 2003 heatwave excess mortality lag in Figure 90 is unusual when compared to prior examples for Adelaide, London and Chicago in that the growth in excess mortality is lagged by several days, yet falls with a familiar three-day lag. The delayed lag in this instance could be attributed to the effect of sustained low-intensity heatwaves beginning in late May 2003, and a brief severe heatwave during July, shown in Figure 91. Some improved adaptation measures may have developed during sustained pre-cursor low-intensity heatwaves until vulnerable people were overwhelmed by the prolonged extreme event. It is also difficult to compare excess mortality across France against a single station (Orly) as heatwave severity is unlikely to have evolved uniformly across the entire country.

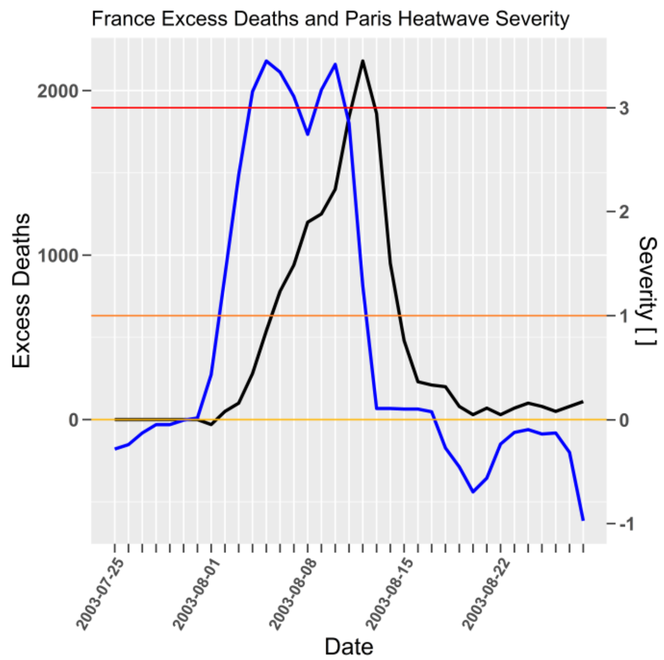


Figure 90. Paris severity (blue) and France excess mortality (black) for 2003 heatwave. Daily excess deaths (Poumadère et al. [180](p.1486, Figure 1)) and severity [ ] on left and right y-axes respectively.

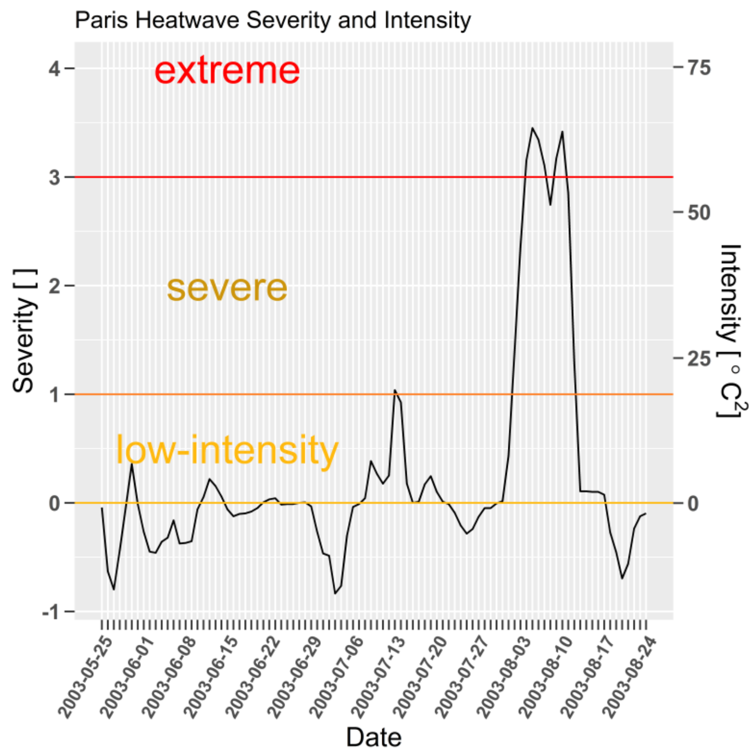


Figure 91. Paris (Orly) EHF severity and intensity for 2003 spring and summer, calculated using site data. Dimensionless heatwave severity [ ] and intensity (EHF, [°C^2]) on left and right y-axes respectively.

3. 5. Moscow heatwave event moments: peak, load

A 2010 European heatwave resulted in 55,000 deaths across Russia [12]. Whilst the 2010 peak (2.2,

Table 12) reached above the severe threshold (1) it was not extreme, and ranked 8 in the climate record. However, the load (46.5) is the highest found amongst the cities investigated in this study (

Table 5). Virstu in Estonia (Supplementary Materials, see article) recorded peak and load moments of 4.5, and 37.8 for this event, showing that Moscow was not the spatial locus for the extreme peak exposure.

The higher peaks (>3) recorded in 1958, 1996, 1998 and 2007 correlate with values where other cities have recorded high impact. Searches have not produced evidence of high impact for these events.

Table 12. Heatwave event peak and load using severity for Moscow (1948 to 2018). Top 10 ranked for event peak severity. Severity is dimensionless [ ] .

Heatwave Period	Peak	rank	Load	rank
26 - 31 May 2007	4.3	1	16.1	4
7 - 14 Jul 1996	4.3	2	13.9	6
8 - 21 Jun 1998	3.7	3	20.5	2
25 - 29 May 1958	3.1	4	8.9	0
4 - 8 Jun 1988	2.6	5	6.1	0
9 - 18 Jul 1951	2.5	6	11.6	0
24 Jun - 3 Jul 1991	2.4	7	9.4	0
1 Jul - 18 Aug 2010	2.2	8	46.5	1
3 - 15 Jul 1954	2.1	9	10.5	0
16 - 20 Jul 1970	2	10	6.3	0

3.6. Guangzhou heatwave event moments: peak, load

A central feature of Guangzhou's top ranked heatwave severity is the lack of pre-21st century heatwaves in the top 20 (top 10 shown in

Table 13). Whilst the 2005 heatwave ranked first on peak (5.5) moment, a recent 2018 event top ranked load (27.0). The recent development of more intense heatwaves supports observation of increased minimum temperatures compounding the intensity of heatwaves for southeast China [171].

Table 13. Heatwave event peak and load using severity for Guangzhou (1945 to 2018). Top 10 ranked for event peak severity. Severity is dimensionless [ ] .

Heatwave Period	**Peak**	**rank**	**Load**	**rank**
12 - 21 Jul 2005	5.5	1	20.4	2
26 Jul - 1 Aug 2017	5.2	2	18.1	5
26 Jun - 3 Jul 2004	4.4	3	16.1	6
23 - 30 Jul 2008	4	4	18.1	4
17 - 31 May 2018	3.5	5	27	1
13 - 17 Jun 2014	3	6	6.9	15
31 May - 2 Jun 2014	2.8	7	3.6	0
7 - 9 Jul 2016	2.8	8	5.2	0
1 - 14 Jul 2010	2.7	9	20.2	3
31 May - 2 Jun 2016	2.6	10	5	0

The 2005 heatwave top ranked peak (5.5) and second ranked load (20.4). The time-series for excess mortality and severity in Figure 92 shows there is a noisier lag relationship between excess mortality and severity on this occasion. Excess mortality reaches a peak of 8 people on 8 July 2005 corresponding to severity >5. Whilst there appears to be a lack of power arising from the number of persons reported it is apparent that a one to two-day lag is present.

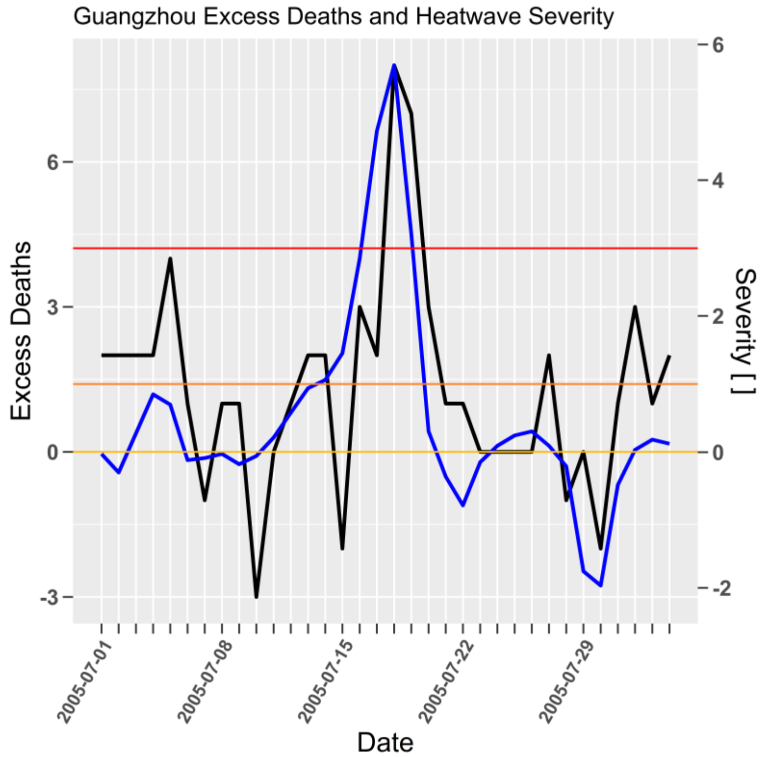


Figure 92. Guangzhou severity (blue) and excess mortality (black) for 2005 heatwave. Daily excess deaths (Jun Yang et al.[181] (p. 650, Figure 1)) and severity [ ] on left and right y-axes respectively.

4. Discussion

EHF severity heatwave event moments (moments) of peak and load have been used to examine significant historical heatwaves. Ranking of these moments has placed these events in context with other significant exposure events.

The 1947 Chicago heatwave eclipsed the 1995 event (peak, 6.1 : 3.7 and load, 35.3 : 11.9). Changes in health record management and/or community resilience may have produced an impact record in 1947 less significant than the 1995 record. There are many examples in section 3 and in the Supplementary Materials (see article) where top ranking heatwave severity events have occurred before high-quality impact records commenced, highlighting the random nature of extreme events and the limits of quality impact records.

Spatial coherence of heatwaves is also revealed. The 2010 Russian heatwave might more correctly be called the 2010 Central European heatwave. Whilst Moscow top ranked load (46.5) moment for all events ranked in this study, Virstu, Berlin, Stockholm, Rome, Dresden, Nice and Ogulin all recorded higher peak moments (2.5-4.5, Supplementary Materials, see article) compared to Moscow (2.2). This is a significant consideration following the time-series results for Adelaide, Melbourne, Heathrow, Chicago, Paris and Guangzhou, where severity peaks greater than 2 have been shown to lead robust mortality and morbidity response.

Location and spread of heatwave impacts is also a significant phenomenon that will be addressed in following studies that will utilise gridded EHF data sets. A recent study into the impact of the 2015 European heatwave used EHF intensity moments to match and correctly rank heatwave exposure to health impact records in the Czech Republic [173]. Unable to access Czech temperature data for this study, analysis of nearby sites revealed that in 2015 Dresden recorded its top ranked peak and load heatwave event moments (4, 11.8, Supplementary Materials, see article), with Munich, Berlin, Paris, Nice, Madrid and Ogulin recording significant peak moments (2.3-3.0, Supplementary Materials, see article). It would seem likely that many more excess deaths would have occurred outside the Czech Republic.

For some of the cities investigated in this study comparison of severity heatwave event moment impacts is not feasible due to the absence or variable nature of the impact data available. However, Adelaide, London, Chicago and Guangzhou impacts are comparable assuming city domain impact data. Chicago 1995 excess deaths peaked at 275 persons for a severity peak of nearly 4. London excess death peaks ranged between 55 and 60 persons for severity peaks between 2 and 3, Adelaide excess deaths reached a peak of 13 persons for a corresponding severity peak over 4 whilst Guangzhou excess deaths peaked at 8 persons for a severity peak of nearly 6. There is little doubt that the 1995 Chicago event was a catastrophic impact event, which has been documented for societal compounding factors [184]. The stability of London impacts demonstrates an inherently more vulnerable and exposed environment when compared to Adelaide and Guangzhou. This is reinforced by comparison of the London 1976 and Guangzhou 2005 heatwaves where a peak severity of 5 in London resulted in a 30.7% increase in mortality whilst a peak severity of 6 in Guangzhou produced a 22% increase. Guangzhou appears to be more resilient than London to heatwaves. This result may be affected by under reporting of mortality given comparable populations and significantly different average mortality rates of these two cities.

Heatwave intensity and severity are repeatedly demonstrated as lead indicators for impact in the time series figures (Figure 84, Figure 85, Figure 87, Figure 88, Figure 89, Figure 90 and Figure 92). Low-intensity heatwaves were associated with oscillating impacts that appeared to be consistent with a harvesting response, where initial rises in severity were followed by modest rises in impact, which then recovered below the long term mean mortality. This pattern was disrupted once the severity rose sharply to greater levels. At severity levels > 2 there was little evidence of a compensating impact recovery below the long-term average mortality. Future epidemiological studies could consider whether a study period might be partitioned according to heatwave severity. This would reduce the statistical power for the extreme events given that they occur so rarely, but is consistent with the study of impacts arising from climate extremes.

Readers are encouraged to use the Supplementary Materials spreadsheet and query the data (see article). Note: start and finish dates are numbered from 1 July for Australian, and 1 January for northern hemisphere stations.

5. Conclusions

The concept of heatwave event moments (HEM) has been introduced to improve the lexicon available to policy makers and responders. Until recently the wider community in Australia has relied upon heatwave length as a suitable measure for heatwave impact. Event severity peak and load have been shown to be superior indicators of impact.

The historical perspective of heatwave impact has been demonstrated by ranking severity peak and load. Heatwave severity moments have correctly ranked human health impact, especially when mortality was used as a health outcome. It is reasonable for policy makers to plan and implement mitigation measures in anticipation of predictable future heatwave severity impact.

Converting heatwave intensity into a dimensionless severity index permits comparison of impact scales between locations around the world. Common impact messages are readily constructed and communicated when good adaptive strategies are assumed for frequently occurring low-intensity heatwaves, whilst rarer more intense heatwaves have severe consequences for vulnerable people and even rarer and much more intense heatwaves produce extreme impacts if protective action is not undertaken. This work has demonstrated rising severity as a good lead indicator for increased human health impact. In the cases examined there is a noticeable shift in mortality mode as heatwaves become more intense. Lower severity is a good lead indicator, although the impact mortality response oscillates around the mean death rate, suggestive of harvesting cycles.

The ability to correctly scale impact events by ranked severity provides the community, response agencies, media and policy makers with a common interpretive tool. Their experience of impact is validated and supported by the severity scale.

Heatwave event moments are common tools for historical and projection climate data that contextualize future scenarios against the lessons of the past. It is equally important that the same tools are visualized in seasonal and multi-week forecasts. The probabilistic nature of these products is helpful in preparing an appropriate mitigation strategy, particularly where likely exposure and impacts are well documented. Finally, when the same tools are used for short term forecasts and warnings, appropriate response levels can be initiated based upon a common language which has been in use across all spatial and temporal scales.

The statistical stability of EHF_{85} has resulted in the application of heatwave severity on a continental scale for Australia's 7-day heatwave service, evaluation within global 7-day probability severity maps in Australia, the UK and the US, and the creation of climate projection scenarios for the Copernicus project. The ongoing utility of these forecast trials is predicated on the effectiveness of EHF severity as a global impact metric.

The results presented in this paper support current national and international service developments based on peak severity heatwave event moment. There is some evidence that the severity load heatwave event moment may be required within an operational heatwave service, particularly for longer events.

Future research will focus on spatial climate records to further develop EHF severity climatic regimes and trends. Additional health outcomes indicators such as ambulance call outs, emergency department visits and hospitalisations will also be included in future assessments.

These analyses will underpin interpretation of global EHF severity climate projection data generated for all impacted sectors, most notably health.

Patents

No patents

Supplementary Materials: The following are available online at [IJERPH | Free Full-Text | Performance of Excess Heat Factor Severity as a Global Heatwave Health Impact Index (mdpi.com)].

Author Contributions: Conceptualization, J. Nairn and B. Ostendorf.; Methodology, J. Nairn.; Software, Coded in R, B. Ostendorf, J. Nairn; Validation, J. Nairn, B. Ostendorf and P. Bi.; Formal Analysis, J. Nairn.; Investigation, J. Nairn.; Resources, J. Nairn and B. Ostendorf.; Data Curation, J. Nairn.; Writing-Original Draft Preparation, J. Nairn.; Writing-Review & Editing, A. Moise, B. Ostendorf and P. Bi.; Visualization, J. Nairn.; Supervision, B. Ostendorf and P. Bi.; Project Administration, NA; Funding Acquisition, NA.

Funding: This research received no external funding

Acknowledgments: Christophe Sarran, UK Met Office. MEDMI daily mortality for England and Wales.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

1A. Heatwave Intensity

The excess heat factor (*EHF*)[56] has been developed as a measure of heatwave intensity. The formulation of *EHF* is a factorisation of two excess daily heat indices which measure:

- heat in excess of the local climatic heatwave threshold and
- heat in excess of the recent experience of heat.

These long and short-term temperature anomalies are described as the Excess Heat Index EHI_{sig} for a significant heat event and the Excess Heat Index EHI_{accl} for a heat event requiring an adaption or acclimatisation response. These anomalies are estimated as

$$EHI_{sig} = DMT_{3-day} - DMT_{95} \quad (1A)$$

$$EHI_{accl} = DMT_{3-day} - DMT_{30-day} \quad (2A)$$

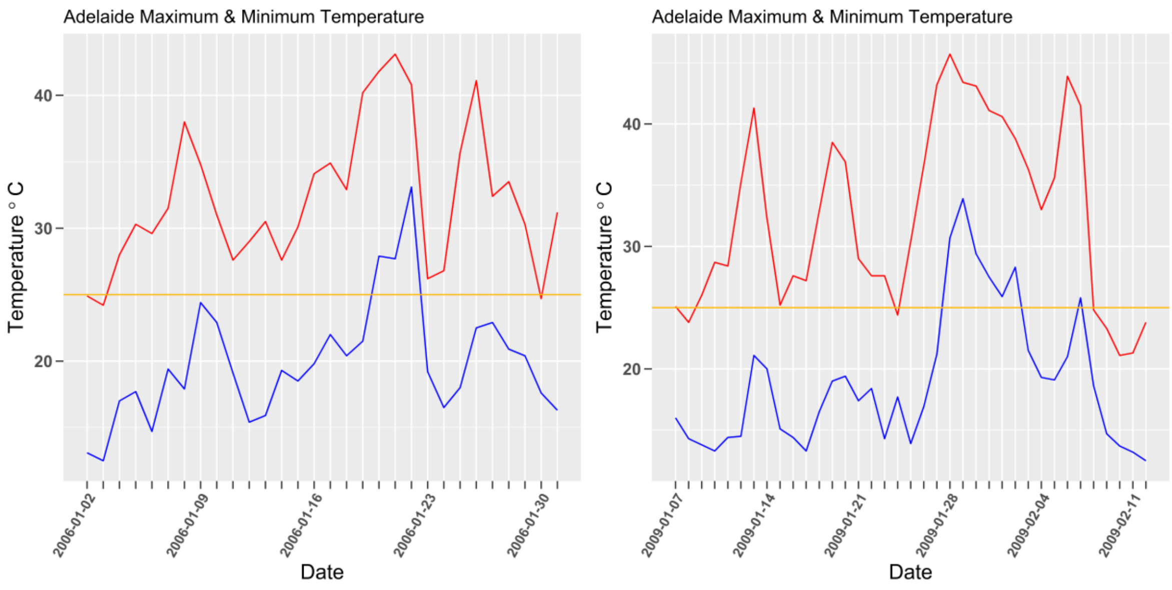
with $DMT_{3\text{-}day}$ denoting the average daily temperature of the next (or t, t+1, t+2) 3 day period, DMT_{95} the percentile of daily temperatures for the 30 year reference period between 1971-2000, and $DMT_{30\text{-}day}$ the average daily temperature of the previous 30 day period, respectively.

During a heatwave, minimum temperature significantly affects the diurnal cycle of heating. High minimum temperature will result in earlier and longer sustained high temperatures with stronger heat accumulation within the diurnal heating cycle. Consequently, the average of maximum and minimum temperatures over three days, or daily mean temperature (*DMT*), is used in these heat anomaly calculations.

Minimum and maximum temperatures are displayed in Figure 93A, (1) and (2), for Adelaide heatwaves in 2006 and 2009, demonstrates the rational for using *DMT*. A reference temperature of 25°C in these figures demonstrates the different capacity for heat to be discharged overnight. By the 8th and 9th of January 2006 the minimum has risen close to 25°C whilst the maximums are much higher in the high 30's. There is little capacity for the heat of the day to be discharged at night with a high minimum temperature. Consequently, this heat is accumulated with an additional heat impost the following day. Heat won't be accumulated whilst the area between the red and yellow lines (maximum temperatures and 25°C) is balanced by the area below the yellow to the blue line (25°C and minimum temperatures). Excess is clearly a problem by 20 January once the minimum temperature has risen above 25°C, where there is no capacity to discharge heat.

In 2009 daily accumulations of heat are being discharged until late January, when suddenly much higher maximum and minimum temperatures commence at the same time. The much higher maximum and minimum temperatures resulted in greater excess heat producing a more intense heatwave.

The use of daily temperature (average of maximum and minimum temperatures) accommodates the concept of heat discharge.



(1) (2)

Figure 93A. Daily maximum and minimum temperatures for Adelaide heatwaves in 2006 (1) and 2009 (2). 25°C reference temperature (yellow line).

Reference periods used for calculating Adelaide's excess temperature anomalies are presented in Figure 94A and Figure 95A. The climatological distribution of daily temperature (*DMT*) for the period 1971 to 2000 is shown in Figure 94A, which illustrates the positive tail in the distribution representing all heatwave events.

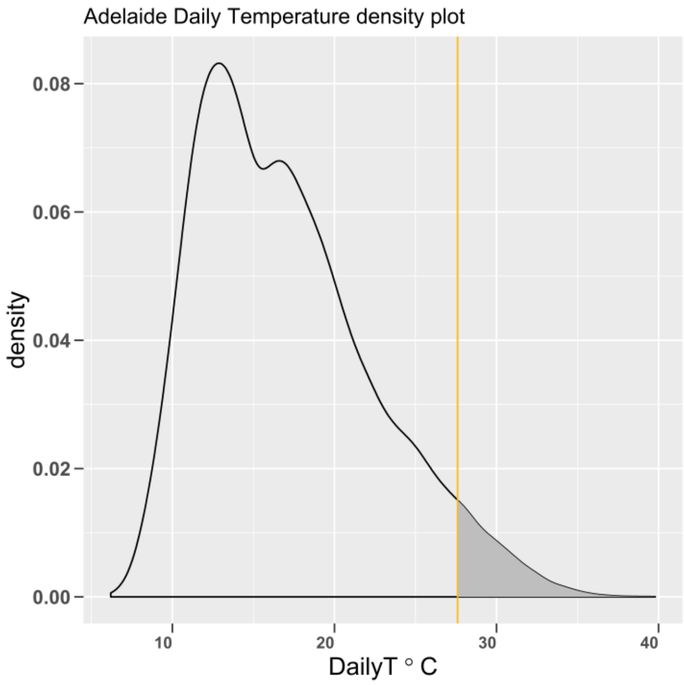


Figure 94A. Distribution function of daily temperature for all days in 1971 to 2000 climate reference period. Grey shade shows 95th percentile tail for all heatwaves present for this reference period.

Unlike the single-day, daily temperature reference period shown above, the 30-day reference period for the short-term temperature anomaly is highly subjective to the weather events occurring over that period. The climatological distribution of the acclimatisation heat index utilises 30-day running mean daily temperatures is shown in Figure 95A illustrates the sample population for the multi-week, weather determined short-term heat anomaly.

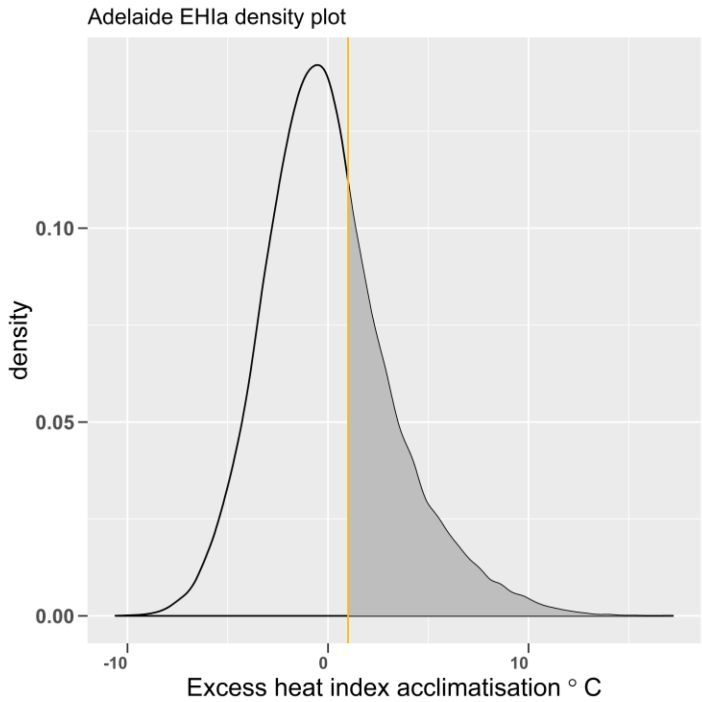


Figure 95A. Distribution function of EHIaccl for 1960 to 2018 climate period. Shaded region >1 shows acclimatisation distribution samples when calculating EHF.

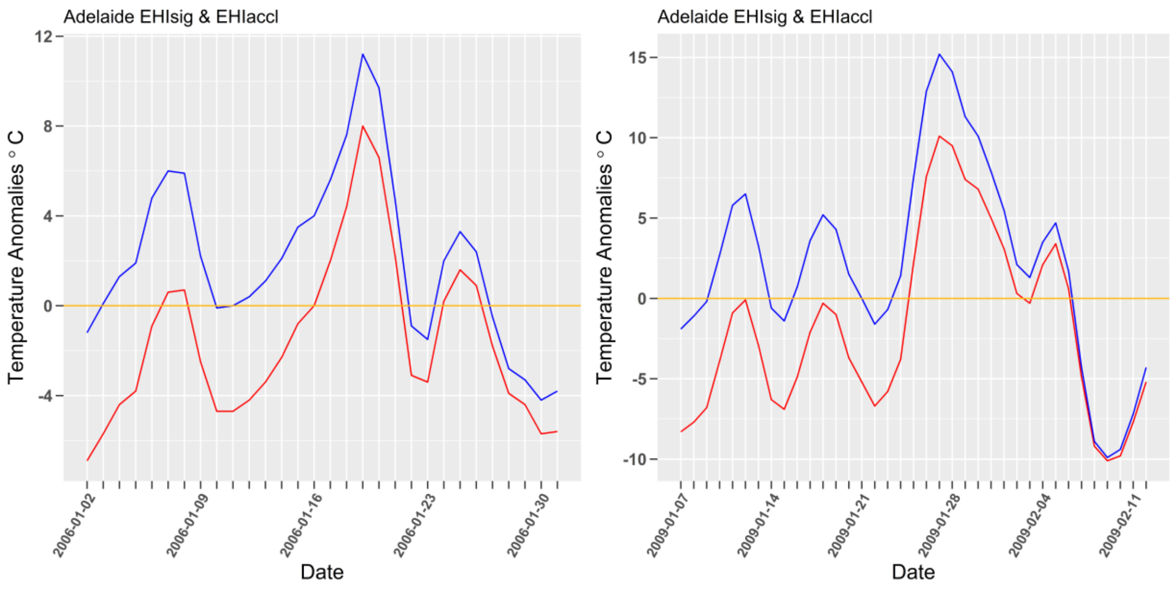
Calculation of heatwave intensity (*EHF*) is designed to treat the acclimatisation index as an amplifying factor which does not reduce the significance of climate threshold excess heat;

$$EHF = EHI_{sig} \cdot \max[1, EHI_{accl}] \quad (3A)$$

The shaded region in Figure 95A shows the distribution of warm acclimatisation events that are > 1. Only a sub-sample of this population subset is related to heatwaves, noting that positive 30-day anomalies can occur at any time during the year.

Adelaide heatwave examples are shown in Figure 96A, (1) and (2), demonstrating the evolution of the EHI_{sig} and EHI_{accl} indices in 2006 and 2009.

The long and short-term temperature anomalies in 2006 show three heatwave events. EHI_{sig} became positive for a short period in early January, with a more significant positive anomaly in both EHI_{sig} and EHI_{accl} lasting for a longer period. Finally, a smaller event, more significant than the first developed briefing after the major heatwave.



(1) (2)

Figure 96A. Acclimatisation (blue) and significance (red) Excess Heat Indices for Adelaide's 2006 (1) and 2009 (2) heatwaves, calculated using site data.

On two occasions during the first half of January 2009 *EHIsig* nearly became positive, so not heatwaves. This was followed by very large long and short-term temperature anomalies (up to 10°C larger than those observed in 2006) resulting in an extreme heatwave that lasted for two weeks.

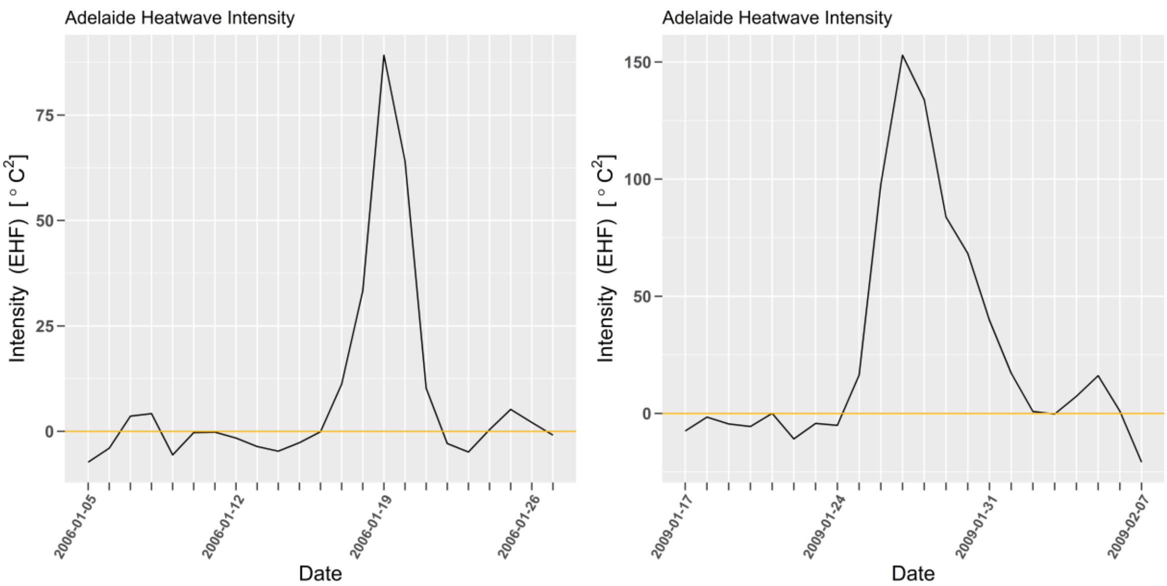
The same Adelaide heatwaves are shown again in Figure 97A, (1) and (2), showing heatwave intensity (Excess Heat Factor).

In 2006 the intensity of the early heatwave is quite small compared to the event in the second half of January. The peak *EHF* value of 67°C^2 is the combination of the peak *EHI* values shown in Figure 96A. When multiplied, large EHI_{sig} and EHI_{accl} values will produce very large *EHF* values, indicating a very intense heatwave. Conversely, smaller EHI_s will produce much smaller *EHF* values, indicative of low-intensity heatwaves.

The third 2006 heatwave shown in Figure 97A(1) is of similar intensity to the first event in early January, despite the higher temperature anomalies observed in Figure 93A(1). This is a consequence of reduced acclimatisation due to the immediately preceding intense heatwave, which can be seen in Figure 96A(1). It is notable that the context in which the high temperature event occurs will determine the intensity of the heatwave. The early January heatwave had low EHI_{sig} but higher EHI_{accl}. Figure 93A(1) shows the lower maximum and minimum temperatures at the start of the month which contributed to the higher short-term temperature anomaly once the heatwave started. The factored *EHI*s for the third event produced the same heatwave intensity, despite the higher temperatures observed. Acclimatisation (or adaptation) can either amplify or dampen the derived heatwave intensity.

In 2009 an extremely intense heatwave is shown in Figure 97A(1). In Figure 93A(2) lower maximum and minimum temperatures abruptly shift into much higher values. This is evident in Figure 96A(2) where EHI_{sig} and EHI_{accl} both change abruptly. The large change in acclimatisation due to the much milder preceding conditions has resulted in significant amplification of the heatwave intensity signal. As seen in the 2006 example, the multiplication of two larger indices has resulted in a significant intensity signal.

EHF measures heatwave intensity, sensitive to the recent past (acclimatisation/adaptation) and the local climate. *EHF* is location specific. The 95th percentile of daily temperature for the 1971 to 2000 climate reference period is specific to each location, and cannot be related to any other location's climate. This is an obstacle to comparing heatwave intensity values between locations.



(1) (2)

Figure 97A. Excess Heat Factor for Adelaide's 2006 (1) and 2009 (2) heatwaves, calculated using site data.

2.A. Heatwave Severity

The strong signal to noise provided by factoring two temperature anomalies provides another heatwave measurement opportunity. As a quadratic calculation [°C^2], positive *EHF* obeys a power law. The population of *EHF* shown in Figure 98A, shows the distribution of positive and negative *EHF* values. Only *EHF* values >0 (shown in yellow) are heatwaves. The power law attributes of positive *EHF* are exhibited by the heavy tail distribution (shaded yellow) of heatwaves in this figure.

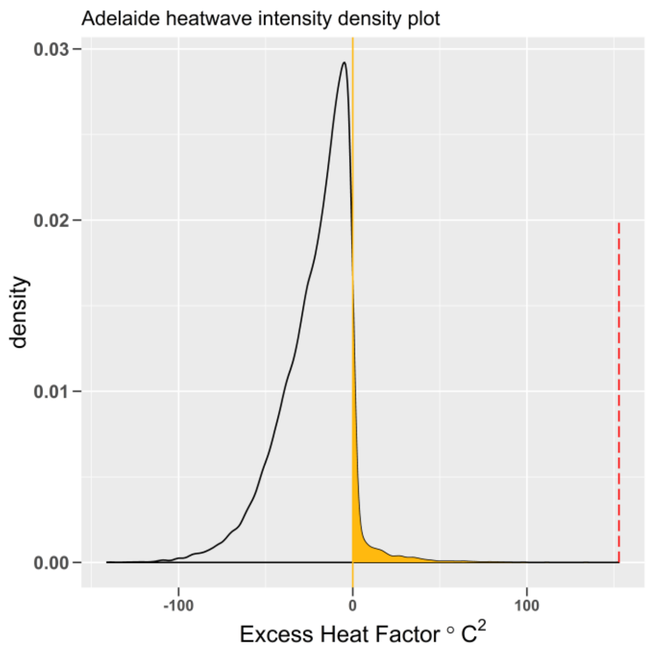


Figure 98A. Distribution function of EHF for period 1887 to 2018. Values greater than zero shown in yellow are heatwaves. Maximum EHF value in distribution is indicated by dashed red line.

A strategy to normalise heatwave intensity has been employed, allowing direct comparison of heatwave severity, irrespective of event location.

Following Nairn and Fawcett [56], the cumulative density function of positive *EHF* (Figure 99A) was demonstrated to exhibit the characteristics of a Generalised Pareto Distribution function which is suited to power function (heavy tail) distributions. It is useful to observe how the heatwave intensity (*EHF*) distribution changes in Figure 99A. Low-intensity heatwaves constitute most of the heatwaves observed. In Figure 99A the 85th percentile has been highlighted with a dashed yellow line. Most, (85%) of all heatwaves are low-intensity. For the latter part of the distribution heatwave intensity rapidly becomes more intense. The transition from frequently observed, low-intensity to increasingly rare and more intense heatwaves has been identified as a transition point for population adaptation limits.

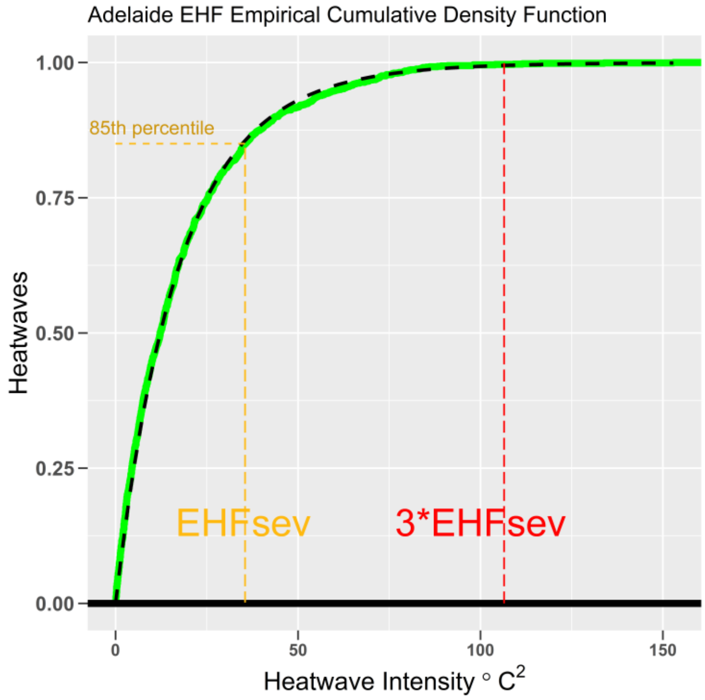


Figure 99A. Adelaide empirical cumulative distribution of positive EHF (green line), overlain with the modelled generalised Pareto distribution (black dashes), and showing the 85th percentile (transition point) for determining the severe EHF threshold (dashed yellow lines). Extreme EHF threshold is shown in red (dashed red lines).

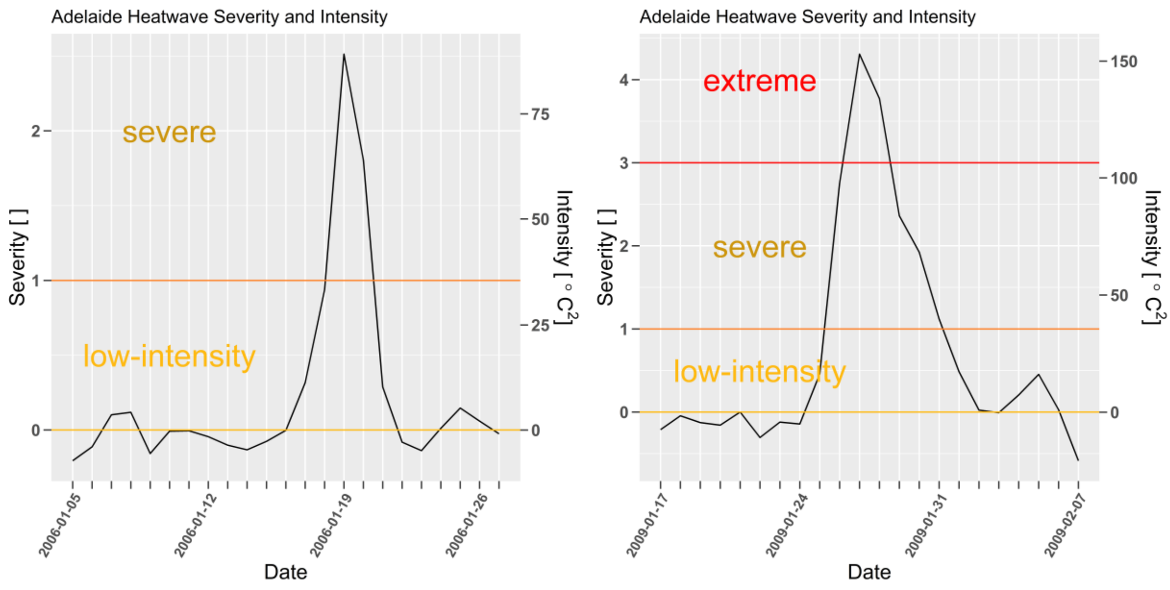
We appealed to the usefulness of the Pareto Principle [140] when considering the proximity of this transition point to the 80th percentile of the distribution function. Juran [185] observed the "vital few and trivial many", a principle that approximately 20 percent of something are responsible for 80 percent of the results, which became known as Pareto's Principle or the 80/20 Rule. In this application, the 85th percentile was selected as a threshold for heatwave severity as a transition point between low-intensity and severe heatwaves. Note the near perfect correspondence between empirical and modelled cumulative density in Figure 99A.

A climatological record of heatwave intensity (30 years or greater) provides a stable 85th percentile *EHF* value (EHF_{85}) which can then be used to normalise heatwave intensity into what has been called heatwave severity categories. A severity quantity of 1 at any location can be interpreted as the last 15% of the cumulative distribution heatwave days.

$$Severity = EHF \div EHF_{85} \quad (4A)$$

Each location has a distribution of heatwave intensity that is determined by the climatological temperature range, which in turn is characterised by its own unique value of EHF_{85}. For Adelaide, these dimensionless severity categories have been shown in Figure 100A, (1) and (2), reaching category 2 in 2006 and over 4 in 2009.

Comparing heatwave intensity at a location can be achieved through analysis of heatwave intensity or severity. However, heatwaves can only be compared between locations by utilising dimensionless severity categories.



(1) (2)

Figure 100A. Excess Heat Factor for Adelaide's 2006 (1) and 2009 (2) heatwaves, calculated using site data. Dimensionless heatwave severity [ ] and intensity (EHF, [°C^2]) on left and right y-axes respectively.

Summary

Daily temperature has been adopted as a means of calculating heat accumulation. High minimum temperature adjusts the rate at which high temperatures are achieved in the following diurnal cycle, and restrict the capacity for heat discharge from the previous heating cycle. In this context minimum temperature is more important than the maximum temperature in the estimation of heat accumulation.

Minimum temperature is also affected in the presence of a humid atmosphere. Water vapour is a very strong greenhouse gas, restricting the rate at which infrared radiation can escape to space, leading to higher minimum temperatures. In this heatwave intensity calculation, the resultant higher heatwave intensity incorporates the physical presence of humidity.

The use of maximum and minimum temperature data has another advantage. These parameters are available in long climate records, and are the highest quality meteorological parameters available to the community on time scales that range across climate, 7-day, multi-week, seasonal and projection forecasts. The use of a single statistically stable index across these time scales provides for forecast and warning services that are consistent with historical context and planning guidance for policy makers.

The *EHF* intensity index can be thought of in SI units as [$°C^2{}_L$]. The subscript $_L$ has not previously been documented and is used to identify *EHF* intensity is specific to the climatology for each location where it is calculated. The stable heavy tail in the *EHF* density distribution function (Figure 98A) generated by the quadratic formulation of *EHF* obeys a power law for positive *EHF*. Within this population EHF_{85} can be objectively determined with the same units as *EHF* at each location, [$°C^2{}_L$]. As a consequence, the calculation of heatwave Severity, shown in equation 4A, is dimensionless, removing location dependency.

Dimensionless *EHF* severity is used to sensibly map heatwaves. Heatwaves may span different climatological regions and be interpreted through severity. It is notable that severity maps have been in public use in Australia since 2014. The same map of severity is used in the tropics, sub tropics and mid-latitudes. Notably, regions that are normally humid during heatwaves are sensibly mapped using severity maps.

The creation of a dimensionless heatwave severity index allows the comparison of heatwaves irrespective of location. Historical, current or forecast events can be compared to consider the scale of the physical, sensible heat impost. Impacts across infrastructure, utilities, human health, and social assets are exposed and their response measured.

Extended abstract presented at 2019 AFAC Conference. [141]

Title:

Paper 6: **South Australian heatwave forecasts and warnings performance and some impacts during January 2019, Australia's hottest month on record.**

Authors: John Nairn[1,7], Chris Beattie[2], Sara Pulford[2], Robert Fawcett[3], Paddy Phillips[4], Neil Langlois[5,7], Jai O'Toole[6], Bertram Ostendorf[7], Dorothy Turner[7], Peng Bi[7], Evan Morgan[3]

1. Bureau of Meteorology, Adelaide, South Australia, Australia
2. State Emergency Service, Adelaide, South Australia, Australia
3. Bureau of Meteorology, Melbourne, Victoria, Australia
4. Department for Health and Wellbeing, South Australia, Australia
5. Forensic Science SA, South Australia
6. Australian Red Cross, Adelaide, South Australia
7. University of Adelaide, Adelaide, South Australia, Australia

Abstract

The 2018-19 summer leapt into life in late November when Queensland experienced an extraordinary outbreak of extreme fire behaviour, with unusually hot, dry and windy conditions, which coincided with an extreme heatwave on Queensland's wet tropical east coast. The multi-year drought throughout most of Queensland and New South Wales, lack of Southern Ocean fronts and delay in the northern monsoon rains each contributed to building heat over the continent, resulting in Australia's hottest month (January 2019) on record [186].

In South Australia (SA) each successive heatwave through December and January increased in intensity as the continental heating cycle built until the fifth Adelaide event climaxed on 24 January with many locations resetting temperature records including Adelaide which achieved Australia's record hottest capital city with a new highest maximum temperature of 46.6°C.

The State Emergency Services (SES) activated SA's Extreme Heat plan on four occasions, the first two activated government and NGO's preparedness arrangements via email messages, the last two activated public warnings when more significant human health impact was anticipated. During this warning phase the SES received daily reports from SA Health and Red Cross (via Telecross REDi(SA)) on human health impacts and interventions that assisted in the fine tuning of the response effort.

Despite Australia's January 2019 record monthly average temperature, the temporal and spatial distribution of heat across SA through December and January did not result in extreme heatwaves, rather severe events which were more likely to impact vulnerable people. In contrast the historically extreme heatwaves of 2009 and 2014 developed when larger increases in both maximum and minimum temperatures were preceded by milder antecedent conditions.

This paper will compare impact data for this season with 2009 and 2014 heatwave impacts, and the differences in community messaging now employed.

Introduction

The Bureau of Meteorology (BoM) commenced the provision of a national GIF-image heatwave service in January 2014, utilising Gridded Optimum Consensus Forecast (GOCF) numerical model-only data. This service was upgraded in October 2018 to a digital gridded heatwave service utilising BoM official (meteorologist adjusted) forecasts available through the Australian Digital Forecast Database (ADFD).

The BoM's heatwave severity service is based on factored long and short-term three-day daily temperature anomalies which is normalized by the 85th percentile of each location's historical heatwave intensity record. Under this scheme 85% of all heatwaves are low-intensity for which adaptive behaviours are expected. Rarer, higher intensity (severe) heatwaves are increasingly risky for vulnerable people, whilst even rarer, more intense (extreme) heatwaves are hazardous for all people reliant upon normally reliable utilities and infrastructure [56], [138].

Human health impact during SA's January 2019 heatwaves were not historically high. Telecross REDi (a telephone contact service for registered vulnerable people run by the Red Cross) activations resulted in interventions, some of which resulted in ambulance conveyance to hospital and a few admissions. Health also reported Emergency Department (ED) and hospital admissions.

During the 2018/19 heatwave season SA's SES collaborated with the BoM and the University of Adelaide to present digital ADFD heatwave service data in a new format to assist with community message decision support. The SES Duty Officer continued to use Kent Town (suburban site adjacent Adelaide CBD) forecast data for decision making with the new decision support formats available for evaluation. The new format has since been reviewed to establish a new spatially driven SES heatwave community message format for the 2019/20 heatwave season.

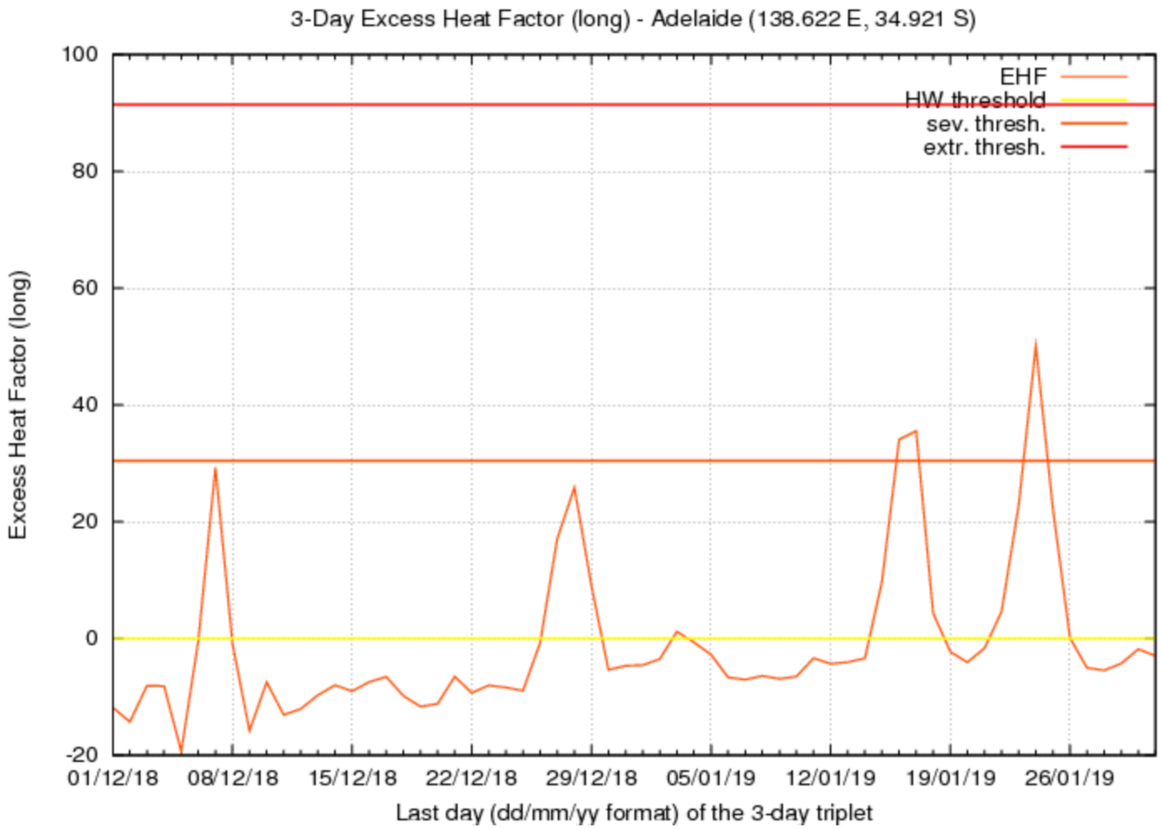


Figure 101. Adelaide EHF for 1 December 2018 to 30 January 2019. Third and fourth heatwaves breached the severe threshold (orange line).

Four heatwaves affected Adelaide during the 2018/19 season (Figure 101), two resulted in advice to government agencies and public warnings for two severe events. The last included Adelaide's hottest record maximum temperature, with 20 other locations also breaking records across SA during Australia's hottest January on record [186], and in which much of Australia experienced their hottest heatwaves on record (Figure 102).

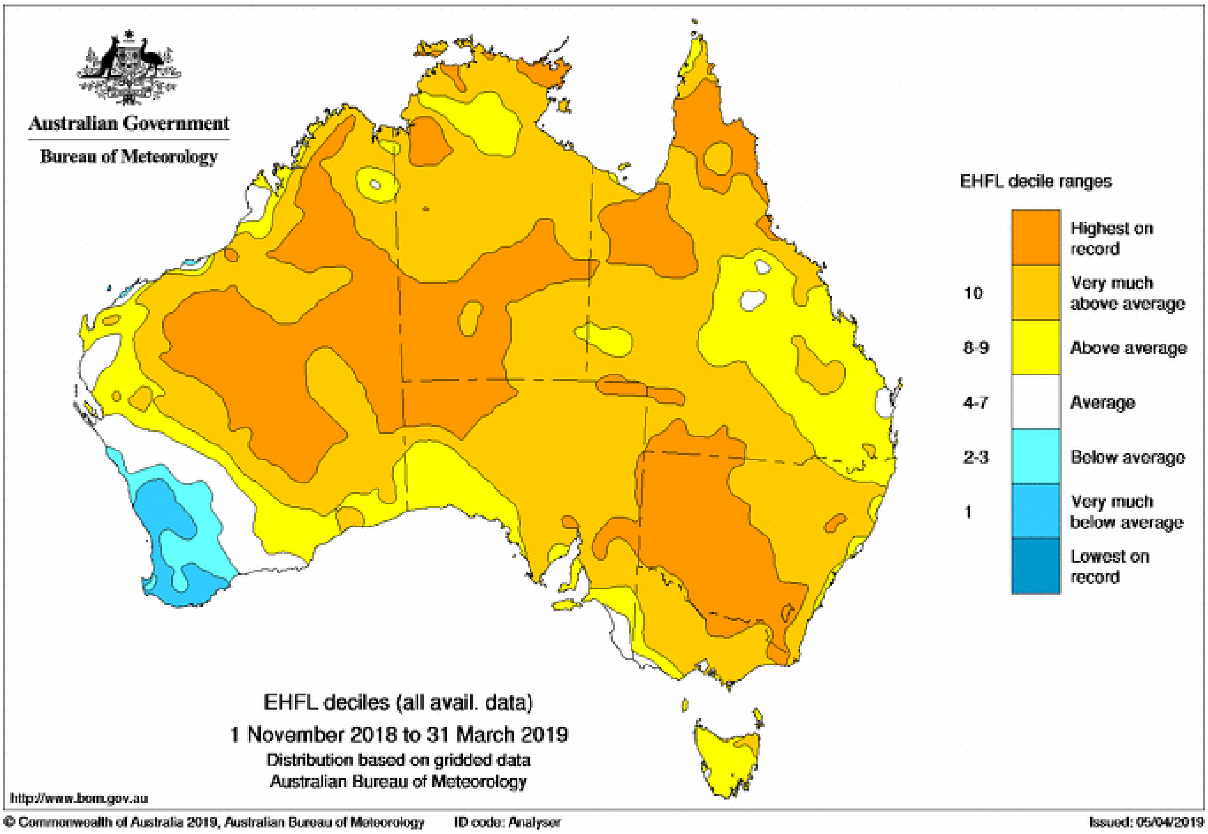


Figure 102. Heatwave intensity (EHF) deciles for November 2018 to March 2019.

Discussion

A severe heatwave impacted Adelaide over 22-24 January 2019. Numerous all-time maximum temperature records were broken on 24 January in northerly winds ahead of a cool change. Over 40 all-time or equal record maximum temperatures were set on 24 January, mainly over the southern half of SA. Adelaide (West Terrace/ngayirdapira) recorded a maximum of 46.6°C (Kent Town recorded 47.7°C) on 24 January, breaking the previous record set in 1939 by 0.5°C (132-year record) making Adelaide the hottest Australian capital city on record. This heatwave followed a severe heatwave that impacted much of SA a week earlier. Other notable maximum records included: Port Pirie 48.6°C (62 year +2.0°C), Port Lincoln 48.3°C (126 year +2.2°C), Ceduna 48.6°C (80 year +0.2°C) and Port Augusta 49.5°C (63 year +0.6°C).

The SES issued a heatwave warning commencing 22 January. By 25 January SA Health had recorded 125 heat-related presentations with 53 admissions over 3 days. In contrast heat-related admissions during the 2009 and 2014 extreme heatwaves (Figure 103 and Figure 104) were 332 and 197 respectively [187]. A lower number of hospital admissions in the 2019 heatwave was anticipated and supported by no apparent increase of number of sudden death admissions to pathology services (personal conversation, Langlois).

SA Ambulance Service recorded 234 attendances with 156 transfers to hospital. Over the 13 extreme heatwave days in 2009 and 2014 an average of 291.1 and 249.5 call-outs occurred, an excess (against seasonal call-outs) of 540 and 214 respectively [187].

In Victoria, excess heatwave deaths decreased by 38% between the 2009 and 2014 heatwaves, whilst public hospital emergency department presentations for Victorians aged 75 years or more decreased by 14% [188]. SA cardiac call-outs reduced by 59%, whilst renal and heat-related ED presentations reduced by 30% and 56% respectively [187]. Reducing human impact over the 2009, 2014 and 2019 heatwaves are attributable to a combination of reduced heatwave severity (Figure 103, Figure 104 and Figure 101 respectively), improved mitigation and planning, and improved messaging. This is despite the extreme single day temperatures experienced on 24 January 2019. The reduced level of human impact under such extraordinary record maximum temperatures illustrates the required effect of prolonged unusually high maximum and minimum temperature (as captured by EHF) building impact from heat retained within the environment over three days.

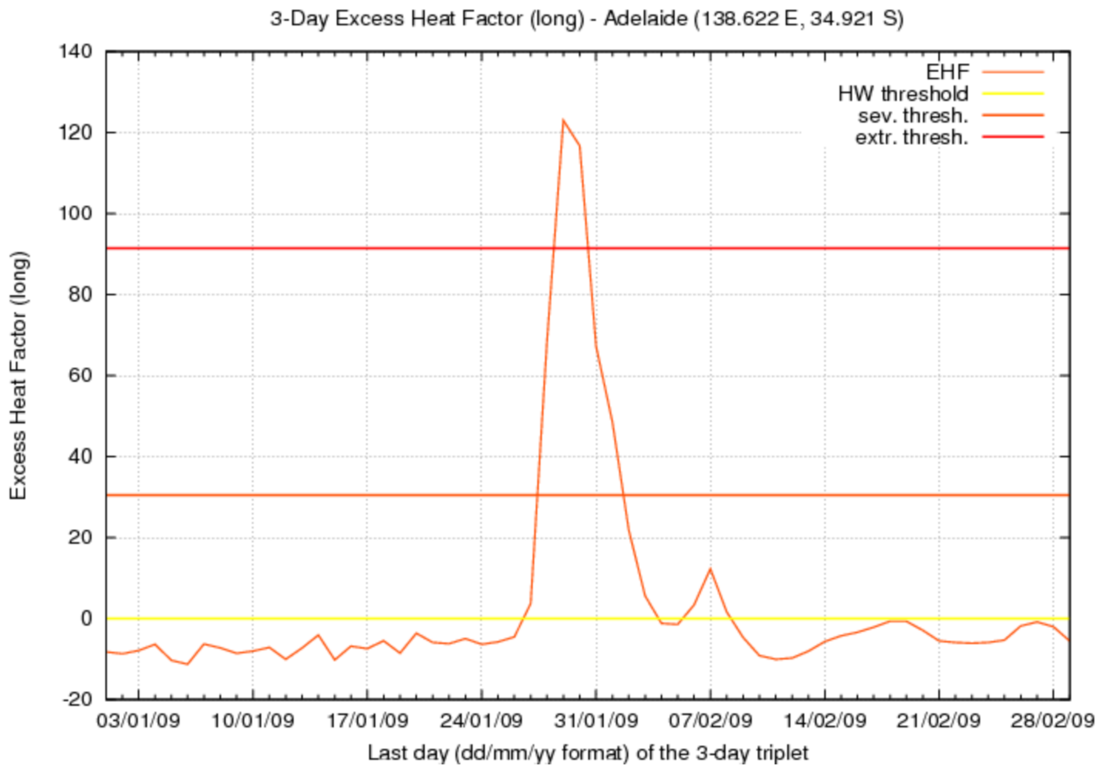


Figure 103. Adelaide EHF for 1 January to 1 March 2009.

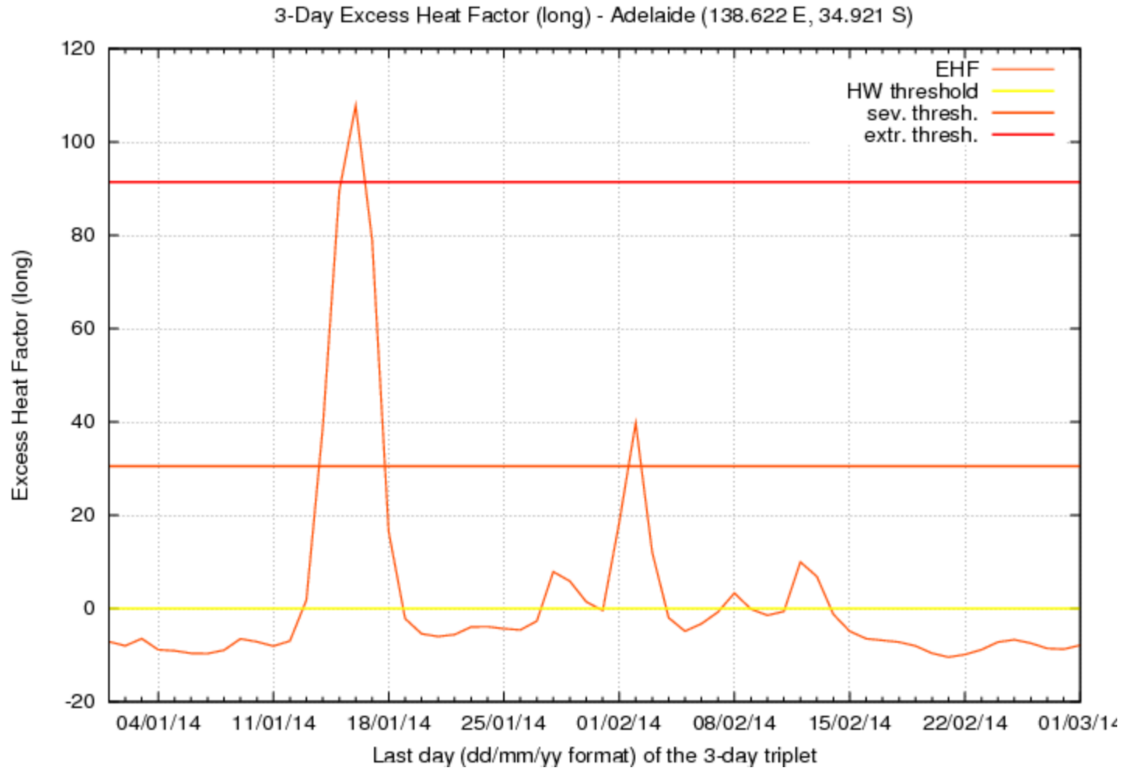


Figure 104. Adelaide EHF for 1 January to 1 March 2014.

Telecross REDi made 1673 welfare calls which resulted in 128 escalations and 3 ambulance call-outs.

SA Department of Human Services activated Code Red protocol for 14-16 January and 25 February to 2 March. Code Red was also activated for the Riverland and Port Augusta from 21-25 January. Code Red protocol delivers additional services to people who are homeless.

The SES responded to 79 calls for assistance from downed trees, which resulted in damage to homes, vehicles and power lines; 25,000 properties lost power on 24 January, which were mostly resolved by the following morning.

Public transport delays were recorded after Metrocard failed whilst reduced tram services were introduced to reduce damage to infrastructure.

Notable impacts to agriculture and animal life, included the loss of approximately 1000 chickens in the Adelaide Hills and at least 1500 flying fox losses in Adelaide's Botanical Gardens [34].

Currently the SA SES heatwave service interrogates Kent Town (Adelaide) temperatures to determine the need for SA's extreme heat warnings. The arrival of the BoM's digital heatwave service has allowed the SES to prepare for spatially tailored services. Comparison of Kent Town and Weather District heatwave severity (2018/19) in Figure 105 demonstrates how the service will be tailored in the 2019/20 heatwave season. Spatial heatwave classifications were determined when 10% or more of the district was affected by the reported heatwave severity. The low-intensity Kent Town heatwaves 5-6 December, 25-27 December and 23 Feb - 2 March demonstrate spatial variability in district heatwave severity, as also occurs for the severe heatwaves 13-16 January and 20-24 January. The strongest variability occurs for the December and January heatwave clusters where the heatwaves were much more extensive north of Kent Town.

Date	Kent Town	Adelaide M	Mount Loft	Yorke Peni	Kangaroo I	Upper Sou	Lower Sou	Riverland	Murraylan	Mid North	Flinders	West Coas	Eastern Ey	Lower Eyre	North Wes	North East
29/10/2018																
30/10/2018											Low intensi		Low intensi			
31/10/2018																Low intensi
1/11/2018																Low intensi
2/11/2018																Low intensi
3/11/2018																
4/11/2018																
5/11/2018																
6/11/2018																
7/11/2018																
8/11/2018																
9/11/2018																
10/11/2018																
11/11/2018																
12/11/2018																
13/11/2018																
14/11/2018																
15/11/2018																
16/11/2018																
17/11/2018																
18/11/2018																
19/11/2018																
20/11/2018																
21/11/2018																
22/11/2018																
23/11/2018																
24/11/2018																
25/11/2018																
26/11/2018																
27/11/2018																
28/11/2018																
29/11/2018																
30/11/2018																
1/12/2018																
2/12/2018																
3/12/2018																
4/12/2018		Low intensi	Low intensi	Low intensi	Low intensi							Severe	Low intensi	Low intensi	Low intensi	
5/12/2018	Low intensi	Low intensi	Severe	Severe	Severe	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Severe	Low intensi	Low intensi
6/12/2018	Low intensi		Low intensi	Low intensi	Low intensi	Low intensi		Severe	Low intensi	Low intensi	Low intensi		Low intensi	Low intensi	Low intensi	Severe
7/12/2018								Low intensi			Low intensi				Low intensi	Low intensi
8/12/2018											Low intensi					Low intensi
9/12/2018																Severe
10/12/2018																Severe
11/12/2018																
12/12/2018																
13/12/2018																
14/12/2018																
15/12/2018																
16/12/2018															Low intensi	
17/12/2018										Low intensi	Severe				Low intensi	Severe
18/12/2018											Low intensi					Severe
19/12/2018																Low intensi
20/12/2018																
21/12/2018																
22/12/2018																
23/12/2018																
24/12/2018		Low intensi	Low intensi					Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi
25/12/2018	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Severe	Severe	Severe	Severe	Low intensi	Severe	Low intensi	Severe	Severe
26/12/2018	Low intensi	Low intensi	Severe	Severe	Low intensi	Low intensi	Low intensi	Severe	Severe	Severe	Severe	Severe	Severe	Low intensi	Severe	Severe
27/12/2018	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi	Low intensi	Severe	Low intensi	Severe	Severe	Low intensi	Low intensi		Severe	Severe
28/12/2018								Low intensi		Low intensi	Low intensi				Severe	Severe
29/12/2018											Low intensi				Severe	Severe
30/12/2018											Low intensi				Low intensi	Severe
31/12/2018											Low intensi	Low intensi			Low intensi	Severe
1/01/2019		Low intensi	Low intensi	Low intensi				Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Severe
2/01/2019	Low intensi	Low intensi	Low intensi			Low intensi		Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi	Severe
3/01/2019											Low intensi					Low intensi
4/01/2019																
5/01/2019																
6/01/2019																
7/01/2019																
8/01/2019																Low intensi
9/01/2019															Low intensi	Low intensi
10/01/2019											Low intensi				Severe	Low intensi
11/01/2019								Low intensi		Low intensi	Low intensi				Severe	Severe
12/01/2019								Low intensi	Low intensi	Low intensi	Low intensi				Severe	Severe
13/01/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Low intensi	Low intensi	Low intensi	Severe	Severe
14/01/2019	Low intensi	Severe	Severe	Severe	Severe	Low intensi	Low intensi	Severe	Severe	Severe	Severe	Severe	Severe	Severe	Severe	Severe
15/01/2019	Severe	Severe	Severe	Severe	Severe	Low intensi	Low intensi	Severe	Severe	Severe	Severe	Low intensi	Severe	Severe	Extreme	Severe
16/01/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Severe
17/01/2019								Low intensi		Low intensi	Low intensi				Low intensi	Severe
18/01/2019											Low intensi				Low intensi	Severe
19/01/2019										Low intensi	Low intensi				Low intensi	Severe
20/01/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Low intensi
21/01/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Low intensi	Severe	Severe	Severe	Severe	Severe	Severe	Severe
22/01/2019	Severe	Severe	Severe	Severe	Severe	Severe	Low intensi	Severe	Severe	Severe	Severe	Severe	Severe	Severe	Severe	Severe
23/01/2019	Severe	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Low intensi	Severe	Severe	Low intensi	Low intensi	Low intensi	Severe	Severe
24/01/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi		Low intensi	Severe
25/01/2019																Low intensi
26/01/2019																Low intensi
27/01/2019																
28/01/2019											Low intensi					
29/01/2019																Low intensi
30/01/2019																Low intensi
31/01/2019																Low intensi
1/02/2019										Low intensi	Low intensi		Low intensi		Low intensi	Low intensi
2/02/2019						Low intensi		Low intensi	Low intensi	Low intensi	Low intensi		Low intensi		Low intensi	Low intensi
3/02/2019											Low intensi				Low intensi	Low intensi
4/02/2019											Low intensi				Low intensi	Low intensi
5/02/2019																Low intensi
6/02/2019																
7/02/2019																
8/02/2019																
9/02/2019																
10/02/2019																
11/02/2019																
12/02/2019																
13/02/2019																
14/02/2019																
15/02/2019												Low intensi				
16/02/2019																Low intensi
17/02/2019																
18/02/2019																
19/02/2019																
20/02/2019																
21/02/2019																
22/02/2019					Low intensi							Low intensi		Low intensi	Low intensi	
23/02/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	
24/02/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		
25/02/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi			
26/02/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi		Low intensi	
27/02/2019	Low intensi	Low intensi	Low intensi	Severe	Low intensi	Severe	Severe	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Severe	Low intensi	Low intensi	Low intensi
28/02/2019	Severe	Severe	Severe	Severe	Severe	Severe	Severe	Low intensi	Severe	Severe	Low intensi	Severe	Severe	Severe	Low intensi	Low intensi
1/03/2019	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Low intensi	Severe	Low intensi	Low intensi
2/03/2019	Low intensi		Low intensi					Low intensi	Low intensi	Low intensi	Low intensi		Low intensi		Low intensi	Low intensi
3/03/2019																
4/03/2019																
5/03/2019																
6/03/2019																
7/03/2019															Low intensi	
8/03/2019												Low intensi			Low intensi	
9/03/2019															Low intensi	Low intensi
10/03/2019															Low intensi	
11/03/2019															Low intensi	
12/03/2019																

Figure 105. 2018/19 heatwave season heatwave severity for Kent Town (Adelaide) and South Australian Weather Districts. Weather district severity categorised by minimum 10% spatial coverage. Yellow for low-intensity, orange for severe and red for extreme heatwave severity.

This is well supported by Figure 106 and Figure 107, where the highest heatwave intensity for the periods 22 December to 4 January and 11-26 January both show extensive severe heatwaves impacting SA.

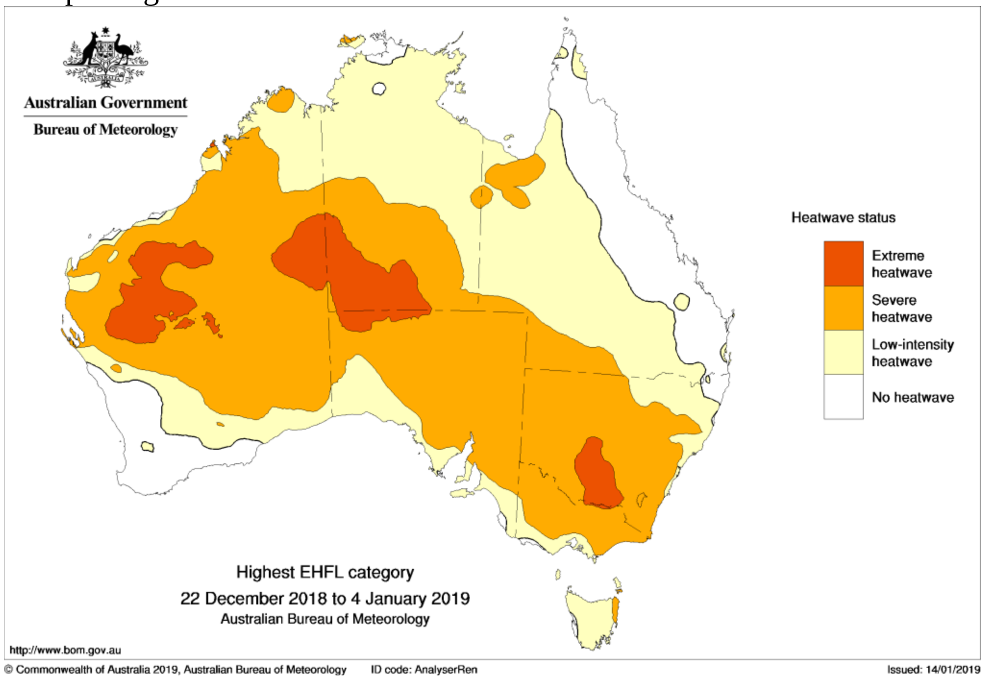


Figure 106. Map of the highest three-day heatwave category for 22 December 2018 to 4 January 2019 [112].

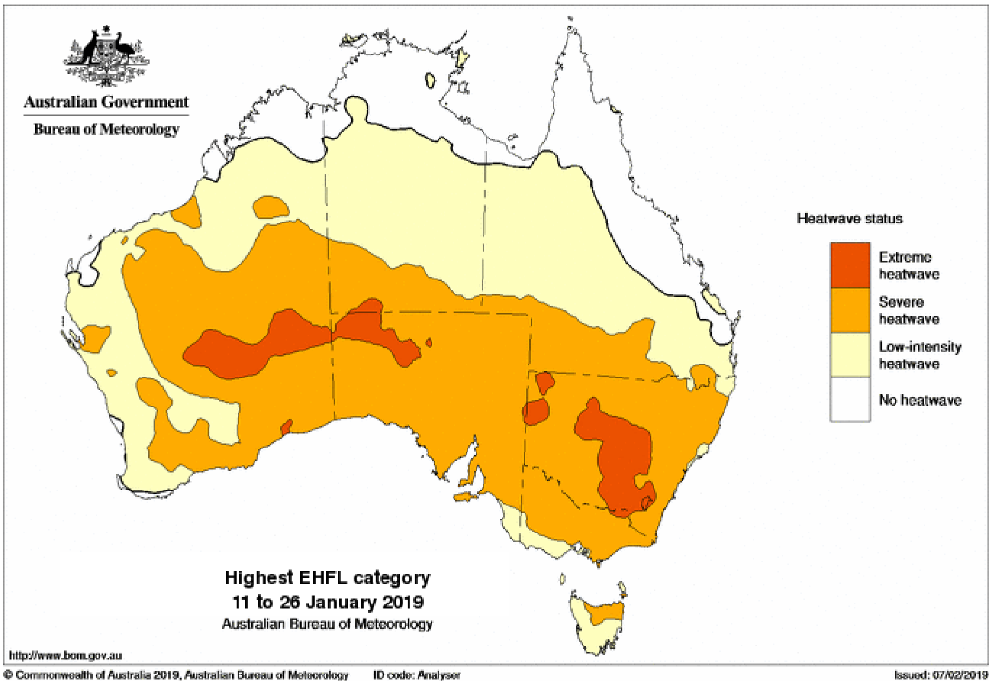


Figure 107. Map of the highest three-day heatwave category for 11 to 26 January 2019 [112].

Under the current service, only the second period received a warning service as Kent Town was not impacted by a severe heatwave during the first period.

In the 2019/20 heatwave season the SES will provide a new modified heatwave warning service on a weather district basis. Messages proposed include:

- "SES Community Readiness Alert" (BoM's multi-day service shows severe and extreme);
- "SES Heatwave Advice" (next-day tabulation of district heatwave severity);
- next-day district-based, heatwave warnings – scaled to heatwave severity;
- "Low-intensity Heatwave Advice"
- "Severe Heatwave Watch and Act" (five templates)
- "Extreme Heatwave Emergency Warning" (four templates), and
- "Heatwave Advice Reduced Threat".

The multiple templates for the Watch and Act, and Emergency Warning have been designed to reduce warning fatigue. Message content advice contained within the "what you should do" section are changed as a heatwave progresses, particularly if long lived (examples included in appendix).

Summary

The absence of normal monsoon rains in 2018/19 summer contributed to an unusually intense Australian heatwave season. Persistent severe and occasionally extreme heatwaves across northern and central Australia intermittently fed into short heatwaves across Australia's southern cities. The SA SES extreme heat service evaluated the BoM's new digital heatwave services, in parallel with the service generated from evaluating heatwave criteria at Kent Town in Adelaide. Severe heatwaves were evident on at least 5 occasions across SA, whilst Kent Town had two reported events, the last reported event coincident with record maximum temperatures recorded across 20 SA sites on 24 January.

Whilst January 2019 was Australia's hottest month on record, and 24 January was Adelaide's hottest day on record, the heatwave severity was not as severe as the 2009 and 2014 events. The human health impacts during 2019 were lower than those recorded in 2009 and 2014. Peak heatwave severity (Figure 103, Figure 104 and Figure 101) correctly ranked against human health impacts. Greatest impacts were recorded in 2009, followed by 2014 with much less noted in 2019. The reduction in impacts in each case can be attributed to rising awareness of heatwave impacts and better mitigation strategies, in combination with lower intensities.

The SES will introduce a district heatwave service in the 2019/20 heatwave season, noting the current service is initiated by Kent Town's temperature data alone, and is unable to supported a tailored state-wide service.

New message formats have been evolved to allow community messages, utilizing the Advice, Watch and Act, and Emergency Warning messages which are scaled to the severity of the next day's impending heatwave severity (low-intensity, severe and extreme respectively).

HEATWAVE

Government of South Australia SES RESCUE

SEVERE HEATWAVE WATCH AND ACT

This Heatwave Watch and Act message is issued for <Location>.
A heatwave is more than just hot weather. When it is very hot during the day and it does not cool down at night, it is hard for your body to cool itself. Babies and young children, the elderly, pregnant women and those who are already unwell are especially at risk in a severe heatwave, but even healthy people should take care. Take action to make sure you and your family stay well during this heatwave event.
What you should do:
<WhatDo>
<AdditionalAdvice>
<ImageURL>

This message was issued by the State Emergency Service.
Health information:
If you are feeling unwell, contact your local doctor
For immediate medical attention telephone 000 (triple zero).
To register for the Telecross REDi service telephone 1800 188 071.
Stay informed:
Check the SES website at www.ses.sa.gov.au
For weather warnings and forecasts visit www.bom.gov.au.
Monitor local conditions and tune in to your local ABC on a battery-powered radio for updates
Call the SA Emergency Infoline on 1800 362 361
People who are deaf, or have a hearing or speech impairment, can contact the SA Emergency Infoline via the National Relay Service on 1800 555 727 (TTY users 1800 555 677)
Follow the SES on Twitter (@SA_SES) or Facebook (SA State Emergency Service)
For SES assistance phone 132 500
For further information visit SA Health or HealthDirect

Message Name: <AlertName>
This message was issued on <DateTimeIssued>
The next update is expected by <DateTimeExpires>, or as the situation changes.

DocumentID: <DocumentID>

Figure 108A. SES severe heatwave Watch and Act message format.

HEATWAVE

Government of South Australia

SES RESCUE

SES HEATWAVE ADVICE

Heatwave conditions have been forecast by the Bureau of Meteorology for the following locations:

Forecast District	Heatwave Forecast
Adelaide Metropolitan	Low Intensity Heatwave
Mount Lofty Ranges	Low Intensity Heatwave
Yorke Peninsula	Low Intensity Heatwave
Kangaroo Island	Low Intensity Heatwave
Upper South East	Low Intensity Heatwave
Lower South East	No heatwave
Riverland	Severe Heatwave
Murraylands	Low Intensity Heatwave
Mid North	Severe Heatwave
Flinders	Severe Heatwave
West Coast	Low Intensity Heatwave
Eastern Eyre Peninsula	Low Intensity Heatwave
Lower Eyre Peninsula	Low Intensity Heatwave
North East Pastoral	Extreme Heatwave
North West Pastoral	Severe Heatwave

The **State Emergency Service** recommends you take action now to make sure that you and your family stay safe.

About Heatwaves:

Low-intensity Heatwaves are common in South Australia during summer and most people are able to cope well, but the very young, elderly or those with medical conditions should take care.

Severe Heatwave are less frequent and are especially challenging for babies and young children, the elderly, pregnant women and those who are already unwell, but even healthy people should take care. The SES will issue a separate Watch and Act message for each area in which a Severe Heatwave is forecast.

Extreme Heatwave are rare, but are dangerous for anyone who does not take precautions to keep cool, even those who are fit and healthy. People who work or exercise outdoors are particularly at risk. The reliability of infrastructure, like power and transport, can also be affected. The SES will issue a separate Emergency Warning message for each area in which an Extreme Heatwave is forecast.

Stay informed:

- Check the SES website at www.ses.sa.gov.au
- For weather warnings and forecasts visit www.bom.gov.au.
- Monitor local conditions and tune in to your local ABC on a battery-powered radio for updates
- Call the SA Emergency Infoline on 1800 362 361
- People who are deaf, or have a hearing or speech impairment, can contact the SA Emergency Infoline via the National Relay Service on 1800 555 727 (TTY users 1800 555 677)
- Follow the SES on Twitter (@SA_SES) or Facebook (SA State Emergency Service)
- For SES assistance phone 132 500
- For further information visit SA Health or HealthDirect

Message Name: <AlertName>

This message was issued on <DateTimeIssued>

The next update is expected by <DateTimeExpires>**, or as the situation changes.**

DocumentID: <DocumentID>

Figure 109A. SES heatwave Advice message format.

HEATWAVE

HEATWAVE ADVICE

REDUCED THREAT

This **Heatwave Advice** message is issued for <Location>.

The risk to your safety due to the recent heatwave has reduced. While temperatures have reduced, hot weather may still be experienced. It may take you a few days to recover and you should continue to take care.

hat you should do:

- **Continue to drink plenty of water**
- **Open doors and windows to cool your home**
- **Get plenty of rest, and**
- **Check on family, friends and neighbours to see if they need help.**
- **Trees may still drop their branches without warning, especially if the weather is windy. Don't let children climb or play under them and avoid parking or camping under large branches.**

<AdditionalAdvice>

<ImageURL>

This message was issued by the **State Emergency Service**.

Health information:

- **If you are feeling unwell, contact your local doctor**
- **For immediate medical attention telephone 000 (triple zero).**
- **To register for the Telecross REDi service telephone 1800 188 071.**

Stay informed:

- Check the SES website at www.ses.sa.gov.au
- For weather warnings and forecasts visit www.bom.gov.au.
- Monitor local conditions and tune in to your local ABC on a battery-powered radio for updates
- Call the SA Emergency Infoline on 1800 362 361
- People who are deaf, or have a hearing or speech impairment, can contact the SA Emergency Infoline via the National Relay Service on 1800 555 727 (TTY users 1800 555 677)
- Follow the SES on Twitter (@SA_SES) or Facebook (SA State Emergency Service)
- For SES assistance phone 132 500
- For further information visit SA Health or HealthDirect

Message Name: <AlertName>

This message was issued on <DateTimeIssued>

The next update is expected by <DateTimeExpires>**, or as the situation changes.**

DocumentID: <DocumentID>

Figure 110A. SES heatwave Advice Reduced Threat message format.

Statement of Authorship

Title of Paper	Australia's Black Summer heatwave impacts [51]
Publication Status	Published
Publication Details	*Australian Journal of Emergency Management Volume 36 No. 1 January 2021*

Principal Author

Name of Principal Author (Candidate)	John Nairn		
Contribution to the Paper	Nairn conceived the idea of the study. Wrote the original paper.		
Overall percentage (%)	70%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	5/11/2021

Co-Author Contributions

Name of Co-Author	Matt Beatty		
Contribution to the Paper	Reviewed concept, reviewed writing, and analysed data. Processed data for and created Table 10 and Figures 82 and 83.		
Overall percentage (%)	15%		
Signature		Date	4/11/2021

Name of Co-Author	Blesson M Varghese		
Contribution to the Paper	Reviewed concept, reviewed writing, and analysed data. Processed data for and created Table 10 and Figures 82 and 83.		
Overall percentage (%)	15%		
Signature		Date	5/11/2021

Paper 7: Australia's Black Summer heatwave impacts

Australia's Black Summer heatwave impacts

John Nairn CF
Honorary Affiliate Bureau of Meteorology (retired), University of Adelaide

Dr Matt Beaty
Department of Health

Dr Blesson M Varghese
Bureau of Meteorology, University of Adelaide

In Australia, the methodology used for heatwave warnings is different across its states and territories. The Bureau of Meteorology is redesigning its heatwave product suite to provide nationally consistent heatwave forecasts and warnings.

Australia's sequence of unprecedented disasters during the 2019–20 Black Summer were not unexpected. There has been declining rainfall over the southern half of Australia with Australia's average temperature rising by 1.4° C since 1910 [9].

Record 2- and 3-year rainfall deficits over eastern Australia (Figure 111) created tinder-dry fuels and an environment prone to extreme heatwaves (Figure 112). Subsequent fires and persistent smoke were responsible for 33 [183] and 417 excess deaths [184], respectively, and an increase in respiratory problems and other health impacts in New South Wales and the Australian Capital Territory [185].

It takes longer to detect heatwave mortality due to strict medical and coronial conventions. However, the death toll may be in the hundreds, noting studies that have demonstrated the disproportionate impact of heatwaves over other climatic hazards [19].

Indirectly, heatwaves played a large part in the size and severity of the Black Summer bushfires.

Heatwaves are defined by the combined effect of high minimum and maximum temperatures with the former playing the greatest role. Higher minimum temperatures reduce the diurnal cooling cycle and sets up earlier and more sustained high temperatures, rapidly building heat stored in the environment. The Bureau of Meteorology combines long- and short-term daily (average of maximum and minimum) temperatures over a 3-day period to determine heatwave severity as shown in Figure 112 [54].

High minimum temperatures are extremely significant as it is difficult, if not impossible, to form a surface inversion, allowing the upper wind structure to remain coupled with the fire overnight. Without the cooling effect and higher relative humidity of a nocturnal surface inversion, fires burn as intensely at night as during the day. Fires expand further and burn more erratically without the normal benefit of reduced overnight fire danger.

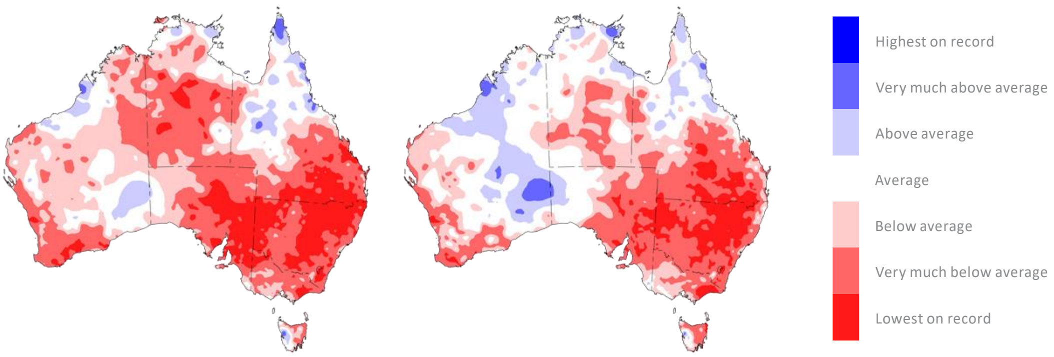


Figure 111: Rainfall deciles for the 24 months from January 2018 to December 2019 (left) and 36 months from January 2017 to December 2019 (right), based on all years from 1900.

The NSW sequences of heatwaves and property impacts are shown in Figure 113. The proportion of NSW that was affected by low-intensity or severe heatwaves can be seen to correlate with property losses the week finishing 23 November. At that time, nearly 80 per cent of NSW experienced a low-intensity heatwave (18 per cent severe) and over 500 homes and structures were destroyed.

The next 2 major destructive bushfire events in January 2020 followed a 6-week heatwave affecting most of NSW, with a major heatwave in early February aligning with further damage.

Antecedent heatwave severity and accumulated heat load is yet to be systematically explored for the relationship with subsequent fire and smoke activity and presents rich grounds for further research.

The Bureau of Meteorology heatwave product is statically displayed and based on a national view of Australia [115]. These forecasts do not support the different needs of stakeholders; their processes or geographical factors. The Bureau's heatwave project team has carried out extensive interviews with health and emergency services stakeholders from government agencies, as well as not-for-profit groups such as Australian Red Cross, to ensure new products meet their needs. Beta products including town and weather district summaries will be trialled with partners in the 2020–21 summer season. Feedback received will help build an operational product intended for release in 2021–22.

The challenge of quantifying the direct human health impacts of heatwaves has been recently studied through a collaborative research project. A 12-month DIPA [186] funded PEAN [187] project was completed during 2020, which aimed to 'Reduce Illness and Lives Lost from Heatwaves' (RILLH). A multi-agency collaboration between the Bureau of Meteorology, Department of Health, Australian Bureau of Statistics, Geoscience Australia, Department of Agriculture, Water and the Environment, Australian Institute of Health and Welfare and the Bushfire and Natural Hazards CRC, the RILLH used big data to demonstrate the utility of linked

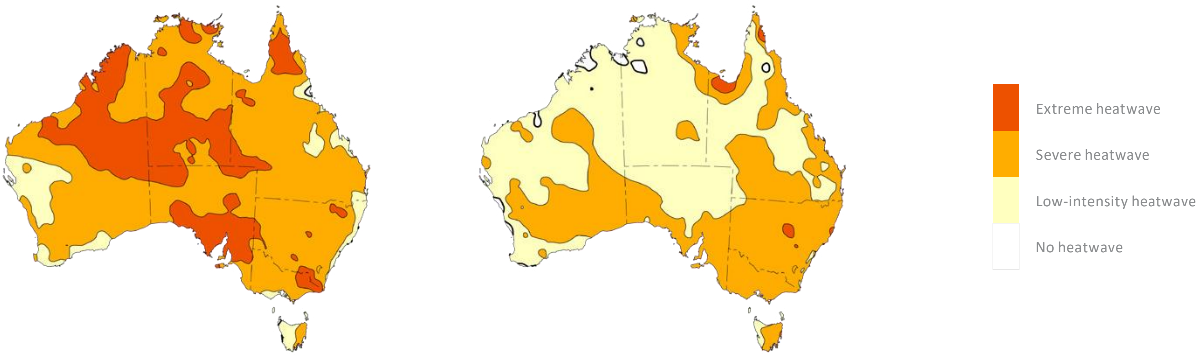


Figure 112: Highest heatwave severity for December 2019 (left) and January 2020 (right).

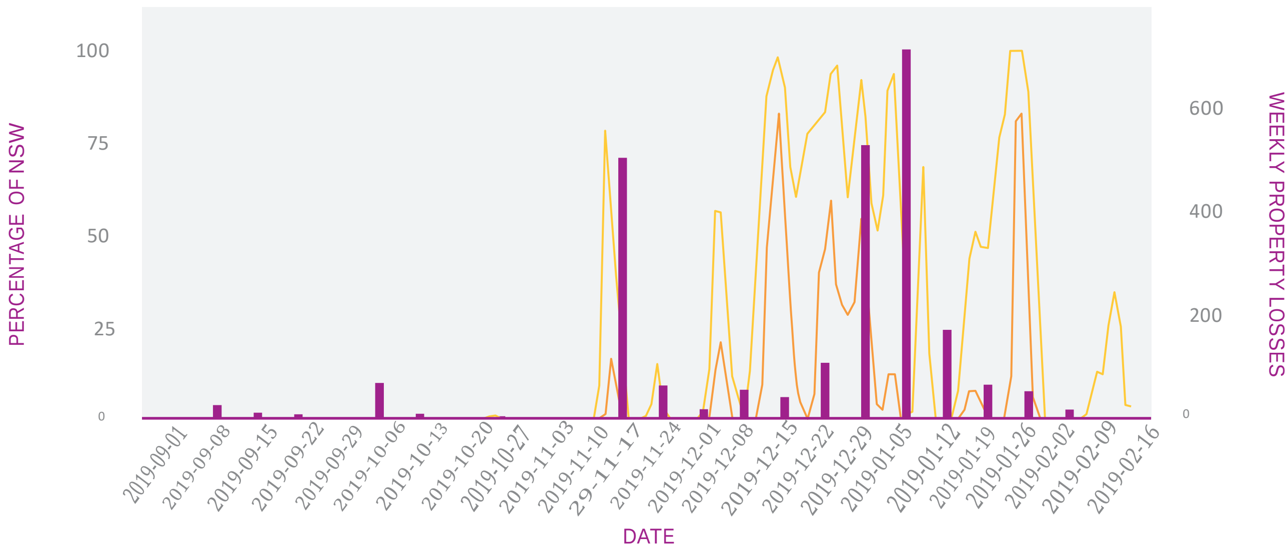


Figure 113: Chronology of heatwave severity and homes lost in NSW from September 2019 to February 2020. Proportion of NSW affected by all (orange line) and severe (red line) heatwaves (left axis). Homes destroyed (purple bar) sourced from NSW Rural Fire Service Building Impact Assessment.

social and environmental data from multiple agencies through the MADIP [188] data asset to understand complex, coupled social and environmental problems. Heatwave vulnerability has been calculated at neighbourhood-level and for individual-level factors for mortality and morbidity.

There is also an opportunity for warning agencies such as the Bureau and partners in health and emergency services to tailor advice to communities, agencies and individuals according to the risks inherent in where they live or their type of health and environmental exposures.

The study determined neighbourhood and individual-level risk factors separately (Table 14). Most of the study's neighbourhood- level spatial results were validated using the linked individual- level data, demonstrating the value of the neighbourhood-level results.

As an example, Figure 114 demonstrates spatial variability in mortality risk and heat-health vulnerability for NSW. Relative Risk in and Figure 115 is a measure of increased or decreased impact during heatwaves compared to comparable non-heatwave periods. Heat vulnerability index is a measure of the combined effects of demographic, socioeconomic, health and the natural and built environment. The results show there is an opportunity to tailor advice to the needs of different regions.

Similarly, the contrast in vulnerability across Sydney in Figure 115 can help authorities develop policy, mitigation and response strategies to effectively manage exposure, sensitivity and adaptive capacity measures.

Heatwaves impact segments of the population in different ways with impacts related to individual characteristics of people and the types of places they live in (social and built environment). Vulnerability to heatwaves exhibits distinct geographies.

The RILLH project has generated a rich set of results with implications for strategic policy and education programs to position and prepare communities for the dangers of increasingly severe heatwaves.

The RILLH project highlights the value of high-quality multi-agency partnership studies and supports a strategic aim to enhance warnings with local behavioural recommendations to improve the value of future heatwave warnings.

Acknowledgments

Advice on redevelopment of the Bureau's heatwave service was received from Monica Long, National Manager Fire Weather, Heatwave and Air Quality Services and Biju George, Project Officer. A version of Figure 113 was presented to the Black Summer joint briefing for commissions of enquiry by Jane Golding, NSW State Manager Bureau of Meteorology, 2020. RILLH results produced under a 12-month DIPA [186] funded PEAN[187] project. The Bureau of Meteorology led the RILLH project, partnered by the Australian Bureau of Statistics, Department of Health, Australian Institute of Health and Welfare, Geoscience Australia and the Bushfire and Natural Hazards CRC. This article does not represent the express view of the Department of Health.

Table 14: RILLH results show the influence of neighbourhood-level and individual-level factors on the heatwave-mortality relationship in New South Wales.

Theme	Neighbourhood-level	Individual-level
Heat Exposure	• Low amounts of vegetation • No residential air-conditioning • Higher average temperatures	
Socio-economic status	• Low-equivalised household income	• Low-equivalised household income
Household composition and instance of disability	• Over 65 years and living alone • Single parent households • Need assistance	• Living alone • Over 65 years and living alone • Dwellings with single parent • Need assistance
Language and culture	• Insufficient English language proficiency	• Insufficient English language proficiency
Housing and transportation	• Private rental property • No access to a vehicle	• No access to a vehicle
Health status and risk factors	• Diabetes • Asthma • Poor mental health • Severe mental illness • Self-reported health being poor • Obesity	• Diabetes • Poor mental health • Severe mental illness
Consistent risk factors across levels	Low-equivalised household income, over 65 years and living alone, dwellings with single parents, need assistance, insufficient English language proficiency, no access to a vehicle, diabetes, mental health conditions.	

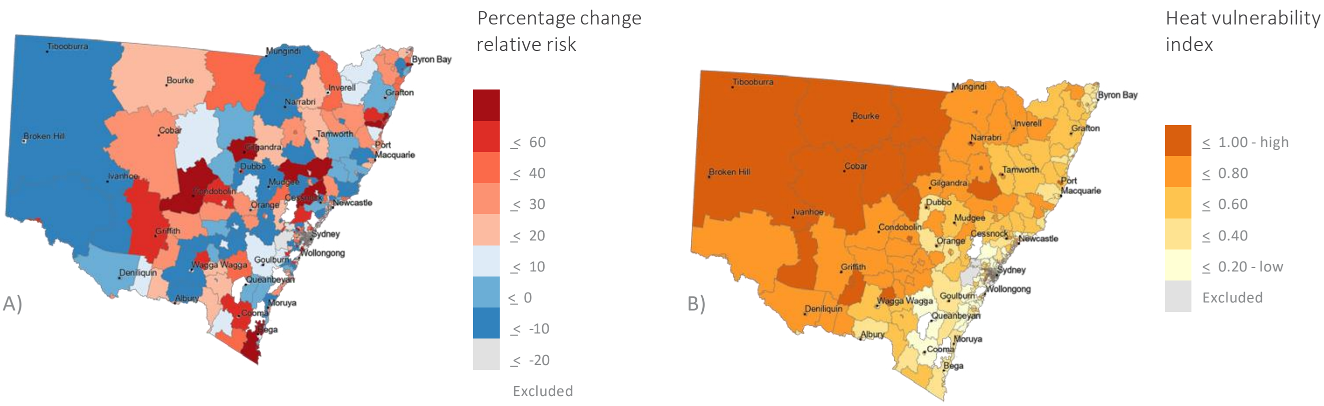


Figure 114: A) Relative Risk of heatwave-related mortality and B) overall heat health vulnerability index in New South Wales, (2007–17).

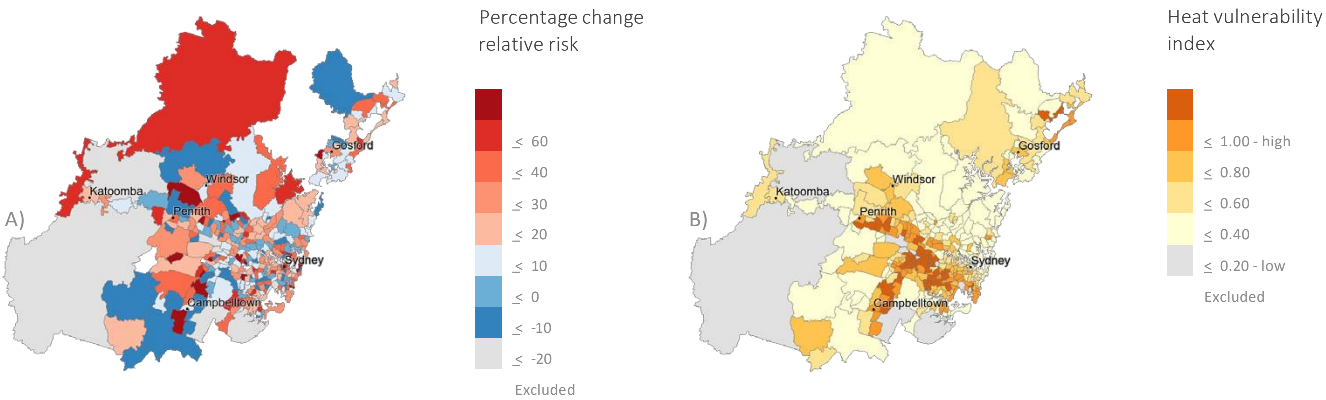


Figure 115: A) Relative Risk of heatwave- related mortality (2007–17) and B) overall heat health vulnerability index in the Sydney Greater Capital Area Statistical Area.

Chapter 5. Australia's heatwave service – crossing the hazard bridge to an impact service

A PWC report (2011, [29], [195]) released in the wake of south east Australia's 2009 extreme heatwave noted the need for a national framework to protect human health and safety during severe and extreme heat events. The Munro Review (2011, [195]) noted how heatwaves are probably the most under-rated weather hazard in Australia, essentially because they are viewed as a 'passive' hazard. Munro noted Bureau of Meteorology customer expectations and need for a simple and easy to understand heatwave warning system. The Bureau's capacity to respond to the Munro Review was governed by adoption of EHF as Australia's official heatwave definition, development of gridded daily climatological data in 2010 [89] and gridded official 7-day forecasts in 2014[4]. The ensuing heatwave forecast service was an essential first step toward a comprehensive national heatwave early warning system.

The path to Munro's 'simple and easy to understand heatwave warning system' entailed complex collaborations between impact-data custodians and warning partners. Collaborator recognition of EHF as an effective national heatwave definition was demonstrated through a series of multi-disciplinary conference papers presented to emergency services and public health conferences (Appendix C) and peer reviewed publications in emergency services and public health journals (Chapter 4).

Paper 8 describes Australia's progress from a hazard-based service toward a comprehensive impact-oriented service that includes coordinated messages across multiple warning agencies and targeted services tailored to specific vulnerabilities within each community. This entailed adaptation of heatwave forecasts as decision-support guidance for the development and release of community warnings and creation of a national heatwave vulnerability data set (based on EHF climate data) generated by the Reducing Illness and Lives Lost from Heatwaves project [193]. Vulnerability data supports heatwave warnings which can carrying adaptive messages appropriate to community exposure, and assists delivery of targeted mitigation measures according to location-based vulnerabilities.

[4] Bureau forecasting technology recognised in international awards

Statement of Authorship

Title of Paper	Australia’s transition from hazard-based to impact-based heatwave warnings and targeted services
Publication Status	Submitted for Publication
Publication Details	*International Journal for Disaster Risk Reduction*

Principal Author

Name of Principal Author (Candidate)	John Nairn		
Contribution to the Paper	Conceptualisation, writing – original draft preparation, review and editing		
Overall percentage (%)	40%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	8 November 2021

Co-Author Contributions

Name of Co-Author	Carla Mooney		
Contribution to the Paper	Conceptualisation, writing – original draft preparation, review and editing		
Overall percentage (%)	30%		
Signature	CJMooney	Date	8 November 2021

Name of Co-Author	Matt Beaty		
Contribution to the Paper	RILLH project data curation and formal analysis, writing review		
Overall percentage (%)	10%		
Signature		Date	5/11/2021

Name of Co-Author	Blesson Varghese		
Contribution to the Paper	RILLH project data curation and formal analysis, writing review		
Overall percentage (%)	10%		
Signature		Date	5/11/2021

Name of Co-Author	Bertram Ostendorf		
Contribution to the Paper	Data curation, software and visualisation, writing review		
Overall percentage (%)	10%		
Signature		Date	5/11/2021

Paper 8: **Australia's transition from hazard-based to impact-based heatwave warnings and targeted services**

John Nairn[1, 3], Carla Mooney[2], Matt Beaty[2], Blesson Varghese[2, 3], Bertram Ostendorf [3]

[1] Bureau of Meteorology, Adelaide (retired); john.nairn@bom.gov.au
[2] Bureau of Meteorology, Melbourne; carla.mooney@bom.gov.au; matt.beaty@abs.gov.au
[3] University of Adelaide, Adelaide; blesson.varghese@adelaide.edu.au; bertram.ostendorf@adelaide.edu.au
* Correspondence: john.nairn@bom.gov.au; Tel.: 614 3887 3412

Abstract: The intensity and frequency of heatwaves has increased with climate change. Injuries and lives lost are likely to grow as temperatures rise. Improved interventions are needed to mitigate the human impact of heatwaves. The Australian Bureau of Meteorology (the Bureau) national heatwave service commenced in 2014. The hazard-based service created an appetite for clarity around expected impacts. Local emergency services have developed impact-oriented heatwave warnings in response to this demand by incorporating the Bureau's hazard-based forecasts into warning decision-support guidance combined with local adaptive behavioural recommendations. National analysis has identified who is at risk of heatwave-related morbidity and mortality. Linked person-level data (deaths, health and social services) combined with heatwave, community, and built-environment data has built a national heat-health vulnerability dataset necessary for location mitigation measures across Australia. A comprehensive national heatwave warning service requires decision-support services, multiple sources of coordinated and timely heatwave warnings with behavioural recommendations and location-specific mitigation measures. We highlight the importance of national partnerships for the development of comprehensive impact-based services and their criticality to the effective mitigation of heatwave impacts on human health.

Keywords: heatwave; hazard-based; heat health; impact-based; warning

1. Introduction

Initially, warnings issued by National Meteorological and Hydrological Services (NMHS) were phenomenon-based services that were broadcast to users. In recent decades, increased forecast skill and a greater understanding of user risk has resulted in a transition to hazard-based warning services. More recently, increased hazard exposure and improved communication with emergency sector users have led to increased awareness by NHMS of specific impacts not addressed by hazard-based warning services.

Understanding impacts requires significant collaboration with trusted partners to safely share, manipulate and query hazard and impact data to predict how people are affected. A transition from hazard-based to impact-based services is now possible, informed by location-specific vulnerability.

Australian heatwaves have become more intense and pervasive since 1950, with increases in peak daily temperature, number of events, frequency and duration [109], [196]. This is consistent with historical and projected global trends in heatwave severity [11], [13], [105], [106], [165], [197]. Heatwaves in Australia have a disproportionate impact on human health, accounting for more lives lost than all other natural hazards combined [19] with loss of life and injury every summer [20]–[25]. The perils of heatwaves are not well understood by the public. They are generally considered to be uneventful with links to potential loss of life rarely made [198]. The need to provide appropriate information and service interventions to minimise harm from heatwaves is pressing in the context of an anticipated increase in their frequency and severity across many parts of Australia. Given the dangers of heatwaves, the Bureau has prioritised the development of a heatwave service over the last decade.

Comprehensive early warning systems require hazard monitoring and prediction augmented by risk assessment, communication, and preparedness activities. Risk is reduced when these systems and processes enable timely action [199]. The Sendai framework call for multi-hazard warning systems is built on the foundation that hazards must be observed and recorded before their interaction can be understood [138], [200].

The *Meteorology Act* 1955 (Cth) (s.6(c)) mandates the Australian Bureau of Meteorology (the Bureau) to issue warnings for weather conditions likely to endanger life or property. The Bureau provides public warnings for eleven hazards ranging from severe weather through to tropical cyclones and by October 2021 will include warnings for heatwave. Typical of National Meteorological and Hydrological Service (NMHS) organisations across the world most of these warning services are based around hazard thresholds.

There has been much discussion about the potential to improve the efficacy of warnings by NMHS agencies by moving away from describing *what the weather is, to what the weather will do* [52], [201]. Impact-based forecasts and warnings provide an assessment of the forecast weather or climate hazard and an assessment of the possible impacts, including when, where and likelihood of impacts [202]. A comprehensive impact-based service ideally supports coordinated impact-based warnings and activation of targeted services which are informed by a granular data-driven understanding of how and where people are impacted by the hazard [203]. More targeted impact-based services can be generated by employing subjective expert-driven processes combined with impact modelling which requires comprehensive knowledge of risk factors of the user group [52]. Kaltenberger et al [204] highlight the impediments to the development of impact-based warning services to include lack of impact data, technical standards, impact-databases, verification methods and resources. These impediments are difficult to address unless data custodians develop a collaborative investment framework that recognises mutual warning and service benefits for their stakeholders.

Around two-thirds of European NMHSs have transitioned from threshold hazard-based warnings to impact-oriented warnings [204]. Impact-oriented warnings are similar to those recommended by the Australian Institute for Disaster Resilience [205] in that they include information on impacts and clear advice on what to do. Morss et al [206] tested a range of message types with a hypothetical hurricane threat in coastal mainland USA. They found that high impact messaging was linked to greater evacuation intentions and risk perceptions. Potter et al [207] found that impact-based warnings may be more effective than phenomenon-based warnings in influencing hazard perception but that this did not necessarily translate into a higher likelihood of intending to take protective action. Weyrich et al [208] found that there was no difference between standard warnings and impact-based warnings for the lower hazard severity levels under study, which suggests that impact-based warnings may only be effective for very severe weather for which people lack knowledge and have difficulties judging its impacts.

Australian context

Warnings save lives and minimise harm by facilitating protective action [187]. However, improvements to current warning systems are recommended following the Black Summer of 2019/20, where cascading drought, heatwave, bushfire and smoke hazards recorded 33 fire and 417 smoke excess deaths [51], [209]. Message content and style are important factors in determining whether people take appropriate protective action [210]. Efforts to improve the quality of warning messages have been ongoing in Australia since the devastating 2009 bushfires in Victoria. The deficiencies in the warning system were closely examined at the time and led to recommendations for reform [27]. The subsequent National Review of Warnings and Information [211] have led to significant reform in warning practice. This includes the development of guidelines on best practice warnings.

Building on Mileti and Sorensen [210], the Public Information and Warning Handbook [205] recommends that a warning should describe the impact and expected consequences for communities. The emphasis is on prioritising information about what people should do and the nature of the threat, ahead of descriptions of the weather conditions leading to the hazard. There is evidence that improvements in warning design can lead to a greater appreciation of danger and the taking of appropriate protective actions [203]. There is clear evidence to support the proposition that timely, tailored and targeted warnings are more effective [187], [212]. There is a benefit in providing information that helps people translate forecasts into appropriate actions. This includes linking forecasts to consequences by providing specific information about location, severity, lead-time and uncertainty [213], [214].

Despite ongoing reform in warning practice in Australia, there is evidence that existing warning frameworks are not well understood by the public and often do not create the desired behavioural response within the community. A recent Australian survey found that of people who were aware that they had been warned, only 56% responded to an extreme heat warning [198]. Efforts to improve the design of Australian warning systems are ongoing with the most recent innovation being the development of a three-tiered warning [215].

Warnings are critical and we argue that a comprehensive warning service should include timely accurate warnings, tailored communications and notifications of adaptation actions to the most vulnerable populations and heat avoidance advice to general populations [168].

In this paper, we aim to facilitate the development of more effective warning and targeted service systems by presenting a South Australian case study that demonstrates early progress in the transition from a hazard-based to an impact-based service. We show the multiple linkages between the Bureau's hazard forecast, the development of epidemiological evidence for behavioural adaptation, and the consequential decision support required to create impact-based warnings and targeted services. To support our narrative, we present an analysis of the spatial variability of impact that demonstrates the benefits of a spatially explicit impact-based system. We discuss the importance of data custodian collaboration that enabled new impact spatial analysis and which has established an ongoing hazard vulnerability diagnosis capability. This in turn now offers a partnership amongst collaborators in the delivery of spatially coherent targeted heatwave services which are effectively coordinated with warning services. (The transition of the Australian heatwave services from hazard-based to impact-based is discussed.)

2. Materials and Results

2.1 Bureau heatwave service

As its first step in the design of a warning service, the Bureau of Meteorology (the Bureau) adopted the Excess Heat Factor (EHF) [74] metric to compose a hazard forecast service. The EHF severity metric combines percentile indices of long- and short-term daily temperature anomalies, where a heatwave spans three days or longer. The development of a national percentile-based heatwave service has relied upon high-quality temperature climate records, maintained by the Bureau since 1911 [98] and multi-day temperature forecasts first introduced during the Melbourne Commonwealth Games in 2006. The three categories of heatwave severity (Low-intensity, Severe and Extreme) are objectively derived from extreme value theory as detailed in Nairn and Fawcett [56]. The stable relationship between rising heatwave severity and impact led to qualitative descriptions of potential health impacts for each category of severity is shown in

Table 15.

Table 15. Heatwave severity defined by Excess Heat Factor (EHF) and potential health impacts.

EHF Severity category[1]	Potential health impacts
Low intensity	Heatwaves are frequently low-intensity events during summer. Most people can cope during these heatwaves.
Severe	Challenging for more vulnerable people, such as those over 65, pregnant women, babies, and young children, and those with a chronic illness.
Extreme	Extreme heatwaves are rare. They are a problem for people who don't take precautions to keep cool—even for healthy people. People who work or exercise outdoors are also at greater risk of being affected. Normally reliable infrastructure may fail (e.g. energy and transport).

[1]*Heatwaves are categorised by the Bureau of Meteorology based on the excess heat factor (EHF) which provides a nationally consistent measure that includes local meteorological observations.*
Source: Bureau of Meteorology Heatwave Service for Australia (bom.gov.au)

The Bureau commenced a pilot heatwave service in January 2014. This service provides hazard-based information about the temporal and spatial distribution of heatwave severity. The service supplies gridded severity levels and graphical severity categories for a 7-day forecast period [117]. The new heatwave service addressed Sendai targets [8] and rising national demands from the health sector. The rigorous EHF statistical heatwave intensity (local modality) and severity (unitless in space and time) record became attractive for epidemiological dose/response (heat exposure/health impact) collaborative studies. EHF has demonstrated sensitivity to increased health impacts as heatwave severity increased [24], [120], [122], [123], [125], [216]–[219]. The functional performance of EHF for heat health warning systems has also been acknowledged by academic [43] and UNESCO organisations [5].

The Bureau's heatwave service post-processes EHF severity from national 6 km resolution gridded observations and forecasts of daily temperature (average of maximum and minimum temperature). Bias corrected ACCESS numerical weather prediction model [131] data is matched with climate reference data fields as part of this process. During the warm season, 7 charts (single heatwave analysis chart example in Figure 116) of heatwave severity forecasts are updated daily and posted on the Bureau's heatwave service website [117].

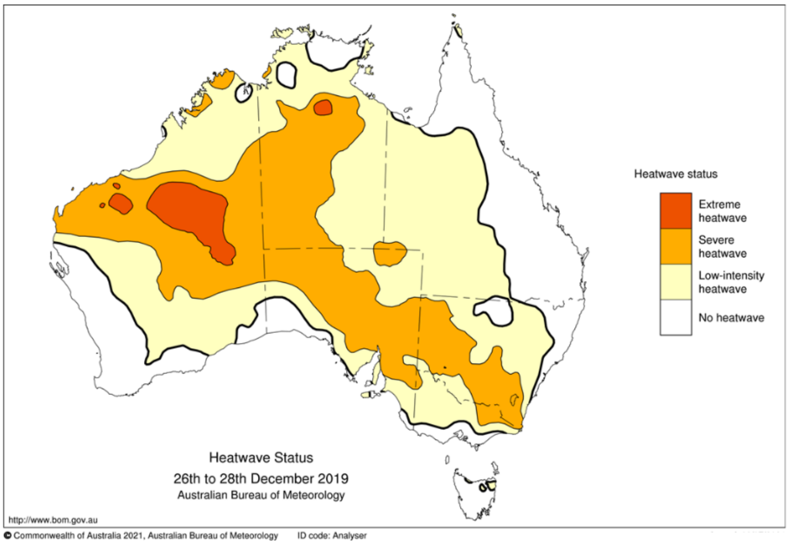


Figure 116. Map of three-day heatwave severity analysis for Saturday 28 December 2019 [186].

2.2 South Australian impact-oriented warnings and impact-based services

The South Australian authorities adopted the Bureau's heatwave service as the basis for emergency and health agencies' impact-based heatwave services in the 2018/19 summer [141]. Whilst other jurisdictions monitor the Bureau's heatwave services in support of local warnings, South Australia's State Emergency Service (SES) was the first to ingest the Bureau's digital data for their impact-based warning service.

The SES converts the Bureau's digital heatwave service data into decision-support guidance. Heatwave severity categories are assigned to weather districts by the EHF severity category with 10% or greater coverage in each district (example in Figure 118). The use of the Bureau's weather districts in Figure 117 follows a convention where hazard and emergency services partners communicate hazardous advice and warnings on common cadastral boundaries. The 10% threshold spatial convention is already used by Australian fire agencies for the assignment of daily district Fire Danger Ratings. The daily gridded data is remapped for both South Australia and Australia as a visual assessment of heatwave severity distribution (Figure 119). Additional guidance is provided for the percentage of each district affected by the three categories of heatwave severity categories described in

Table 15 including towns and cities located within each district (complete decision support guidance for this example is provided in supplementary materials).

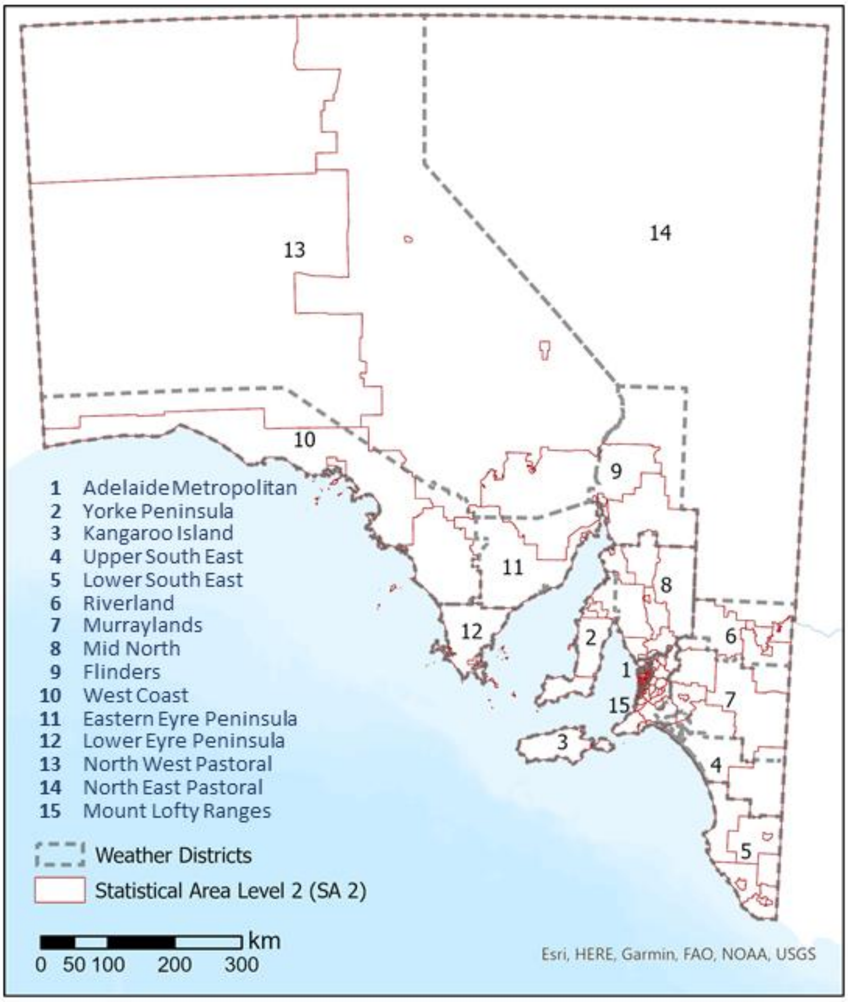


Figure 117. Bureau of Meteorology weather, South Australia Country Fire Service fire weather and State Emergency Service heatwave warning districts and SA2 Statistical Areas.

The heatwave hazard decision-support guidance assists the SES initiate and update warnings [141]. Behavioural recommendations are included according to the phase of the heatwave event. Next day heatwave conditions are released daily as a Heatwave Advice message. If any district has a severe or extreme category for the next day an impact-oriented Heatwave Warning is generated. As the heatwave progress and categories lower to Low-Intensity or Nil, a Reduced Threat Warning is issued.

The final decision for the reported heatwave category is left to the SES Duty Officer, based on the community they wish to target in their messaging. Qualitative assessment of heatwave vulnerability is based on local knowledge about affected communities and their characteristic vulnerabilities. This subjective expert-driven process is a recognised approach in the transition to quantitative impact warning although this may not be ultimately achieved [204]. The SES warning messages are in the form of a generalised impact-oriented warning as these messages include broad behavioural recommendations based upon epidemiological heatwave studies conducted in South Australia [23], [71], [120], [125], [139], [187], [216], [220], [221].

District	Wed-Today, 2019-12-27	Thu-Sat, 2019-12-28	Today-Sun, 2019-12-29	Sat-Mon, 2019-12-30	Sun-Tue, 2019-12-31	Mon-Wed, 2020-01-01	Tue-Thu, 2020-01-02
Adelaide Metropolitan	Low	Low	Severe	Low			
Mount Lofty Ranges	Low	Low	Severe	Low			
Yorke Peninsula	Low	Low	Severe	Low			
Kangaroo Island			Low	Low	Low		
Upper South East		Low	Severe	Low			
Lower South East		Low	Severe	Low			
Riverland	Low	Severe	Severe	Severe	Low		
Murraylands	Low	Low	Severe	Severe	Low		
Mid North	Severe	Severe	Severe	Severe	Low		
Flinders	Severe	Severe	Severe	Severe	Low		Low
West Coast	Low	Low	Severe	Low			
Eastern Eyre Peninsula	Low	Low	Severe	Severe	Low		
Lower Eyre Peninsula	Low	Low	Severe	Low	Low		
North West Pastoral	Severe	Severe	Extreme	Severe	Low	Low	Low
North East Pastoral	Low	Severe	Severe	Severe	Low	Severe	Severe

Figure 118. Seven-day South Australian district heatwave severity forecasts issued 27 December 2019.

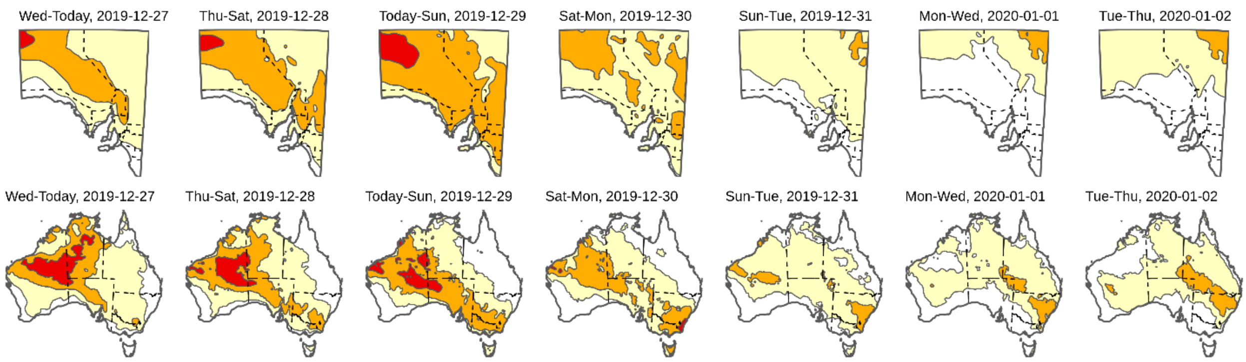


Figure 119. Seven-day heatwave severity forecasts for South Australia (top row) and Australia (bottom row), issued 27 December 2019.

In the example shown in Figure 119, the first column shows the three-day heatwave severity for weather districts ending on the day of issue. In this example, the SES would have considered a heatwave warning for the Mid North, Flinders and North West Pastoral districts based on this guidance. The supporting maps in Figure 119 contextualise this advice. Notably, the North West Pastoral and Flinders districts have significant severe (orange) heatwave coverage, with the North West Pastoral district affected by a small but reportable (> 10%) extreme heatwave area. The Mid North severe heatwave coverage is smaller and could have been discounted. However, the extent of coverage in subsequent days suggests that it would likely have been included. Figure 118 and Figure 119 show significant coverage of severe heatwave conditions over subsequent days, guidance which would assist the SES in modifying the warning message for the protracted heatwave conditions. The National map provides additional context, showing significant severe and extreme heatwave conditions extending over the northern half of Western Australia during this period which would contextualise deployment of national resources beyond the borders of South Australia.

Specific targeted impact-based service interventions are activated by SES warnings under SA Health's Extreme Heat Action Plan [222]. In the preparedness phase responding agencies and departments review their plans, train staff and update education resources. Media extreme heat campaigns are put in place and health services are encouraged to review plans and identify vulnerable clients. The next Extreme Heat Watch phase is activated when the SES provides advice of an impending low-intensity heatwave (no public warning issued). SA Health activates their State Control Centre, appropriate heat health messages are released, and health services raise their situational awareness and action Extreme Heat plans in readiness for full activation if a 'Severe Heatwave – Watch and Act' is issued. Once a severe heatwave is forecast the SES releases a public Severe Heatwave – Watch and Act alert, SA Health monitors internal health network reports for health impacts, capacity and capability, and provides coordinated daily briefings to SES and Health Media. Health Media release 'heat health warnings' whilst ambulance services and local health networks activate their components of the Extreme Heat Plan. Through SA Health's action plan, Telecross-REDi activates its extreme heat plan in response to SES alerts [141]. The service (https://www.redcross.org.au/get-help/community-services/telecross/telecross-redi) supports registered vulnerable people by calling them daily during declared heatwaves.

2.3 Towards a national system: Reducing Illness and Lives Lost from Heatwaves project

Health studies in South Australia [23], [71], [120], [125], [139], [187], [216], [220], [221], Western Australia [122], [223], News South Wales [123], Tasmania [224] and Victoria [188], [225], [226] have delivered heatwave vulnerability data that has assisted local warning authorities to develop impact-based heatwave warnings and targeted services. An Australian capital cities heatwave vulnerability study [227] has provided further insight to these authorities. However, these disaggregated epidemiological studies using different heatwave definitions have not allowed the development of a national operational impact-based heatwave service.

The development of nationally consistent impact-based heatwave services requires an understanding of where and when people are vulnerable to heatwaves using a consistent heatwave definition. This gap was addressed when the PEAN [228] Reducing Illness and Lives Lost from Heatwaves (RILLH) project combined linked person-level demographic and health data [194] with the Bureau's operational heatwave climatology (EHF), community, and built-environment data to provide a unique heat-health vulnerability dataset for Australia [193]. Access to these data sets required collaboration between the Department of Agriculture, Water and Environment, Australian Department of Health, Australian Institute of Health and Welfare, Australian Bureau of Statistics, Geoscience Australia, Bushfire and Natural Hazards Cooperative Research Centre and Bureau of Meteorology. These agencies shared very large datasets with varying degrees of sensitivity that required the use of securely managed computing environments.

Methodological and analytical approaches focused on understanding how health outcomes related to heatwaves were modified by individual and neighbourhood characteristics at different spatial scales. The RILLH Project using mortality and morbidity data (GP visits, ambulance callouts, and ED visits) demonstrated the vulnerability of places and people to the effects of heatwaves [216], [229]–[232]. At its highest level, the Project identified that mortality/morbidity increases during heatwaves in Australia, but the magnitude of the increase varies by location and significantly across relatively short geographic distances. It also demonstrated that individuals and neighbourhood level factors are important in driving patterns of risk of dying and getting sick during heatwaves. Individuals are more susceptible if they have certain underlying health conditions, are from vulnerable groups or live in heat exposed neighbourhoods.

There is considerable spatial variation in heat vulnerability and health outcomes across Australia. The RILLH study estimated the percent increase risk in health outcomes (mortality/GP visits) during heatwaves (defined by EHF) using a time-stratified case-crossover design with a conditional logistic regression model [193]. Figure 120 shows spatial percent increase (using relative risk) variability for mortality (2007-2017) and morbidity (2011-2016) in South Australia, extracted from the national RILLH project. It highlights the need to consider spatial variability in the development of targeted impact-based services. Whilst the SA SES case study resolved weather districts as the spatial resolution for warnings results from the RILLH project demonstrate that targeted health services can be delivered at a finer scale. This is particularly evident in this example in the east of the state where the top relative risk category (dark red) for primary care attendance during severe/extreme heatwaves corresponded to a very low relative risk for mortality (light blue) in a subset of the Murray Lands (see Figure 117) for overlay of weather districts and SA2). Effective primary care may have reduced the risk of death during severe/extreme heatwaves in this instance. Further investigation into local primary care policies in this region is merited, it appears to have been effective in reducing the risk of death.

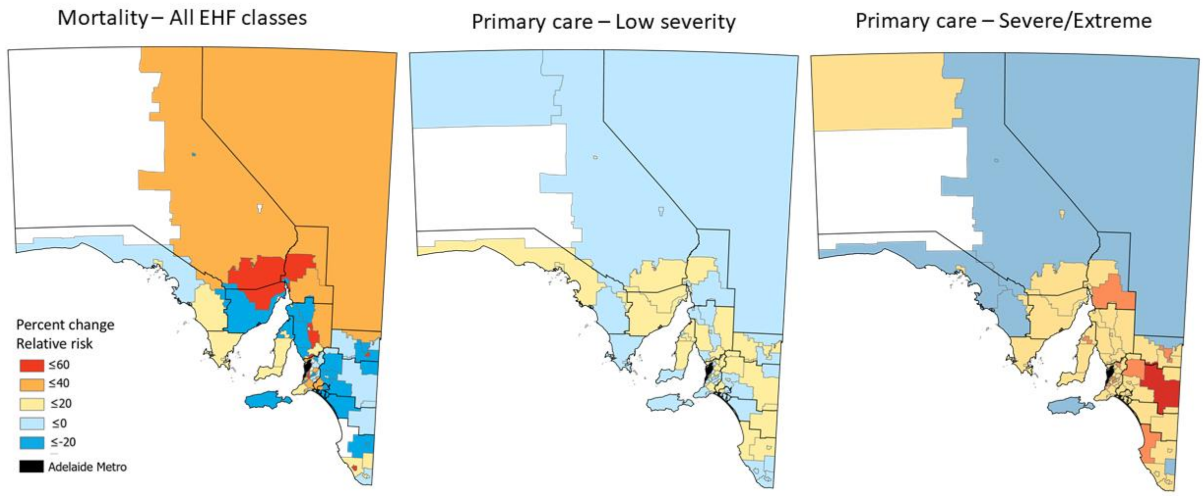


Figure 120. Spatial distribution of mortality (2007-2017) for all heatwaves, and morbidity (2011-2016) for low and severe/extreme heatwaves.

In this case, RILLH project results support investigation for the effectiveness of primary care interventions and future development of weather district behavioural recommendations based on a common national heatwave forecast service.

Under a coherent national impact-based heatwave service, heatwave forecasts would support local emergency services heatwave warnings that would activate local health plans. Health authorities would incorporate higher resolution forecast products to deliver targeted services.

3. Discussion

Demand for effective heatwave warning services has grown over recent years with the changing frequency and intensity of heat-related severe weather events [5], [233], [234]. Coherent development and improved understanding of heatwave vulnerability have been an important step towards a comprehensive coherent national heatwave service where all warning agencies operate within a common decision-support framework which also supports policy development where mitigation agencies deliver targeted service interventions and more nuanced impact-oriented warnings and services.

The heatwave service forecasts 7 days of heatwave severity daily. This is an atypical type of hazard forecast because the Bureau's local percentile-based temperature index's (EHF) statistical classification of severity is consistent with the risk of impact. The EHF severity index provides information about the relative magnitude of maximum and minimum temperature extremes at each location which can be summarised by region or weather district. From this perspective, it has the character of a warning which readily supports local emergency service warning decisions. Epidemiological studies based on EHF have shown a good fit with health impacts in many studies.

Formal responsibility for heat-hazard warnings is vested with local agencies who translate the heatwave service hazard forecast into impact-oriented warnings. The slow fuse nature and forecast-ability of the heatwave hazard make it well suited to the use of impact-oriented warnings. Depending on the heatwave severity, the extent of coverage of the weather district and a qualitative assessment of community-level vulnerability a heatwave warning may be issued. These warnings are targeted at the relevant community and include broad behavioural recommendations. These are described as 'calls to action' in the Australian warning context. As such, they can be described as impact-oriented warnings [204] in that they include information about both the hazard and advice on what people should do to mitigate the potential harm. Partnerships between the Bureau and response agencies has enabled the creation of impact-oriented warnings.

The schematic diagram shown in Figure 121 represents the transition from hazard advice (hazard-based national heatwave service, dark blue), supported by vulnerability information, to the impact-oriented warning service (impact-based warning and data service, pale blue). The local SES case (top line) is an example where a local emergency services agency sourced heatwave hazard information from the national weather agency, converted this information into decision-support guidance and combined this with local knowledge of their user groups and local heatwave vulnerability studies to generate an impact-oriented warning service. The lower pathways through 'vulnerabilities by neighbourhood and individual' shows the potential benefit of more nuanced health information utilised by the RILLH project discussed in the previous section. It also marks the transition where the hazard-based data is supplied in a nationally consistent warning decision-support format.

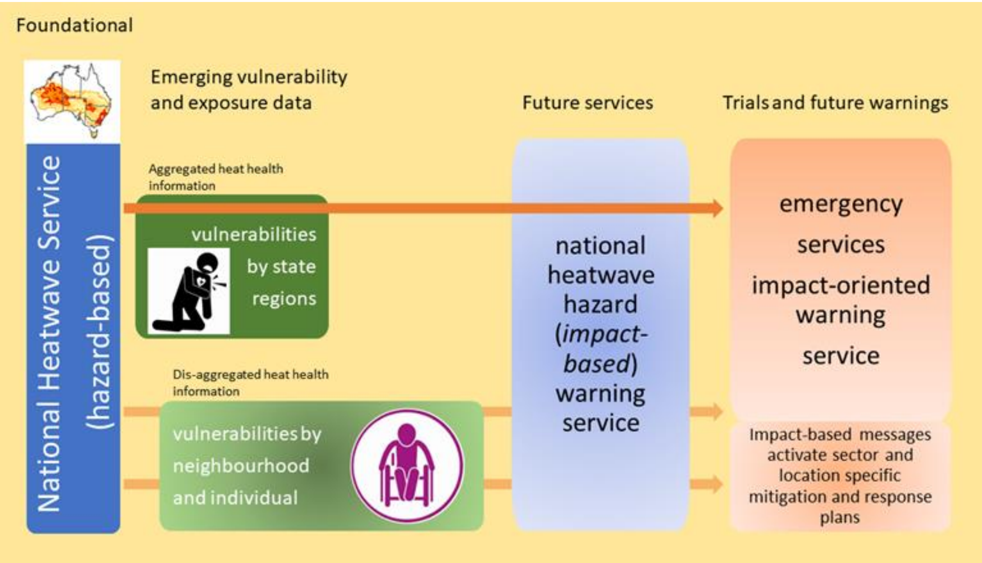


Figure 121. Evolution of a comprehensive national heatwave warning service (authored for this article).

The delivery of heatwave warnings and tailored sector-specific services is shown at the bottom of Figure 121 where the impact-oriented warning service model initiated in South Australia is rolled out for all Australian jurisdictions. Nationally coordinated messaging will also allow the Bureau to release (impact-oriented) national heatwave warnings, noting that for the first time all jurisdictions will use the same guidance to coordinate their public warnings and targeted messages. The national heatwave vulnerability data set (bottom of Figure 121) enables the development of national heatwave impact services that are resolved at a higher resolution than the activating warnings.

Heatwave health studies like the RILLH project support the development of more targeted services determined by place and personal circumstance. Opportunities for spatially targeted interventions, response plans and outreach as well as generalised input for impact-oriented warnings can be developed from this insight. Managers of medical facilities, utilities and infrastructure would benefit from planning and policy insights, improved mitigation advice, and targeted warning messages that incorporate location-based vulnerability. Doctors could monitor specific patients and modify drug programs; utility managers adjust maintenance regimes and infrastructure managers adjust the exposure of plant and equipment.

RILLH results provide data that can support other jurisdictions to establish or extend targeted impact-based health services. As an example, the Australian Red Cross can use RILLH results to develop a national recruitment campaign of vulnerable people into the successful Telecross-REDi service currently operated in South Australia. Local engagement can be informed by the relevant factors found to influence vulnerability.

After extensive consultation with health and emergency service partners, the Bureau plans to commence a formal national heatwave warning service in late 2021. The heatwave warning will utilise EHF and be issued up to 3 days ahead of the expected impact. The warning can be described as a hazard-based warning but will include impact-oriented messaging which is more effective in mobilising public response. The 3-day warning lead time was chosen based on a perceived balance between the certainty of impact, required time to initiate mitigation activity and the risk of over-warning the community.

In addition to the new public warning, the Bureau is planning to provide decision-support advice directly to response agencies 7 days ahead of expected impact. This early advice provides sufficient time for interventions such as outreach to the vulnerable and cancellation of outdoor events to mitigate the expected impacts. We have described this as impact-based service development. The understanding of exposure and vulnerability means that there can be confidence in the types of interventions required to mitigate harm and the timing of those activities.

Studies like the RILLH project provide a significant leap forward in the understanding of the location and nature of impact which has been used to inform the development of an emergent national impact-based warning service. The RILLH insights required collaboration between several agencies where data sharing and privacy requirements optimised analysis scale and protected identity.

4. Conclusions

We have charted the evolution of Australia's heatwave service since its inception 7 years ago. The Bureau's initial hazard-based heatwave service was founded on EHF and utilized by South Australian emergency services to deliver impact-oriented heat-health warnings and targeted services. This experience along with international guidance on the requirements of impact-based services highlighted a gap in national level vulnerability data.

This gap was addressed through national collaboration between hazard, health, demographic and environmental science data custodians which made the development of a national heatwave vulnerability data set possible. This also established the capability to safely share and query impact data. Further development to transition impact-based services for flood, dust, bushfire, smoke and other natural hazards are anticipated.

The Bureau's decision-support service combined with heatwave vulnerability data will enable coordinated national impact-oriented heatwave warnings, local heat-health warnings, and targeted services across Australia. The service will be more comprehensive once it includes decision-support services, with location-specific behavioural recommendations and targeted mitigation measures based on accurate, timely heatwave warnings. It will be further improved as it moves to include seasonal forecasts [96] applying EHF across climate, multi-day, multi-week and multi-decade prediction time scales. Longer time frames provide the opportunity to appropriately prepare for both good and bad seasons.

These services will help to mitigate the impact of Australia's most deadly natural hazard and reduce the burden of illness amongst those most vulnerable to heatwaves. Continued collaboration amongst data custodians is required to measure the effectiveness of new impact-based services. The transition from hazard-based to impact-based warning services marks a significant step on the journey towards the development of a comprehensive heatwave warning service for Australia.

Author Contributions: Conceptualization, writing—original draft preparation, writing – review and editing, Nairn, J. and Mooney, C.; South Australian decision-support guidance – data curation, - software, - visualization, Ostendorf, B; RILLH project - data curation, - formal analysis, Beaty, M and Varghese, B. All authors have read and agreed to the published version of the manuscript.

Funding: The Reducing Illness and Lives Lost from Heatwaves project funded the publication of this article. RILLH results produced under a 12-month DIPA [192] funded PEAN [228] project. The Bureau of Meteorology led the RILLH project, partnered by the Australian Bureau of Statistics, Department of Health, Australian Institute of Health and Welfare, Geoscience Australia and the Bushfire and Natural Hazards CRC. This article does not represent the express view of the Department of Health.

Data Availability Statement: Data used to generate Figure 119 and Supplementary data were created under contract for the South Australian State Emergency Service by the University of Adelaide, utilizing Australian Digital Forecast Database gridded data. Heatwave forecasts are released to Australian authorities requesting access as detailed in this link. The Australian Digital Forecast Database (bom.gov.au). Data as part of the Multi-Agency Data Integration Project are available for approved projects to approved government and non-government users at [https://www.abs.gov.au/websitedbs/D3310114.nsf/home/Statistical+Data+Integration+-+MADIP] [235].

Acknowledgments: Dr Robert Fawcett from the Bureau of Meteorology, Melbourne Australia assisted in the production of Figure 116 and is a valued collaborator in the development of heatwave services in Australia.

Conflicts of Interest: Operational heatwave diagnostics in, Figure 119 and Supplementary spreadsheet were developed under contract to the South Australian State Emergency Service by Bertram Ostendorf from the University of Adelaide. Heatwave analysis and operational forecast data were sourced from the Australian Bureau of Meteorology.

Supplementary Materials

South Australian State Emergency Service (SES) daily decision-support spreadsheet pages, issued 27 December 2019

District Summary

District	Wed-Today, 2019-12-2	Thu-Sat, 2019-12-28	Today-Sun, 2019-12-29	Sat-Mon, 2019-12-3	Sun-Tue, 2019-12-31	Mon-Wed, 2020-01-	Tue-Thu, 2020-01-02
Adelaide Metropolitan	Low intensity	Low intensity	Severe	Low intensity			
Mount Lofty Ranges	Low intensity	Low intensity	Severe	Low intensity			
Yorke Peninsula	Low intensity	Low intensity	Severe	Low intensity			
Kangaroo Island			Low intensity	Low intensity	Low intensity		
Upper South East		Low intensity	Severe	Low intensity			
Lower South East		Low intensity	Severe	Low intensity			
Riverland	Low intensity	Severe	Severe	Severe	Low intensity		
Murraylands	Low intensity	Low intensity	Severe	Severe	Low intensity		
Mid North	Severe	Severe	Severe	Severe	Low intensity		
Flinders	Severe	Severe	Severe	Severe	Low intensity		Low intensity
West Coast	Low intensity	Low intensity	Severe	Low intensity			
Eastern Eyre Peninsula	Low intensity	Low intensity	Severe	Severe	Low intensity		
Lower Eyre Peninsula	Low intensity	Low intensity	Severe	Low intensity	Low intensity		
North West Pastoral	Severe	Severe	Extreme	Severe	Low intensity	Low intensity	Low intensity
North East Pastoral	Low intensity	Severe	Severe	Severe	Low intensity	Severe	Severe

Figure 122S. Weather district heatwave severity forecasts issued 27 December 2019.

Figure 122S has been produced as Figure 118 in a condensed format in the main text. This figure provides a high level over view of the 7-day forecast of heatwave severity where each category displayed is the highest severity with at least 10% coverage of the weather district.

Figure 123S provides 7-day forecast severity for town or city locations in each of the weather districts. This provides the SES with finer scale decision support guidance which may affect whether they decide to adopt the high-level district guidance in Figure 122S, or consider a potentially different severity category forecast for a significant population centre. For example, on the Saturday-Monday, 2019-12-30 (column 7, Figure 123S) Naracoorte in the Lower South East weather district is forecast to have a severe heatwave (1.2 severity), whilst other towns including the largest city, Mount Gambier are forecast to have a low-intensity heatwave. The district assessment in Figure 122S supports discounting the severe heatwave forecast for Naracoorte as the area affected is less than 10% of the weather district, and the larger population centres have forecasts for low-intensity heatwaves. Figure 124S provides additional support for this decision with Lower South East weather district forecast to experience 5% severe and 81% low-intensity heatwave coverage. Figure 125S and Figure 126S provide an additional visual guide to the distribution of forecast heatwave severity.

Towns Summary

Wed-Today, 2019-12-27	Thu-Sat, 2019-12-28	ID	District	Town	Today-Sun, 2019-12-29	Sat-Mon, 2019-12-30	Sun-Tue, 2019-12-31	Mon-Wed, 2020-01-01	Tue-Thu, 2020-01-02
1.8	1.9	1	North West Pastoral	Pukatja / Ernabella	***2.1***	1.1	0.3	0.1	0.2
0.8	1.1	2	North West Pastoral	Marla	***1.5***	0.8	0.2	0	0.1
1.2	1.1	3	North West Pastoral	Coober Pedy	***1.4***	0.8	0.1	0	0
0.2	0.7	4	North West Pastoral	Oak Valley	***2.3***	0.8	0.1	-0.1	0.2
1.5	1.4	5	North West Pastoral	Roxby Downs	***1.8***	1	0.1	-0.1	0
1.8	1.7	6	North West Pastoral	Tarcoola	***2***	0.9	0	-0.1	0
1.3	1.3	7	North West Pastoral	Woomera	***1.7***	0.8	0	-0.1	-0.1
0.7	1.1	8	North East Pastoral	Oodnadatta	***1.5***	1	0.2	0	0.1
0.4	0.5	9	North East Pastoral	Moomba	***0.7***	0.9	1	1	1
0.5	0.6	10	North East Pastoral	Marree	***0.9***	0.5	0.1	0	0
0.8	0.9	11	North East Pastoral	Leigh Creek	***1.1***	0.6	0.2	0	0.1
0.9	1	12	North East Pastoral	Yunta	***1.6***	0.9	0.1	-0.1	-0.1
-0.2	-0.1	13	West Coast	Nullabor	***0.2***	-0.1	-0.1	-0.2	-0.1
-0.1	-0.2	14	West Coast	Ceduna	***0.2***	0	-0.1	-0.2	-0.1
0.5	0.8	15	West Coast	Wudinna	***2***	0.9	0	-0.2	-0.1
-0.2	-0.1	16	West Coast	Elliston	***0.2***	0	-0.1	-0.2	-0.1
0.4	0.4	17	Eastern Eyre Peninsula	Whyalla	***0.9***	0.5	-0.1	-0.2	-0.2
0.3	0.7	18	Eastern Eyre Peninsula	Kimba	***2***	0.9	0	-0.2	-0.1
0	0.2	19	Eastern Eyre Peninsula	Cleve	***1.2***	0.7	0	-0.1	-0.1
0.1	0.2	20	Lower Eyre Peninsula	Cummins	***1.6***	0.7	0	-0.2	-0.1
0	-0.1	21	Lower Eyre Peninsula	Coffin Bay	***0.4***	0.1	0	-0.1	-0.1
-0.1	0	22	Lower Eyre Peninsula	Port Lincoln	***0.5***	0.2	-0.1	-0.1	-0.1
1.2	1.1	23	Flinders	Hawker	***1.3***	0.7	0.1	-0.1	0
0.8	0.8	24	Flinders	Port Augusta	***1.4***	0.7	0	-0.2	-0.1
1.1	1.3	25	Flinders	Orroroo	***1.6***	0.8	0	-0.1	-0.1
0.5	0.6	26	Mid North	Port Pirie	***1.3***	0.7	-0.1	-0.2	-0.1
1.1	1.4	27	Mid North	Jamestown	***1.9***	0.9	0	-0.1	-0.1
0.6	0.7	28	Mid North	Snowtown	***1.5***	0.7	-0.1	-0.2	-0.2
0.9	1.1	29	Mid North	Clare	***1.9***	0.9	-0.1	-0.2	-0.1

0.5	0.9	30	Mid North	Roseworthy	***1.5***	0.8	-0.1	-0.2	-0.2
0.5	0.8	31	Mount Lofty Ranges	Nuriootpa	***1.4***	0.6	-0.1	-0.2	-0.1
0.2	0.6	32	Mount Lofty Ranges	Stirling	***1.5***	0.7	-0.1	-0.1	-0.1
0.3	0.5	33	Mount Lofty Ranges	Mount Barker	***1.4***	0.7	0	-0.1	-0.2
0.1	0.2	34	Mount Lofty Ranges	Strathalbyn	***0.9***	0.4	-0.1	-0.2	-0.2
-0.1	0	35	Mount Lofty Ranges	Victor Harbor	***0.3***	0.1	-0.1	-0.1	-0.2
-0.2	-0.2	36	Mount Lofty Ranges	Parawa	***0.2***	0	-0.1	-0.2	-0.2
0.4	0.8	37	Adelaide Metropolitan	Elizabeth	***1.5***	0.7	-0.1	-0.2	-0.1
0.2	0.4	38	Adelaide Metropolitan	Adelaide	***1***	0.4	-0.1	-0.2	-0.1
0.1	0.2	39	Adelaide Metropolitan	Glenelg	***0.4***	0.1	-0.1	-0.2	-0.1
0	0.2	40	Adelaide Metropolitan	Noarlunga	***0.6***	0.2	-0.1	-0.2	-0.1
0.1	0.2	41	York Peninsula	Kadina	***0.7***	0.2	-0.2	-0.2	-0.2
0.1	0.3	42	York Peninsula	Maitland	***1.1***	0.5	-0.1	-0.2	-0.1
0	0.2	43	York Peninsula	Minlaton	***1***	0.5	0	-0.1	-0.1
-0.2	-0.2	44	York Peninsula	Edithburgh	***0***	-0.1	-0.2	-0.2	-0.2
-0.1	-0.1	45	York Peninsula	Stenhouse Bay	***0.2***	0	-0.1	-0.2	-0.2
-0.2	-0.2	46	Kangaroo Island	Kingscote	***0.2***	0.1	-0.1	-0.1	-0.2
-0.1	0	47	Kangaroo Island	Parndana	***0.8***	0.4	-0.1	-0.1	-0.1
0.6	0.9	48	Riverland	Waikerie	***1.8***	1.1	0.1	-0.1	-0.1
0.8	1.1	49	Riverland	Renmark	***1.9***	1.2	0.2	-0.1	-0.1
0.1	0.2	50	Murraylands	Murray Bridge	***1***	0.5	-0.1	-0.2	-0.2
0.2	0.5	51	Murraylands	Karoonda	***1.6***	0.9	0	-0.2	-0.2
0.2	0.7	52	Murraylands	Lameroo	***1.7***	0.9	-0.1	-0.2	-0.2
-0.2	-0.2	53	Upper South East	Meningie	***0***	-0.1	-0.2	-0.2	-0.2
-0.2	0.2	54	Upper South East	Keith	***1.3***	0.7	-0.2	-0.2	-0.2
-0.2	0.3	55	Upper South East	Bordertown	***1.4***	0.7	-0.1	-0.2	-0.2
-0.2	-0.2	56	Lower South East	Robe	***-0.2***	-0.2	-0.2	-0.2	-0.2
-0.2	0.1	57	Lower South East	Naracoorte	***1.2***	0.7	-0.1	-0.1	-0.2
-0.2	0	58	Lower South East	Coonawarra	***0.8***	0.4	-0.2	-0.2	-0.2
-0.3	-0.1	59	Lower South East	Mount Gambier	***0.3***	0.2	-0.1	-0.1	-0.2

Figure 123S. South Australian town and city heatwave severity guidance issued 27 December 2019.

Districts

Proportion of district affected

Category	District	Wed-Today, 2019-12-27	Thu-Sat, 2019-12-28	Today-Sun, 2019-12-29	Sat-Mon, 2019-12-30	Sun-Tue, 2019-12-31	Mon-Wed, 2020-01-01	Tue-Thu, 2020-01-02
Low Intensity	Adelaide Metropolitan	91	100	57	100	4	0	0
Low Intensity	Mount Lofty Ranges	65	83	42	94	2	0	0
Low Intensity	Yorke Peninsula	59	81	65	93	7	0	0
Low Intensity	Kangaroo Island	0	1	93	84	19	0	0
Low Intensity	Upper South East	0	73	37	98	0	0	0
Low Intensity	Lower South East	0	24	69	81	0	0	0
Low Intensity	Riverland	100	50	0	21	96	0	0
Low Intensity	Murraylands	88	98	8	82	34	0	0
Low Intensity	Mid North	69	40	9	72	37	0	0
Low Intensity	Flinders	29	37	15	87	80	4	15
Low Intensity	West Coast	42	43	63	62	0	0	8
Low Intensity	Eastern Eyre Peninsula	86	88	15	86	29	0	0
Low Intensity	Lower Eyre Peninsula	47	55	50	95	25	0	0
Low Intensity	North West Pastoral	32	23	4	51	80	31	68
Low Intensity	North East Pastoral	94	72	39	65	90	50	62
Severe	Adelaide Metropolitan	0	0	43	0	0	0	0
Severe	Mount Lofty Ranges	0	1	56	1	0	0	0
Severe	Yorke Peninsula	0	0	35	1	0	0	0
Severe	Kangaroo Island	0	0	0	0	0	0	0
Severe	Upper South East	0	0	62	0	0	0	0
Severe	Lower South East	0	0	19	5	0	0	0
Severe	Riverland	0	50	100	79	0	0	0
Severe	Murraylands	0	1	92	18	0	0	0
Severe	Mid North	31	60	91	28	0	0	0
Severe	Flinders	71	63	85	13	0	0	0
Severe	West Coast	0	1	34	0	0	0	0

Severe	Eastern Eyre Peninsula	0	5	85	14	0	0	0
Severe	Lower Eyre Peninsula	0	0	48	0	0	0	0
Severe	North West Pastoral	58	71	77	48	0	0	0
Severe	North East Pastoral	6	28	61	35	10	13	15
Extreme	Adelaide Metropolitan	0	0	0	0	0	0	0
Extreme	Mount Lofty Ranges	0	0	0	0	0	0	0
Extreme	Yorke Peninsula	0	0	0	0	0	0	0
Extreme	Kangaroo Island	0	0	0	0	0	0	0
Extreme	Upper South East	0	0	0	0	0	0	0
Extreme	Lower South East	0	0	0	0	0	0	0
Extreme	Riverland	0	0	0	0	0	0	0
Extreme	Murraylands	0	0	0	0	0	0	0
Extreme	Mid North	0	0	0	0	0	0	0
Extreme	Flinders	0	0	0	0	0	0	0
Extreme	West Coast	0	0	0	0	0	0	0
Extreme	Eastern Eyre Peninsula	0	0	0	0	0	0	0
Extreme	Lower Eyre Peninsula	0	0	0	0	0	0	0
Extreme	North West Pastoral	4	6	19	0	0	0	0
Extreme	North East Pastoral	0	0	0	0	0	0	0

Figure 124S. Heatwave severity forecast by proportion of weather district, issue 27 December 2019.

Maps

State and national maps of heatwave severity

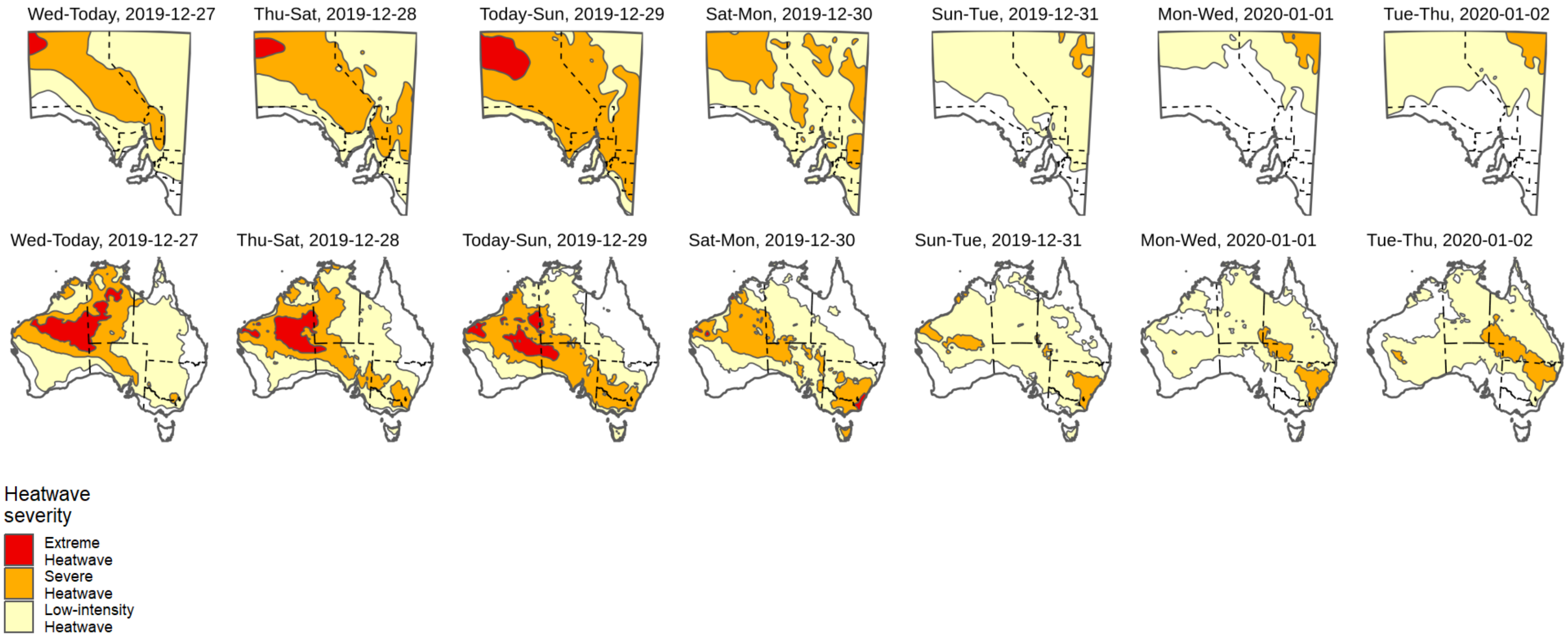


Figure 125S. Spatial heatwave severity forecasts, issued 27 December 2019.

Detailed State maps

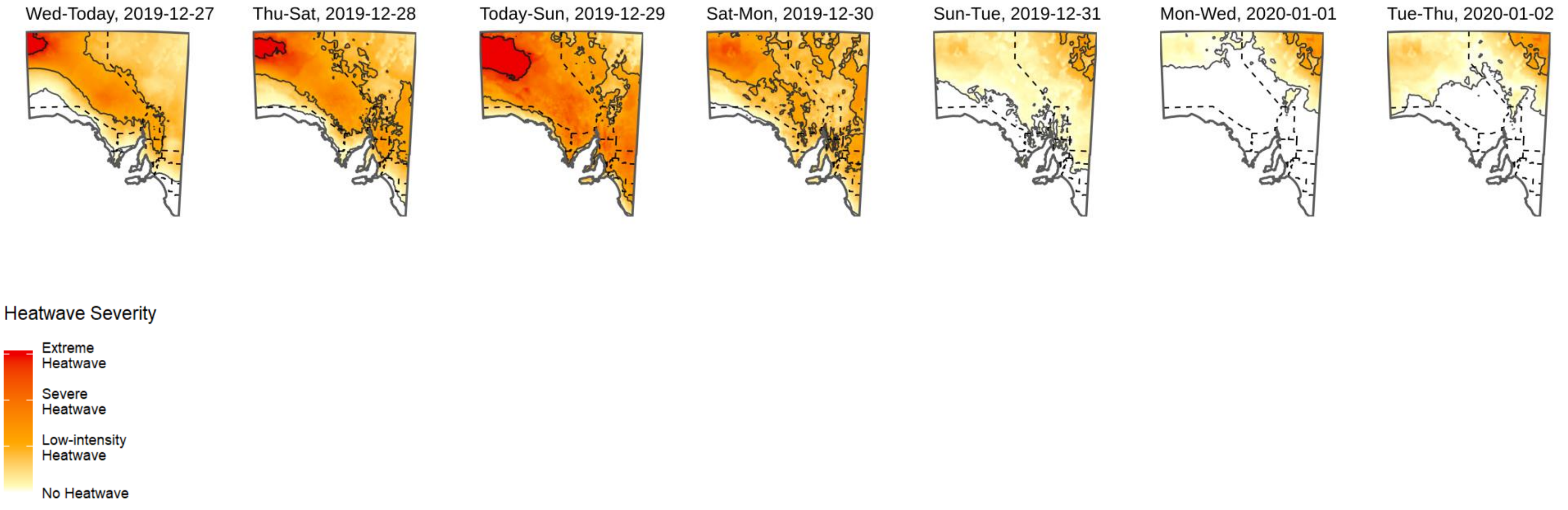


Figure 126S. Detailed heatwave severity forecasts, issued December 2019.

Chapter 6. General Discussion, Concluding Statement and Future Directions

General Discussion

The new temperature-only, percentile-based heatwave index developed in Chapter 2 measures heatwave intensity and severity. Capacity to map and analyse the heatwave climate record underpinned Australia's inaugural national heatwave service. This measure of generalised heatwave severity presented the opportunity to educate the community to the risk of heatwave impact where and whenever a vulnerable sector was exposed.

Heatwave definitions in the meteorological literature have focused on mapping climate trends of heatwaves or warm spells with some investigations into the climate and synoptic mechanisms that supported their development, longevity and intensity. These heatwave definitions focussed on percentiles of maximum, minimum and daily temperature. Simplistic meteorological maximum temperature heatwave monitoring practices in use by national weather services were at odds with a daily temperature (average of maximum and minimum) definition being used for public health warnings in Victoria [70]. Inclusion of the minimum in daily temperature captures sensitivity to accumulating heat due to the minima's modification of the diurnal temperature cycle. Widespread interpretation of heatwaves via maximum temperature alone is a cultural impediment to a climate resilient response to current and predicted increasing frequency, duration and intensity of heatwaves.

Development of the Excess Heat Factor (EHF) heatwave definition in this research initially focussed on creation of a climate record that could contextualise recorded historical impacts. Whilst humidity was recognised as a thermal stressor, the quality of humidity data in the climate record was considered to be quite poor. A temperature-only index would utilise the best data in climate records, and enable development of an effective seamless service across all prediction scales. Importantly, a temperature-only index delivers access and equity outcomes for the developing world. More complex heatwave indexes require high quality meteorological parameters (ie. humidity, radiation, wind) which can be difficult to collect in developing countries whereas the EHF can be used at any location across the globe with no additional effort.

Daily temperature (average of minimum and maximum) is used as a proxy for the diurnal heating cycle. High minimum temperature during a heatwave will result in earlier and more sustained higher temperatures the following day. Daily temperatures during a heatwave will be substantially elevated due to higher maximum and minimum temperatures.

Long- and short-term daily temperature anomalies are factored together to create local heatwave intensity. The long-term temperature anomaly samples a three-day average daily temperature record against a fixed percentile value from the local daily temperature 30-year climate record. Similarly, the short-term temperature anomaly samples the same three-day average daily temperature record against the previous local 30-day average daily temperature record. Local heatwave magnitude and local heatwave adaptation indices are factored together, producing a strong signal to noise intensity amplitude. The same methodology was suitable for monitoring coldwaves, but I did not develop the concept further here.

The temperature-only, percentile-based heatwave intensity index (Excess Heat Factor) allowed site by site analysis of the heatwave climate record but was not suited to inter-site comparison of heatwaves, as each site's climate temperature record created a unique intensity range. Points over threshold (POT) from extreme value theory (EVT) was utilised to address this issue. As a fat tail distribution, the Generalised Pareto Distribution Function (GPDF) was tested and proved to successfully match the Cumulative Distribution Function of EHF data. In effect the 'Pareto Effect' permitted a normalisation of each location's intensity via the 85th percentile of each site's EHF cumulative distribution function, creating a severity threshold which matched excess mortality in two Australian cities. Heatwaves were classified as: low-intensity (initial use of 'heatwave' for this classification was confusing to users), severe and extreme.

Climatologies for the annual incidence of heatwaves at various levels of severity were presented. Severe heatwaves occurred up to three times per year, extreme approximately once every decade. Trend in annual maximum EHF demonstrated a strong rise across southern Australia with a slight fall across some northern areas consistent with expected temperature changes expected under global warming.

A case study for the January and February 2009 extreme heatwave in southeast Australia examined Adelaide and Melbourne EHF (intensity) time-series, mapped maximum EHF and accumulated EHF (heat load). Human health impacts were successfully compared with international extreme heatwaves, a capability hitherto not possible until the development of EHF severity.

Humanitarian climate-smart Disaster Risk Reduction (DRR) and Forecast-Based Financing (FBF) can benefit from extended forecast ranges that are only possible with a temperature-only heatwave index. Cascading drought, heatwave, fire, smoke, water quality and landslip vulnerabilities have been exposed by increasing frequency, intensity and severity of heatwaves under the influence of global warming. This has led to the development of Australia's Excess Heat Factor heatwave index (EHF). Australia's temperature-only percentile-based heatwave index provides a common framework in which a comprehensive heatwave service supports communication across climate analysis and multi-day warning to multi-week preparedness disaster management time scales. Understanding the operational limitations of a temperature-only percentile-based heatwave index provides operational confidence in preparing for dangerous heatwaves.

The second paper (2) in Chapter 2 returns to the fundamental capability of EHF to reliably support an early warning system for damaging severe and extreme heatwaves.
This study examined whether the effectiveness of Australia's heatwave service is affected by inclusion of humidity in EHF across Australia's diverse climate zones and suggests a differentiated approach for heatwave warnings. The study has revealed that most of Australia's climate zones are well served by the current operational temperature-only version of EHF. Results support ongoing use of a local temperature-only percentile-based heatwave index for detection of both dry and humid severe heatwaves in 5 of Australia's 6 climate zones. This differs in Australia's hot and humid tropical climate zone. This region experiences rare, unusually dry and very humid heatwaves. A comprehensive heatwave service in the tropics needs to operate the temperature-only and humidity-included versions of Australia's Excess Heat Factor heatwave index (EHF) in order to capture unusually humid heatwave events to operate an effective warning service.

As a statistically robust heatwave intensity and severity heatwave measure EHF presented climate resilient opportunities to investigate past events, forecast near-term events and climate projection scenarios. EHF was adopted by the Bureau of Meteorology as Australia's operational forecast service [117], was included in the UK Met Office internal Global Hazard Map (UKMO, GHM) [174] to forecast the probability of heatwaves and coldwaves, and used to fulfill a Copernicus contract to provide heatwave climate projections for the Australian Health sector [148] which is now available as an open resource for assessment of future heatwave scenarios anywhere on the globe.

The 2013/14 heatwave included in the appendix in paper 1 and in paper 3 was presented to the combined Australasian Fire and emergency services Authorities Council of Australia (AFAC) and Bushfires and Natural Hazards Cooperative Research Centre (BNHCRC) 2015 Conference, presenting the new operational service, its performance and examined a sequence of significant heatwaves that affected six of Australia's seven states and Territories that summer. Breaking new ground, this presentation revealed the Australia's exposure to severe and extreme heatwaves. At this time the BNHCRC had not included heatwaves within their remittance as a natural hazard (subsequently corrected).

The Heatwaves in Queensland article was presented at the 2016 AFAC/BNHCRC conference in Brisbane. The climatology and climate change in all, severe and extreme heatwaves demonstrated that Queensland was undergoing an increase in the frequency and severity of heatwaves. Historical case studies were presented to demonstrate exposure and impacts for notable events in December 1972, February 2004, and January and November 2014. The linkage between increased severity and impacts was clearly demonstrated. Queensland Fire and Emergency Services engaged strongly with this article, subsequently securing the services of University of Queensland and Queensland Health to independently develop EHF climatology and projection data for heatwaves[109] resulting in the development of the Queensland State Heatwave Risk Assessment in 2019 [236]. Queensland Health subsequently changed their heat health plan [142] to activate on EHF rather than the previous temperature threshold system.

Collaborators who adopted EHF for the UKMO Global Hazard Map (GHM) [174] and included EHF in the AirRater app [237] co-authored a presentation for the 2017 International Biometeorology Congress in Durham, UK (Appendix C). We noted the utility EHF provided for visualising probability of severe heatwave (and coldwave) within the GHM, the high rate of successful forecasts and the extreme challenge in verifying heatwave impacts on a global scale. AirRater was included to demonstrate a system that recruits users who are susceptible to asthma in order to supply them with targeted hazardous atmospheric conditions. The app collects clinical symptoms from registered users, and was noted as a model for verification of heatwave impacts (amongst other hazards). AirRater includes EHF heatwave forecasts generated by the Bureau of Meteorology's heatwave service.

Epidemiological studies into the impact of heatwaves are historically a steep challenge for National Meteorological and Hydrological Services to assimilate within impact-based forecast and warning systems due to the wide range of heatwave measures employed. Typically, earlier heat health studies used temperature threshold definitions devised for health impacts at specific locations. These frequently included a wide range of possible meteorological parameters that were tested for significance. Maximum, minimum temperatures and humidity were frequently selected, tailored to syndromic impacts studied. Radiation and wind speed could be included for outdoor applications. These measures were tailored specifically for known stressors to human thermo-regulation for occupational activities, then translated to public health scales. The introduction of the EHF temperature-only percentile-based index appealed to health impact studies in Western Australia [122], [153], New South Wales [123]and South Australia [24], [93], [120], [125], [216], [218], [219], [230] due to intuitive interpretation, simplicity of calculation, and its normalisation for ease of inter-site comparison.

EHF was tested in Paper 5 for published extreme heatwave events around the world, testing the validity of the EHF exposure/impact relationship for events outside Australia. It was found to have good predictive skill for these extreme heatwaves, and provided a means by which these disparate events could be compared and contrasted.

The extended abstract for the 2019 AFAC Conference (Paper 6) has been included as it captured an extraordinary spring and summer of heat. For the first time in recorded history, Queensland's wet tropical forests burnt in unusually dry and hot heatwave conditions during spring, November 2018. The summer that followed produced Australia's hottest January (2019) on record. Most of Australia was impacted by very much above average to highest on record EHF (intensity/severity), apart from the southwest of Western Australia which was below average. South Australian agencies (State Emergency Service (SES), Department of Health and Wellbeing, Forensic Science SA, Australian Red Cross and the University of Adelaide) participated in this study, demonstrating how they engaged with heatwave forecasts in a new decision support system to activate heatwave warnings and plans. These are the first Australian examples of impact-based heatwave services that had been linked to the Bureau's hazard-based heatwave service.

Paper 7, Australia's Black Summer heatwave impacts was requested by the Australian Journal of Emergency Management editorial board for their January 2021 edition. Significant drought had affected SE Australia in the lead up to the Black Summer Bushfires. Severe and extremes heatwaves were shown to precede significant property loss associated with that summer's mega-fires. Bushfires grew rapidly under the influence of unusual enhanced overnight fire behaviour, attributable to high minimum temperatures. Reduced nocturnal inversions resulted in unusually higher winds and lower relative humidity, enhancing fire behaviour. Fire behaviour that normally reduced overnight remained elevated resulting in bigger fires that spread further than expected, a compounding effect of bushfire cascading after extreme heatwaves. The article noted the role of extreme heatwaves within an escalating cascade of climate change driven natural hazards (drought, heatwave, fire and smoke) that resulted in significant loss of life and damage.

A presentation to 2020 The Royal Commission into National Natural Disaster Arrangements [189] used this material to advise on the contribution of severe/extreme heatwaves to the elevated fire behaviour experienced.

Conference contributions to the International Congress of Biometeorology (Durham, 2017), AFAC/BNHCRC Conference (Perth, 2018), and Australian Public Health Conference (online, 2020) track the growing sophistication in application of EHF within early warning systems (Appendix C). The 2017 Durham conference shared how EHF skill in Australian epidemiological studies had led to desire for a national heatwave warning framework. A working group was established by the Australian and New Zealand Emergency Council (ANZEMC) which reports to Emergency Management Australia (EMA). Within ANZEMC's Hazard Services Forum, The Bureau of Meteorology engaged with emergency services from each state and territory, and with representatives from EnHealth (Environmental Health, subcommittee answering to Australian Health Protection Principal Committee - AHPPC) to carry out this work.

The 2018 Perth conference progressed this theme, demonstrating prototype impact-based heatwave warning systems developed in South Australia. Multi-disciplinary co-authors from meteorological, social, spatial and health sciences, and emergency services demonstrated the partnerships required to build effective heatwave warning and impact-based services. The 2020 APH conference marked a significant turning point in the step toward impact-based hazard services. Progress in reduction of harm from natural hazards was addressed through collaborative partnerships between hazard and impacted sector data custodians. The public health community was put on notice of new resources arising from the "Reducing Illness and Lives Lost from Heatwaves" (RILLH) project that would provide patterns of heat mortality and illness vulnerability across major cities and regional areas.

Paper 8. 'Australia's transition from hazard-based to impact-based heatwave warnings and targeted services' has been submitted to IJDRR. Spatial heterogeneity of heatwave mortality was demonstrated to be responsive to primary health care interventions at different levels of heatwave severity. Capacity to offer nationally coordinated heatwave warnings and targeted impact-based services in Australia is enabled by RILLH project outcomes.

Concluding Statement

This thesis has developed and introduced the capacity to measure, track, forecast and establish a heatwave impact-oriented early warning system.

Research reported in this study focused on development of a definition that could support the foundations for a comprehensive national heatwave service. Early gains from an Australian heatwave definition included improved operational analysis skill, detection of climate trends, forecast diagnostics and knowledge sharing. Subsequent demand from epidemiologists for this new heatwave climate data for heat health exposure/impact studies (see Appendix A) raised health sector demand for national and tailored impact-oriented early warning systems. This work has identified a collaborative mechanism that can readily be applied to other impacted sectors.

Creation of a national heatwave early warning system is a very large challenge. Whilst heatwaves are slow to become established and are readily forecast with multiple day lead times, they are not easily accommodated within current early warning systems. Dangerous, extreme heatwaves affect much larger regions than other natural hazards with unexpected consequences. Federated state and territory system vulnerabilities have been revealed when extreme heatwaves occur. This is particularly apparent when the distributed energy system is exposed to the very large footprint of extreme heatwaves. Normal energy capacity is drastically impacted when energy demand is high across many impacted jurisdictions whilst generation and transmission capacity has been reduced. Failure of normally reliable utilities and infrastructure during these dangerous heatwaves impacts health and business sectors apart from direct heatwave impacts to the natural environment. The current relative infrequency of extreme heatwaves makes it difficult to allocate resources to mitigate this challenge. However, the ability to demonstrate increased frequency, duration, severity and footprint of heatwaves in climate and projection data provides compelling support for policy change.

The combination of a novel heatwave intensity utilising long- and short-term temperature anomalies with extreme value theory to create normalised heatwave severity categories has produced a seamless heatwave toolset in time and space. This is a unique and advantageous attribute amongst other atmospheric hazards.

Future Directions

Research and services will grow as heatwave impacts continue to increase in a warming world. The creation and application of EHF has set the stage for effective impact-based early warnings and targeted services in Australia.

The application of extreme value theory to a temperature-only, percentile-based heatwave intensity index has provided a valuable tool for scaling the heatwave hazard to human and natural system impact. There may be potential in considering whether this application of extreme value theory could be applied to other natural hazards. It is noteworthy that the heatwave intensity index was composed by factorising a long- and short-term anomaly, creating a quadratic temperature function. A similar concept may be able to be applied to other natural hazards, where a long-term climate anomaly is factored with a short-term weather anomaly.

The wet tropics vulnerability to very dry and very humid heatwaves will require additional investigation to understand the underlying mechanisms for these unusual events. Research is required into how very dry and very humid heatwaves occur in the wet tropics. Dangerously high wet bulb temperature is very likely associated with very hot and dry continental air masses interacting with warming shallow seas. Sea breeze mechanisms recirculate extremely hot continental airmasses within a coastal transition zone, that builds a hot, very humid marine boundary layer which raises wet bulb temperature. Research into this mechanism through climatological and numerical model studies will offer opportunities to anticipate their occurrence and develop mitigation policies. This mechanism may impact more populous southern coastal communities where shallow summer marine wind changes fail on the coast adjacent persistent deep heatwave boundary layer. Marine changes can slowly deepen and build higher wet bulb temperature at the hot coastal interface.

Extension of these heatwave studies to other humid tropical climates subject to global warming would be highly beneficial for parts of SE Asia and equatorial/tropical Africa and South America.

Occupational exposure, intensive agriculture, environment [35], [157], infrastructure [238], power [239] and water utilities will need to develop risk assessments, mitigation and adaptation strategies. Collaborative exposure/impact studies have been demonstrated through the RILLH project in paper 8. Each of the impact sectors identified above can be engaged to safely share impact and exposure data required to build awareness of risk. An emphasis on safe data sharing between data custodians is required to build effective planning and response in sectors yet to appreciate this risk. New multi-disciplinary studies must be prioritised and supported at all levels of leadership within government, businesses, authorities and academic organisations.

New surprises are to be expected as extreme phenomenon break past records. This may reveal new impacts that emerge from cascading natural hazards, as has been revealed when drought increases the intensity of heatwaves and manifests in megafires. Collaborative studies utilising Australia's heatwave severity climatology would be beneficial in understanding the cascade/compound relationship between drought, heatwave, bushfire, dust and smoke hazards. International extension to other locations with similar climatic exposures would also be valuable.

Further development of early warning systems to coordinate messages across authorities is required to build and sustain community confidence. Community confidence requires an education strategy focussed on building resilience models that support effective preparation, mitigation and responses to heatwaves.

Widespread availability of the climate parameters used to create the excess heat factor present an opportunity to extend heatwave risk communication to low- and middle-income countries. Comprehensive climate data can be included as a community engagement tool to raise awareness of risk, and assist communities develop stronger adaptation and mitigation strategies, including early warning systems.

This thesis has not presented the use of the excess heat factor in climate projection data. There is a significant opportunity to investigate the performance of this index in climate projection data, and to apply this to vulnerable sectors according to exposure scenarios.

The use of the same temperature-only, percentile-based heatwave severity index in the climate record, multi-day and multi-week forecasts and climate projection data is novel in the atmospheric sciences. The simplicity of the algorithm provides the unique opportunity for user hazard awareness using the same algorithm within the climate record, wide spread sector impact assessment from pooling the climate record with impact data, user adaption and mitigation responses to multi-day and multi-week forecasts, and early impact-oriented warnings and policy settings from multi-decade projection forecasts.

Finally, EHF has been presented as a valuable tool for education in the climate record, seasonal and early warning systems and for application within climate projection data. There is unique utility in a severity index that can be applied seamlessly, supporting effective communication across community, health and emergency management sectors and policy makers. This does not preclude the need for other heatwave indices designed to assist decision makers at finer time scales or within specific activities or industries. An area in which additional research will need to continue.

References

[1] R. Amery, S. Greenwood, and Jasmin Morley, *Kaurna Warrapiipa, Kaurna Dictionary*. Adelaide, South Australia: Kaurna Warra Pintyanthi, Discipline of Linguistics, School of Humanities in asscoation with Wakefield Press, 2021. Accessed: Mar. 22, 2022. [Online]. Available: https://universityofadelaide.app.box.com/s/s9hnmdh8eao1wzb4js2p21v8pw2jhi7f

[2] J. Nairn, "To assess strategies for reducing health and business impacts of severe and extreme heatwaves - Churchill Trust," *Churchill Trust*, 2013. https://www.churchilltrust.com.au/project/to-assess-strategies-for-reducing-health-and-business-impacts-of-severe-and-extreme-heatwaves/ (accessed Jul. 26, 2021).

[3] D. Lowe, K. L. Ebi, and B. Forsberg, "Heatwave Early Warning Systems and Adaptation Advice to Reduce Human Health Consequences of Heatwaves," *International Journal of Environmental Research and Public Health*, vol. 8, no. 12, pp. 4623–4648, Dec. 2011, doi: 10.3390/ijerph8124623.

[4] K. L. Ebi, "Towards an Early Warning System for Heat Events," *Journal of Risk Research*, vol. 10, no. 5, pp. 729–744, Jul. 2007, doi: 10.1080/13669870701447972.

[5] G. R. McGregor, P. Bessemoulin, K. Ebi, and B. Menne, *Heatwaves and Health: Guidance on Warning-System Development*, no. 1142. 2015. Accessed: Oct. 07, 2020. [Online]. Available: https://www.who.int/globalchange/publications/WMO_WHO_Heat_Health_Guidance_2015.pdf?ua=1

[6] K. Zhang *et al.*, "Comparing exposure metrics for classifying 'dangerous heat' in heat wave and health warning systems," *Environment International*, 2012, doi: 10.1016/j.envint.2012.05.001.

[7] N. Watts *et al.*, "The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come," *The Lancet*, vol. 392, no. 10163. pp. 2479–2514, Dec. 2018. doi: 10.1016/S0140-6736(18)32594-7.

[8] UNDRR, "Sendai Framework for Disaster Risk Reduction 2015-2030," 2015.

[9] Bureau of Meteorology, "State of The Climate 2020," 2020. Accessed: Nov. 17, 2020. [Online]. Available: http://www.bom.gov.au/state-of-the-climate/

[10] J. Tollefson, "Heatwaves blamed on global warming," *Nature*, vol. 488, no. 7410, pp. 143–144, 2012, [Online]. Available: <Go to ISI>://WOS:000307267000007

[11] G. A. Meehl and C. Tebaldi, "More intense, more frequent, and longer lasting heat waves in the 21st century," *Science*, vol. 305, no. 5686, pp. 994–997, 2004.

[12] S. Russo, J. Sillmann, and E. M. Fischer, "Top ten European heatwaves since 1950 and their occurrence in the coming decades," *Environmental Research Letters*, vol. 10, no. 12, p. 124003, Dec. 2015, doi: 10.1088/1748-9326/10/12/124003.

[13] S. Russo *et al.*, "Magnitude of extreme heat waves in present climate and their projection in a warming world," *Journal of Geophysical Research Atmospheres*, vol. 119, no. 22, 2014, doi: 10.1002/2014JD022098.

[14] C. Rooney, A. J. McMichael, R. S. Kovats, and M. P. Coleman, “Excess mortality in England and Wales, and in Greater London, during the 1995 heatwave.,” *Journal of epidemiology and community health*, vol. 52, no. 8, pp. 482–6, Aug. 1998, doi: 10.1136/JECH.52.8.482.

[15] K. E. Kunkel, S. A. Changnon, B. C. Reinke, and R. W. Arritt, “The July 1995 heat wave in the midwest: A climatic perspective and critical weather factors,” *Bulletin of the American Meteorological Society*, vol. 77, no. 7, pp. 1507–1518, 1996.

[16] J.-M. Robine *et al.*, “Death toll exceeded 70,000 in Europe during the summer of 2003,” *C. R. Biologies*, vol. 331, pp. 171–178, 2008, doi: 10.1016/j.crvi.2007.12.001.

[17] J. F. Dhainaut, Y. E. Claessens, C. Ginsburg, and B. Riou, “Unprecedented heat-related deaths during the 2003 heat wave in Paris: consequences on emergency departments,” *Crit Care*, vol. 8, no. 1, pp. 1–2, 2004, doi: 10.1186/cc2404.

[18] D. Barriopedro, E. M. Fischer, J. Luterbacher, R. M. Trigo, and R. García-Herrera, “The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe,” *Science*, vol. 332, no. 6026, pp. 220–224, Apr. 2011, doi: 10.1126/SCIENCE.1201224.

[19] L. Coates, K. Haynes, J. O’Brien, J. McAneney, and F. D. de Oliveira, “Exploring 167 years of vulnerability: An examination of extreme heat events in Australia 1844–2010,” *Environmental Science & Policy*, vol. 42, pp. 33–44, Oct. 2014, doi: 10.1016/J.ENVSCI.2014.05.003.

[20] S. Tong, X. Y. Wang, W. Yu, D. Chen, and X. Wang, “The impact of heatwaves on mortality in Australia: A multicity study,” *BMJ Open*, vol. 4, no. 2, 2014.

[21] A. J. McMichael *et al.*, “Human health and climate change in oceania: a risk assessment 2002.” Commonwealth of Australia, Australia, 2003. doi: ISBN: 0642 82179 8.

[22] T. McMichael, H. Montgomery, and A. Costello, “Health risks, present and future, from global climate change,” *Bmj-British Medical Journal*, vol. 344, 2012, doi: 10.1136/bmj.e1359.

[23] M. Nitschke, G. R. Tucker, A. L. Hansen, S. Williams, Y. Zhang, and P. Bi, “Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis,” *Environ Health*, vol. 10, p. 42, 2011, doi: 10.1186/1476-069X-10-42.

[24] G. Hatvani-Kovacs, M. Belusko, J. Pockett, and J. Boland, “Can the Excess Heat Factor Indicate Heatwave-Related Morbidity? A Case Study in Adelaide, South Australia.,” *EcoHealth*, Dec. 2015, doi: 10.1007/s10393-015-1085-5.

[25] A. Schaffer, D. Muscatello, R. Broome, S. Corbett, and W. Smith, “Emergency department visits, ambulance calls, and mortality associated with an exceptional heat wave in Sydney, Australia, 2011: a time-series analysis,” *Environ Health*, vol. 11, no. 1, p. 3, 2012, doi: 10.1186/1476-069x-11-3.

[26] B. of M. National Climate Centre, “The exceptional January-February 2009 heatwave in south-eastern Australia. Special Climate Statement 17.,” 2009. [Online]. Available: http://www.bom.gov.au/climate/current/statements/scs17d.pdf

[27] B. Teague, R. McLeod, and S. Pascoe, “The 2009 Victorian bushfires royal commission final report,” 2010. www.royalcommission.vic.gov.au/Commission-Reports/Final-Report

[28] Department of Health and Human Services, Department of Human Services, and V. Victorian Government Department of Human Services Melbourne, “January 2009 heatwave in Victoria: an assessment of health impacts,” 2009. [Online]. Available: http://docs.health.vic.gov.au/docs/doc/F7EEA4050981101ACA257AD80074AE8B/$FILE/heat_health_impact_rpt_Vic2009.pdf

[29] PricewaterhouseCoopers, *Protecting human health and safety during severe and extreme heat events. A national framework.* Commonwealth of Australia, 2011. [Online]. Available: https://www.pwc.com.au/publications/pdf/extreme-heat-events-nov11.pdf

[30] ABC News, "‘Extreme heat’ interrupts Australian Open,” 2009. https://www.abc.net.au/news/2009-01-28/extreme-heat-interrupts-australian-open/276022 (accessed Mar. 06, 2022).

[31] C. Houston and T. Reilly, “Heat leaves $100m black hole,” *The Age*, 2009. Accessed: Mar. 06, 2022. [Online]. Available: https://www.theage.com.au/national/heat-leaves-100m-black-hole-20090131-7ugc.html

[32] Clay Lucas, “Train system completely off the rails | theage.com.au,” *The Age*, 2009. Accessed: Mar. 06, 2022. [Online]. Available: https://web.archive.org/web/20090201034248/http://www.theage.com.au/national/train-system-completely-off-the-rails-20090130-7u1a.html

[33] AAP, “Thousands still without power,” *The Age*, 2009. https://www.theage.com.au/national/thousands-still-without-power-20090131-7u9b.html (accessed Mar. 06, 2022).

[34] B. Evans, “Adelaide’s extreme heat kills thousands of chickens and bats,” *ABC NEWS*, Adelaide, 2019. Accessed: Jul. 07, 2019. [Online]. Available: https://www.abc.net.au/news/2019-01-27/adelaide-heatwave-kills-thousands-of-bats-and-chickens/10753248

[35] J. A. Welbergen, C. Booth, and J. Martin, “Killer climate: tens of thousands of flying foxes dead in a day.” https://theconversation.com/killer-climate-tens-of-thousands-of-flying-foxes-dead-in-a-day-23227 (accessed Nov. 10, 2021).

[36] J. L. McBride, G. A. Mills, and A. G. Wain, “NoThe Meteorology of Australian Heatwaves. Title,” 2009.

[37] N. Nicholls and S. Larsen, “Impact of drought on temperature extremes in Melbourne, Australia,” *Australian Meteorological and Oceanographic Journal*, vol. 61, pp. 113–116, 2011, Accessed: Mar. 08, 2022. [Online]. Available: http://www.bom.gov.au/climate/change/

[38] E. Black, M. Blackburn, G. Harrison, B. Hoskins, and J. Methven, “Factors contributing to the summer 2003 European heatwave,” *Weather*, vol. 59, no. 8, pp. 217–223, Aug. 2004, doi: 10.1256/wea.74.04.

[39] J. Kala, J. P. Evans, and A. J. Pitman, “Influence of antecedent soil moisture conditions on the synoptic meteorology of the Black Saturday bushfire event in southeast Australia,” *Quarterly*

Journal of the Royal Meteorological Society, vol. 141, no. 693, pp. 3118–3129, Oct. 2015, doi: 10.1002/qj.2596.

[40] A. B. Pezza, P. van Rensch, and W. Cai, "Severe heat waves in Southern Australia: Synoptic climatology and large scale connections," *Climate Dynamics*, vol. 38, no. 1–2, pp. 209–224, 2012, doi: 10.1029/2008GL033390.

[41] J. A. Francis and S. J. Vavrus, "Evidence linking Arctic amplification to extreme weather in mid-latitudes," *Geophysical Research Letters*, vol. 39, no. 6, p. n/a-n/a, Mar. 2012, doi: 10.1029/2012GL051000.

[42] Y. Kosaka, H. Nakamura, Y. Kosaka, and H. Nakamura, "Mechanisms of Meridional Teleconnection Observed between a Summer Monsoon System and a Subtropical Anticyclone. Part I: The Pacific–Japan Pattern," *Journal of Climate*, vol. 23, no. 19, pp. 5085–5108, Oct. 2010, doi: 10.1175/2010JCLI3413.1.

[43] S. E. Perkins and L. V Alexander, "On the Measurement of Heat Waves," *Journal of Climate*, vol. 26, no. 13, pp. 4500–4517, 2013, doi: 10.1175/jcli-d-12-00383.1.

[44] P. J. Robinson, "On the Definition of a Heat Wave," *Journal of Applied Meteorology*, vol. 40, no. 4, pp. 762–775, Apr. 2001, doi: 10.1175/1520-0450(2001)040<0762:OTDOAH>2.0.CO;2.

[45] Z. Xu, G. FitzGerald, Y. Guo, B. Jalaludin, and S. Tong, "Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis.," *Environment international*, vol. 89–90, pp. 193–203, Feb. 2016, doi: 10.1016/j.envint.2016.02.007.

[46] K. Chen, J. Bi, J. Chen, X. Chen, L. Huang, and L. Zhou, "Influence of heat wave definitions to the added effect of heat waves on daily mortality in Nanjing, China," *Science of the Total Environment*, 2015, doi: 10.1016/j.scitotenv.2014.10.092.

[47] S. Tong *et al.*, "Exploration of the health risk-based definition for heatwave: A multi-city study," *Environmental Research*, vol. 142, 2015, doi: 10.1016/j.envres.2015.09.009.

[48] C. B. Field *et al.*, "IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014. Accessed: Mar. 07, 2022. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/02/ar5_wgII_spm_en.pdf

[49] S. J. Sutanto, C. Vitolo, C. di Napoli, M. D'Andrea, and H. A. J. van Lanen, "Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale," *Environment International*, vol. 134, p. 105276, Jan. 2020, doi: 10.1016/J.ENVINT.2019.105276.

[50] L. Hess, "Fires 2020: Experts explain the global wildfire crisis," 2020. https://news.globallandscapesforum.org/47794/fires-2020-experts-explain-the-global-wildfire-crisis/ (accessed Jul. 31, 2021).

[51] J. Nairn, M. Beaty, and B. M. Varghese, “Australia’s Black Summer heatwave impacts,” *Australian Journal of Emergency Management*, vol. 36, no. 1, pp. 17–20, 2021, Accessed: May 28, 2021. [Online]. Available: https://knowledge.aidr.org.au/resources/ajem-january-2021-australia-s-black-summer-heatwave-impacts/

[52] WMO, “WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services,” Geneva, 2015. doi: 978-92-63-11150-0.

[53] H. Alibašić, “The Administrative and Ethical Considerations of Climate Resilience: The Politics and Consequences of Climate Change,” *https://doi.org/10.1080/10999922.2020.1838142*, vol. 24, no. 1, pp. 33–50, 2020, doi: 10.1080/10999922.2020.1838142.

[54] R. J. B. Fawcett and J. Nairn, “The Heatwaves of the 2013/14 Australian Summer,” 2015.

[55] J. Nairn and R. Fawcett, “Heatwaves in Queensland,” *Australian Journal of Emergency Management*, vol. 32, no. 1, 2017, [Online]. Available: https://ajem.infoservices.com.au/items/AJEM-32-01-11

[56] J. R. Nairn and R. Fawcett, “The Excess Heat Factor: A Metric for Heatwave Intensity and Its Use in Classifying Heatwave Severity,” *Int J Environ Res Public Health*, vol. 12, no. 1, p. 227, 2014, [Online]. Available: http://www.mdpi.com/1660-4601/12/1/227

[57] L. Coates, “An overview of fatalities from some natural hazards in Australia,” 1996.

[58] S. A. Changnon, K. E. Kunkel, and B. C. Reinke, “Impacts and responses to the 1995 heat wave: A call to action,” *Bulletin of the American Meteorological Society*, vol. 77, no. 7, pp. 1497–1506, Jul. 1996, doi: 10.1175/1520-0477(1996)077<1497:IARTTH>2.0.CO;2.

[59] L. V. Alexander, P. Hope, D. Collins, B. Trewin, A. Lynch, and N. Nicholls, “Trends in Australia’s climate means and extremes: A global context,” *Australian Meteorological Magazine*, vol. 56, no. 1, pp. 1–18, 2007, doi: 10.1029/2005JD006119.

[60] A. Amengual *et al.*, “Projections of heat waves with high impact on human health in Europe,” *Global and Planetary Change*, vol. 119, no. 0, pp. 71–84, 2014, doi: http://dx.doi.org/10.1016/j.gloplacha.2014.05.006.

[61] CSIRO, Bureau of Meteorology, and CSIRO, “Climate change in Australia: technical report 2007,” CSIRO, 2007. [Online]. Available: http://www.csiro.au/Organisation-Structure/Divisions/Marine--Atmospheric-Research/Climate-Change-Technical-Report-2007.aspx

[62] S. E. Perkins, L. v. Alexander, and J. R. Nairn, “Increasing frequency, intensity and duration of observed global heatwaves and warm spells,” *Geophysical Research Letters*, vol. 39, no. 20, p. 2012GL053361, Oct. 2012, doi: 10.1029/2012GL053361.

[63] T. J. Parker, G. J. Berry, and M. J. Reeder, “The influence of tropical cyclones on heat waves in Southeastern Australia,” *Geophysical Research Letters*, vol. 40, no. 23, pp. 6264–6270, 2013, doi: 10.1002/2013GL058257.

[64] M. Hirschi *et al.*, “Observational evidence for soil-moisture impact on hot extremes in southeastern Europe,” *Nature Geoscience*, vol. 4, no. 1, pp. 17–21, 2011, doi: 10.1038/ngeo1032.

[65] D. Hudson, A. G. Marshall, and O. Alves, “Intraseasonal Forecasting of the 2009 Summer and Winter Australian Heat Waves Using POAMA,” *Weather and Forecasting*, vol. 26, no. 3, pp. 257–279, 2011, doi: 10.1175/waf-d-10-05041.1.

[66] A. G. Marshall *et al.*, “Intra-seasonal drivers of extreme heat over Australia in observations and POAMA-2,” *Climate Dynamics*, pp. 1–23, 2013, [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84889043227&partnerID=40&md5=f453135a0895066050f1d9cf67fbfe2c

[67] M. Stéfanon, P. Drobinski, F. D’Andrea, C. Lebeaupin-Brossier, and S. Bastin, “Soil moisture-temperature feedbacks at meso-scale during summer heat waves over Western Europe,” *Climate Dynamics 2013 42:5*, vol. 42, no. 5, pp. 1309–1324, May 2013, doi: 10.1007/S00382-013-1794-9.

[68] N. Nicholls, “Is Australia’s continued warming caused by drought?,” *Australian Meteorological and Oceanographic Journal*, vol. 62, pp. 93–96, 2012, doi: 10.1029/2008GL033390.

[69] S. Pattenden, B. Nikiforov, and B. G. Armstrong, “Mortality and temperature in Sofia and London,” *J Epidemiol Community Health*, vol. 57, no. 8, pp. 628–633, 2003, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/12883072

[70] N. Nicholls, C. Skinner, M. Loughnan, and N. Tapper, “A simple heat alert system for Melbourne, Australia,” *International journal of biometeorology*, vol. 52, no. 5, pp. 375–384, 2008, [Online]. Available: http://download.springer.com/static/pdf/341/art%253A10.1007%252Fs00484-007-0132-5.pdf?auth66=1396399801_974ba4dda92415c8534c079abadde902&ext=.pdf

[71] M. Nitschke, G. R. Tucker, and P. Bi, “Morbidity and mortality during heatwaves in metropolitan Adelaide,” *Med J Aust*, vol. 187, no. 11–12, pp. 662–665, 2007.

[72] M. Saez, J. Sunyer, J. Castellsague, C. Murillo, and J. M. Anto, “Relationship between weather temperature and mortality - a time-series analysis approach in Barcelona,” *Int J Epidemiol*, vol. 24, no. 3, pp. 576–582, 1995, doi: 10.1093/ije/24.3.576.

[73] S. Hajat, R. S. Kovats, R. W. Atkinson, and A. Haines, “Impact of hot temperatures on death in London: a time series approach,” *J Epidemiol Community Health*, vol. 56, no. 5, pp. 367–372, 2002.

[74] J. Nairn and R. Fawcett, “Defining heatwaves: heatwave defined as a heat-impact event servicing all community and business sectors in Australia,” Centre for Australian Weather and Climate Research, 2013. doi: 551.5250994.

[75] N. Langlois, J. Herbst, K. Mason, J. Nairn, and R. W. Byard, “Using the Excess Heat Factor (EHF) to predict the risk of heat related deaths,” *J Forensic Leg Med*, vol. 20, no. 5, pp. 408–411, 2013, doi: 10.1016/j.jflm.2012.12.005.

[76] A. L. F. Braga, A. Zanobetti, and J. Schwartz, "The Time Course of Weather-Related Deaths," *Epidemiology*, vol. 12, no. 6, pp. 662–667, 2001.

[77] F. C. Curriero, K. S. Heiner, J. M. Samet, S. L. Zeger, L. Strug, and J. A. Patz, "Temperature and mortality in 11 cities of the eastern United States," *Am J Epidemiol*, vol. 155, no. 1, pp. 80–87, 2002, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/11772788

[78] S. Vandentorren *et al.*, "August 2003 heat wave in France: Risk factors for death of elderly people living at home," *European Journal of Public Health*, vol. 16, no. 6, pp. 583–591, 2006, doi: 10.1093/eurpub/ck1063.

[79] S. Tong, C. Ren, and N. Becker, "Excess deaths during the 2004 heatwave in Brisbane, Australia," *Int J Biometeorol*, vol. 54, no. 4, pp. 393–400, 2010, doi: 10.1007/s00484-009-0290-8.

[80] L. S. Kalkstein, "Saving lives during extreme weather in summer - Interventions from local health agencies and doctors can reduce mortality," *Br Med J*, vol. 321, no. 7262, pp. 650–651, 2000, doi: 10.1136/bmj.321.7262.650.

[81] R. G. Steadman, "A Universal Scale of Apparent Temperature," *Journal of Climate and Applied Meteorology*, vol. 23, no. 12, pp. 1674–1687, Dec. 1984, doi: 10.1175/1520-0450(1984)023<1674:AUSOAT>2.0.CO;2.

[82] R. G. Steadman, "The Assessment of Sultriness. Part II: Effects of Wind, Extra Radiation and Barometric Pressure on Apparent Temperature," *Journal of Applied Meteorology*, vol. 18, no. 7, pp. 874–885, Jul. 1979, doi: 10.1175/1520-0450(1979)018<0874:TAOSPI>2.0.CO;2.

[83] R. G. Steadman, "The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science," *Journal of Applied Meteorology*, vol. 18, no. 7, pp. 861–873, 1979, doi: 10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2.

[84] L. v. Alexander and J. M. Arblaster, "Assessing trends in observed and modelled climate extremes over Australia in relation to future projections," *International Journal of Climatology*, vol. 29, no. 3, pp. 417–435, 2009, doi: 10.1002/joc.1730.

[85] F. M. Woldemeskel, A. Sharma, B. Sivakumar, and R. Mehrotra, "An error estimation method for precipitation and temperature projections for future climates," *Journal of Geophysical Research-Atmospheres*, vol. 117, p. 13, 2012, doi: 10.1029/2012jd018062.

[86] A. J. McMichael *et al.*, "International study of temperature, heat and urban mortality: the 'ISOTHURM' project," *Int J Epidemiol*, vol. 37, no. 5, pp. 1121–1131, 2008, doi: 10.1093/ije/dyn086.

[87] A. C. Guyton and J. E. Hall, *Textbook of medical physiology*. Elsevier Saunders, 2006. [Online]. Available: http://books.google.com.au/books?id=0mdqAAAAMAAJ

[88] J. Nairn, R. Fawcett, and D. Ray, "Defining and predicting excessive heat events, a national system," *Understanding high impact weather, CAWCR modelling workshop*. Bureau of Meteorology, Melbourne, Australia, 2009.

[89] D. A. Jones, W. Wang, and R. Fawcett, “High-quality spatial climate data-sets for Australia,” *Australian Meteorological and Oceanographic Journal*, vol. 58, no. 4, pp. 233–248, 2009, [Online]. Available: <Go to ISI>://WOS:000274700500002

[90] P. K. Sen, “Estimates of the Regression Coefficient Based on Kendall’s Tau,” *Journal of the American Statistical Association*, vol. 63, no. 324, pp. 1379–1389, 1968, doi: 10.1080/01621459.1968.10480934.

[91] A. F. Siegel, “Robust regression using repeated medians,” *Biometrika*, vol. 69, no. 1, pp. 242–244, 1982.

[92] E. Black, M. Blackburn, G. Harrison, B. Hoskins, and J. Methven, “Factors contributing to the summer 2003 European heatwave,” *Weather*, vol. 59, no. 8, pp. 217–223, Aug. 2004, doi: 10.1256/wea.74.04.

[93] K. Mason, J. Nairn, J. Herbst, and P. Felgate, “Heatwave - the Adelaide experience,” *20th international symposium on the forensic sciences*. Sydney, 2010.

[94] Department of Human Services, “January 2009 heatwave in Victoria: an assessment of health impacts,” 2009.

[95] L. Toulemon and M. Barbieri, “The mortality impact of the August 2003 heat wave in France: investigating the ‘harvesting’ effect and other long-term consequences,” *Popul Stud (Camb)*, vol. 62, no. 1, pp. 39–53, 2008, doi: 10.1080/00324720701804249.

[96] D. Hudson and A. G. Marshall, *Extending the Bureau of Meteorology’s heatwave forecast to multi-week timescales*, no. September. 2014.

[97] Bureau of Meteorology, “heatwave forecast service,” 2014. http://www.bom.gov.au/australia/heatwave/index.shtml

[98] R. Fawcett, T. Hume, and Iop, “The GOCF/AWAP System - forecasting temperature extremes,” *17th National Conference of the Australian Meteorological and Oceanographic Society*, vol. 11, 2010, doi: 10.1088/1755-1315/11/1/012005.

[99] Y. Guo *et al.*, “Global Variation in the Effects of Ambient Temperature on Mortality,” *Epidemiology*, vol. 25, no. 6, pp. 781–789, Nov. 2014, doi: 10.1097/EDE.0000000000000165.

[100] J. Yang *et al.*, “Heatwave and mortality in 31 major Chinese cities: Definition, vulnerability and implications,” *Science of the Total Environment*, vol. 649, pp. 695–702, Feb. 2019, doi: 10.1016/j.scitotenv.2018.08.332.

[101] W. Ma *et al.*, “The short-term effect of heat waves on mortality and its modifiers in China: An analysis from 66 communities,” *Environment International*, vol. 75, pp. 103–109, Feb. 2015, doi: 10.1016/j.envint.2014.11.004.

[102] S. C. Sheridan and M. J. Allen, “Temporal trends in human vulnerability to excessive heat,” *Environmental Research Letters*, vol. 13, no. 4, p. 043001, Apr. 2018, doi: 10.1088/1748-9326/aab214.

[103] D. Lowe, K. L. Ebi, and B. Forsberg, "Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves," *Int J Environ Res Public Health*, vol. 8, no. 12, pp. 4623–4648, 2011, doi: 10.3390/ijerph8124623.

[104] S. E. Perkins, "A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale," *Atmospheric Research*, vol. 164–165, pp. 242–267, 2015, doi: http://dx.doi.org/10.1016/j.atmosres.2015.05.014.

[105] D. Argüeso, A. Di Luca, S. E. Perkins-Kirkpatrick, and J. P. Evans, "Seasonal mean temperature changes control future heat waves," *Geophysical Research Letters*, vol. 43, no. 14, 2016, doi: 10.1002/2016GL069408.

[106] P. M. Della-Marta and M. Beniston, *Summer heat waves in western Europe, their past change and future projections*, vol. 33. Dordrecht: Springer, 2008. doi: 10.1007/978-1-4020-6766-2_16.

[107] S. E. Perkins, L. V. Alexander, and J. R. Nairn, "Increasing frequency, intensity and duration of observed global heatwaves and warm spells," *Geophysical Research Letters*, vol. 39, no. 20, 2012, doi: 10.1029/2012GL053361.

[108] P. Rohini, M. Rajeevan, and A. K. Srivastava, "On the Variability and Increasing Trends of Heat Waves over India," *Scientific Reports*, 2016, doi: 10.1038/srep26153.

[109] R. Trancoso, J. Syktus, N. Toombs, D. Ahrens, K. Koon-Ho Wong, and R. Dalla Pozza, "Heatwaves intensification in Australia: A consistent trajectory across past, present and future," *Science of the Total Environment*, 2020, doi: 10.1016/j.scitotenv.2020.140521.

[110] Y. Wang, F. Nordio, J. Nairn, A. Zanobetti, and J. D. Schwartz, "Accounting for adaptation and intensity in projecting heat wave-related mortality," *Environmental Research*, vol. 161, 2018, doi: 10.1016/j.envres.2017.11.049.

[111] Y. Guo *et al.*, "Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study," *PLoS Medicine*, vol. 15, no. 7, Jul. 2018, doi: 10.1371/journal.pmed.1002629.

[112] Z. Xu, J. Cheng, W. Hu, and S. Tong, "Heatwave and health events: A systematic evaluation of different temperature indicators, heatwave intensities and durations," *Science of the Total Environment*, vol. 630, pp. 679–689, Jul. 2018, doi: 10.1016/j.scitotenv.2018.02.268.

[113] X. Zhang *et al.*, "Indices for monitoring changes in extremes based on daily temperature and precipitation data," *Wiley Interdisciplinary Reviews-Climate Change*, vol. 2, no. 6, pp. 851–870, 2011, doi: 10.1002/wcc.147.

[114] J. Nairn, R. Fawcett, L. Anderson-Berry, B. Ostendorf, and P. Bi, "Australia's Future National Heatwave Forecast and Warning Service: Operational Considerations.," 2018. Accessed: Mar. 13, 2019. [Online]. Available: https://www.bnhcrc.com.au/sites/default/files/managed/downloads/374id144._john_nairn.pdf

[115] A. Gasparrini *et al.*, “Mortality risk attributable to high and low ambient temperature: a multicountry observational study,” *The Lancet*, 2015, doi: 10.1016/S0140-6736(14)62114-0.

[116] J. Gao, Y. Sun, Q. Liu, M. Zhou, Y. Lu, and L. Li, “Impact of extreme high temperature on mortality and regional level definition of heat wave: A multi-city study in China,” *Science of the Total Environment*, vol. 505, pp. 535–544, 2015.

[117] L. Bettio, J. R. Nairn, S. C. McGibbony, P. Hope, A. Tupper, and R. J. Fawcett, “A HEATWAVE FORECAST SERVICE FOR AUSTRALIA,” *Royal Society of Victoria*, 2019, doi: 10.1071/RS19006.

[118] Y. Guo *et al.*, “Heat wave and mortality: A multicountry, multicommunity study,” *Environmental Health Perspectives*, vol. 125, no. 8, pp. 1–11, 2017, doi: 10.1289/EHP1026.

[119] K. Zhang, Y. Li, J. D. Schwartz, and O. N. MS, “What weather variables are important in predicting heat-related mortality? A new application of statistical learning methods,” *Environ Res*, vol. 132C, pp. 350–359, 2014, doi: 10.1016/j.envres.2014.04.004.

[120] J. Herbst *et al.*, “Heat-related deaths in Adelaide, South Australia: Review of the literature and case findings - An Australian perspective,” *Journal of Forensic and Legal Medicine*, vol. 22, pp. 73–78, 2014, [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84891792363&partnerID=40&md5=11d50c1217089a88bb497aa5f05ea80f

[121] B. D. Scalley *et al.*, “Responding to heatwave intensity: Excess Heat Factor is a superior predictor of health service utilisation and a trigger for heatwave plans,” *Australian and New Zealand Journal of Public Health*, vol. 39, no. 6, 2015, doi: 10.1111/1753-6405.12421.

[122] J. Xiao *et al.*, “Variation in population vulnerability to heat wave in Western Australia,” *Frontiers in Public Health*, vol. 5, no. APR, 2017, doi: 10.3389/FPUBH.2017.00064.

[123] E. Jegasothy, R. McGuire, J. Nairn, R. Fawcett, and B. Scalley, “Extreme climatic conditions and health service utilisation across rural and metropolitan New South Wales,” *International Journal of Biometeorology*, vol. 61, no. 8, 2017, doi: 10.1007/s00484-017-1313-5.

[124] S. Williams *et al.*, “Heat-health warnings in regional Australia: examining public perceptions and responses,” *Environmental Hazards*, vol. 18, no. 4, 2019, doi: 10.1080/17477891.2018.1538867.

[125] M. Borg, M. Nitschke, S. Williams, S. McDonald, J. Nairn, and P. Bi, “Using the excess heat factor to indicate heatwave-related urinary disease: a case study in Adelaide, South Australia,” *International Journal of Biometeorology*, pp. 1–13, Jan. 2019, doi: 10.1007/s00484-019-01674-5.

[126] B. M. Varghese *et al.*, “Heatwave and work-related injuries and illnesses in Adelaide, Australia: a case-crossover analysis using the Excess Heat Factor (EHF) as a universal heatwave index,” *International Archives of Occupational and Environmental Health*, vol. 92, no. 2, pp. 263–272, Feb. 2019, doi: 10.1007/s00420-018-1376-6.

[127] E. Oppermann, M. Brearley, L. Law, J. A. Smith, A. Clough, and K. Zander, “Heat, health, and humidity in Australia’s monsoon tropics: a critical review of the problematization of ‘heat’ in

a changing climate," *Wiley Interdisciplinary Reviews: Climate Change*, vol. 8, no. 4, p. e468, Jul. 2017, doi: 10.1002/wcc.468.

[128] G. M. Budd, "Wet-bulb globe temperature (WBGT)—its history and its limitations," *Journal of Science and Medicine in Sport*, vol. 11, no. 1, pp. 20–32, 2008, doi: http://dx.doi.org/10.1016/j.jsams.2007.07.003.

[129] K. Błazejczyk *et al.*, "An introduction to the Universal thermal climate index (UTCI)," *Geographia Polonica*, 2013, doi: 10.7163/GPol.2013.1.

[130] A. Piticar, A. E. Croitoru, F. A. Ciupertea, and G. V. Harpa, "Recent changes in heat waves and cold waves detected based on excess heat factor and excess cold factor in Romania," *International Journal of Climatology*, vol. 38, no. 4, pp. 1777–1793, 2018, doi: 10.1002/joc.5295.

[131] Bureau of Meteorology, "Operational implementation of the ACCESS Numerical Weather Prediction systems," Melbourne, Australia, 2010. Accessed: Jul. 08, 2021. [Online]. Available: http://www.bom.gov.au/australia/charts/bulletins/apob83.pdf

[132] S. Heo and M. L. Bell, "Heat waves in South Korea: differences of heat wave characteristics by thermal indices," *Journal of Exposure Science & Environmental Epidemiology 2018 29:6*, vol. 29, no. 6, pp. 790–805, Oct. 2018, doi: 10.1038/s41370-018-0076-3.

[133] S. Tong, X. Y. Wang, and A. G. Barnett, "Assessment of heat-related health impacts in Brisbane, Australia: comparison of different heatwave definitions," *PLoS One*, vol. 5, no. 8, Aug. 2010, doi: 10.1371/journal.pone.0012155.

[134] R. G. Steadman, "Norms of apparent temperature in Australia," Australian Meteorological Magazine 43:1, Melbourne, Australia, pp. 1–16, Mar. 1994.

[135] G. B. Anderson, M. L. Bell, and R. D. Peng, "Methods to Calculate the Heat Index as an Exposure Metric in Environmental Health Research," *Environmental Health Perspectives •*, vol. 121, no. 10, 2013, doi: 10.1289/ehp.1206273.

[136] P. T. May *et al.*, "Verification of moist surface variables over northern Australia in a high-resolution reanalysis (BARRA)," *Journal of Southern Hemisphere Earth Systems Science*, vol. 71, no. 2, pp. 194–202, Sep. 2021, doi: 10.1071/ES21007.

[137] A. Grundstein and E. Cooper, "Assessment of the Australian Bureau of Meteorology wet bulb globe temperature model using weather station data," *International Journal of Biometeorology*, vol. 62, no. 12, pp. 2205–2213, Dec. 2018, doi: 10.1007/s00484-018-1624-1.

[138] J. Nairn, B. Ostendorf, and P. Bi, "Performance of Excess Heat Factor Severity as a Global Heatwave Health Impact Index," *International journal of environmental research and public health*, vol. 15, no. 11, 2018, doi: 10.3390/ijerph15112494.

[139] S. Williams *et al.*, "Regional morbidity and mortality during heatwaves in South Australia," *International Journal of Biometeorology*, pp. 1–16, Aug. 2018, doi: 10.1007/s00484-018-1593-4.

[140] M. E. J. Newman, “Power laws, Pareto distributions and Zipf’s law,” *Contemporary Physics*, vol. 46, no. 5, pp. 323–351, 2005, doi: 10.1080/00107510500052444.

[141] J. Nairn *et al.*, “South Australian heatwave forecasts and warnings performance and some impacts during January 2019, Australia’s hottest month on record.,” 2019. Accessed: Oct. 13, 2020. [Online]. Available: https://www.afac.com.au/events/proceedings/28-08-19/article/south-australian-heatwave-forecasts-and-warnings-performance-and-some-impacts-during-january-2019-australia’s-hottest-month-on-record

[142] Queensland Health, “Heatwave Management Sub-Plan,” 2019. https://www.health.qld.gov.au/__data/assets/pdf_file/0032/628268/heatwave-response-plan.pdf%0D

[143] NSW Government, “STATE HEATWAVE SUB PLAN A SUB PLAN OF THE NSW STATE DISASTER PLAN,” 2011.

[144] T. F. Loughran, A. J. Pitman, and S. E. Perkins-Kirkpatrick, “The El Niño–Southern Oscillation’s effect on summer heatwave development mechanisms in Australia,” *Climate Dynamics*, vol. 52, no. 9–10, pp. 6279–6300, 2019, doi: 10.1007/s00382-018-4511-x.

[145] G. Brunet *et al.*, “Collaboration of the weather and climate communities to advance subseasonal-to-seasonal prediction,” *Bulletin of the American Meteorological Society*, vol. 91, no. 10, pp. 1397–1406, Oct. 2010, doi: 10.1175/2010BAMS3013.1.

[146] “S2S Forecasting: Towards Seamless Prediction | World Meteorological Organization.” https://public.wmo.int/en/resources/bulletin/s2s-forecasting-towards-seamless-prediction (accessed Oct. 28, 2021).

[147] J. Robbins *et al.*, “Challenges for verifying global heatwave and coldwave forecasts: Can emerging technology help?,” Sep. 2017.

[148] Copernicus, “Heatwave climate projections for Australian Health sector,” 2019. https://climate.copernicus.eu/global-showcases#bom (accessed Aug. 15, 2019).

[149] J. Reeves, “Impacts and adaptation response of infrastructure and communities to heatwaves: the southern Australian experience of 2009.,” Gold Coast, Australia, 2010.

[150] S. J. Pyne, *Burning bush: a fire history of Australia*. USA: Holt, 1991.

[151] ABC, “Heatwave toll expected to top 400,” 2014. http://www.abc.net.au/news/2014-01-23/heatwave-death-toll-expected-to-top-almost-400/5214496 (accessed May 21, 2014).

[152] L. C. Ashcroft, “extending the instrumental climate record of southeastern Australia.,” 2013.

[153] B. D. Scalley *et al.*, “Responding to heatwave intensity: Excess Heat Factor is a superior predictor of health service utilisation and a trigger for heatwave plans,” *Australian and New Zealand Journal of Public Health*, p. 6, 2015, doi: 10.1111/1753-6405.12421.

[154] Attorney-General’s Department, “Heatwave December 1972.” www.emknowledge.org.au/resource/624/1972/environmental---heatwave-dec-1972

[155] Queensland and Ambulance Service, “QAS Fact sheet - Heat wave (from 11am press conference).,” Queensland Government, 2004.

[156] J. Englart, “Extreme Heatwave hits Southeast Australia.,” *Climate Citizen*, 2014. www.takvera.blogspot.com.au/2014/01/extreme-heatwave-hits-southeast.html

[157] J. a Welbergen, S. M. Klose, N. Markus, and P. Eby, “Climate change and the effects of temperature extremes on Australian flying-foxes,” *Proceedings: Biological Sciences*, vol. 275, no. 1633, pp. 419–425, 2008, doi: 10.1098/rspb.2007.1385.

[158] A. Edwards and M. Eaton, “G20 Brisbane: World leaders swelter as locals hit the beach for long weekend,” ABC News, 2014. [Online]. Available: www.abc.net.au/news/2014-11-14/g20-leaders-swelter-as-brisbane-residents-head-to-the-beach/5891494

[159] M. Loughnan, N. Tapper, and T. Phan, “Identifying Vulnerable Populations in Subtropical Brisbane, Australia: A Guide for Heatwave Preparedness and Health Promotion,” *ISRN Epidemiology*, vol. 2014, pp. 1–12, 2014, doi: 10.1155/2014/821759.

[160] S. N. Gosling *et al.*, “A glossary for biometeorology,” *International journal of biometeorology*, vol. 58, no. 2, pp. 277–308, 2014.

[161] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, and B. Tinz, “Comparison of UTCI to selected thermal indices,” *International Journal of Biometeorology*, vol. 56, no. 3, pp. 515–535, 2012, doi: 10.1007/s00484-011-0453-2.

[162] A. Le Tertre *et al.*, “Impact of the 2003 Heatwave on All-Cause Mortality in 9 French Cities,” *Epidemiology*, vol. 17, no. 1, pp. 75–79, 2006, doi: 10.1097/01.ede.0000187650.36636.1f.

[163] R. Mechler, S. Hochrainer, A. Aaheim, H. Salen, and A. Wreford, “Modelling economic impacts and adaptation to extreme events: Insights from European case studies,” *Mitigation and Adaptation Strategies for Global Change*, vol. 15, no. 7, pp. 737–762, 2010, doi: 10.1007/s11027-010-9249-7.

[164] A. Yates, “Death modes from a loss of energy infrastructure continuity in a community setting,” *Journal of Homeland Security and Emergency Management*, 2013, doi: 10.1515/jhsem-2012-0048.

[165] S. E. Perkins, L. V. Alexander, and J. R. Nairn, “Increasing frequency, intensity and duration of observed global heatwaves and warm spells,” *Geophysical Research Letters*, vol. 39, no. 20, 2012, doi: 10.1029/2012GL053361.

[166] D. B. Kiktev, J. Caesar, and L. Alexander, “Temperature and precipitation extremes in the second half of the twentieth century from numerical modeling results and observational data,” *Izvestiya Atmospheric and Oceanic Physics*, vol. 45, no. 3, pp. 284–293, 2009, doi: 10.1134/s0001433809030025.

[167] L. V Alexander, N. Tapper, X. Zhang, H. J. Fowler, C. Tebaldi, and A. Lynch, “Climate extremes: progress and future directions,” *International Journal of Climatology*, vol. 29, no. 3, pp. 317–319, 2009, doi: 10.1002/joc.1861.

[168] R. S. Kovats and L. E. Kristie, “Heatwaves and public health in Europe,” *European Journal of Public Health*. 2006. doi: 10.1093/eurpub/ckl049.

[169] A. Zia and C. H. Wagner, “Mainstreaming Early Warning Systems in Development and Planning Processes: Multilevel Implementation of Sendai Framework in Indus and Sahel,” *International Journal of Disaster Risk Science*, 2015, doi: 10.1007/s13753-015-0048-3.

[170] E. Black, M. Blackburn, G. Harrison, B. Hoskins, and J. Methven, “Factors contributing to the summer 2003 European heatwave,” *Weather*, vol. 59, no. 8, pp. 217–223, 2004.

[171] Y. Chen and P. Zhai, “Revisiting summertime hot extremes in China during 1961–2015: Overlooked compound extremes and significant changes,” *Geophysical Research Letters*, 2017, doi: 10.1002/2016GL072281.

[172] N. Langlois, J. Herbst, K. Mason, J. Nairn, and R. W. Byard, “Using the Excess Heat Factor (EHF) to predict the risk of heat related deaths,” *Journal of Forensic and Legal Medicine*, vol. 20, no. 5, 2013, doi: 10.1016/j.jflm.2012.12.005.

[173] A. Urban, H. Hanzlíková, J. Kyselý, and E. Plavcová, “Impacts of the 2015 Heat Waves on Mortality in the Czech Republic—A Comparison with Previous Heat Waves,” *International Journal of Environmental Research and Public Health*, vol. 14, no. 12, p. 1562, Dec. 2017, doi: 10.3390/ijerph14121562.

[174] Helen A. Titley and Joanne C. Robbins, “Met Office Global Hazard Map – a prototype GIS Web Map Service for forecasting high-impact weather across the globe for the week ahead,” *EMS Annual Meeting Abstracts*, vol. 10, no. EMS2013-256,2013, p. 1, 2013, Accessed: Sep. 22, 2015. [Online]. Available: http://meetingorganizer.copernicus.org/EMS2013/EMS2013-256.pdf

[175] N. Gobron, J. S. Adams, F. Cappucci, C. Lanconelli, B. Mota, and F. Mélin, “Joint research centre copernicus climate change service (C3S) fitness for purpose (F4P) platform,” 2016.

[176] A. M. G. Klein Tank *et al.*, “Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment,” *International Journal of Climatology*, vol. 22, no. 12, pp. 1441–1453, Oct. 2002, doi: 10.1002/joc.773.

[177] S. Whitman, G. Good, E. R. Donoghue, N. Benbow, W. Shou, and S. Mou, “Mortality in Chicago attributed to the July 1995 heat wave.,” *American Journal of Public Health*, vol. 87, no. 9, pp. 1515–1518, Sep. 1997, doi: 10.2105/AJPH.87.9.1515.

[178] R. Kaiser, A. Le Tertre, J. Schwartz, C. A. Gotway, W. R. Daley, and C. H. Rubin, “The effect of the 1995 heat wave in Chicago on all-cause and cause-specific mortality.,” *American journal of public health*, 2007, doi: 10.2105/AJPH.2006.100081.

[179] J. E. Dematte *et al.*, “Near-fatal heat stroke during the 1995 heat wave in Chicago,” *Annals of Internal Medicine*, 1998, doi: 10.7326/0003-4819-129-3-199808010-00001.

[180] M. Poumadère, C. Mays, S. le Mer, and R. Blong, “The 2003 heat wave in France: Dangerous climate change here and now,” *Risk Analysis*. 2005. doi: 10.1111/j.1539-6924.2005.00694.x.

[181] J. Yang *et al.*, “Impact of heat wave in 2005 on mortality in guangzhou, china,” *Biomedical and environmental sciences: BES*, 2013, doi: 10.3967/0895-3988.2013.08.003.

[182] M. A. Palecki, S. A. Changnon, and K. E. Kunkel, “The nature and impacts of the July 1999 heat wave in the midwestern United States: Learning from the lessons of 1995,” *Bulletin of the American Meteorological Society*, 2001, doi: 10.1175/1520-0477(2001)082<1353:TNAIOT>2.3.CO;2.

[183] A. Fouillet *et al.*, “Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave,” *International Journal of Epidemiology*, vol. 37, no. 2, pp. 309–317, Apr. 2008, doi: 10.1093/ije/dym253.

[184] S. A. Changnon, K. E. Kunkel, and B. C. Reinke, “Impacts and responses to the 1995 heat wave: A call to action,” *Bulletin of the American Meteorological Society*, vol. 77, no. 7, pp. 1497–1506, 1996.

[185] J. M. Juran, F. M. Gryna, and R. S. Bingham, *Quality control handbook*. New York: McGraw Hill, 1974.

[186] Bureau of Meteorology, “Special Climate Statement 68—widespread heatwaves during December 2018 and January 2019,” 2019. http://www.bom.gov.au/climate/current/statements/scs68.pdf (accessed Feb. 11, 2019).

[187] M. Nitschke, G. Tucker, A. Hansen, and S. Williams, “Evaluation of a heat warning system in Adelaide, South Australia , using case-series analysis,” 2016, doi: 10.1136/bmjopen-2016-012125.

[188] Department of Health and Human Services, “The health impacts of the January 2014 heatwave in Victoria,” Melbourne, 2014.

[189] Commonwealth of Australia, *Royal Commission into National Natural Disaster Arrangements Report*. 2020. Accessed: Nov. 17, 2020. [Online]. Available: https://naturaldisaster.royalcommission.gov.au/system/files/2020-11/Royal Commission into National Natural Disaster Arrangements - Report %5Baccessible%5D.pdf

[190] N. Borchers Arriagada, A. J. Palmer, D. MJS Bowman, G. G. Morgan, B. B. Jalaludin, and F. H. Johnston, “Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia,” *Research letters MJA*, vol. 213, no. 6, 2020, doi: 10.5694/mja2.50545.

[191] Australian Institute of Health and Welfare, *Australian bushfires 2019–20: Exploring the short-term health impacts*. Canberra, 2020. Accessed: Nov. 27, 2020. [Online]. Available: https://www.aihw.gov.au/getmedia/a14c3205-784c-4d81-ab49-a33ed4d3d813/aihw-phe-276.pdf.aspx?inline=true

[192] Australian Government, “Data Integration Partnership for Australia | Department of the Prime Minister and Cabinet,” 2017. https://pmc.gov.au/public-data/data-integration-partnership-australia (accessed Jul. 27, 2021).

[193] PEAN, “Heatwaves and health | PEAN,” 2021. https://www.pean.gov.au/projects/heatwaves-and-health (accessed Jul. 14, 2021).

[194] ABS, “Multi-Agency Data Integration Project (MADIP),” 2015. https://www.abs.gov.au/about/data-services/data-integration/integrated-data/multi-agency-data-integration-project-madip (accessed Jul. 07, 2021).

[195] C. Munro, “Review of the Bureau of Meteorology’s capacity to respond to future extreme weather and natural disaster events and to provide seasonal forecasting services Report by Chloe Munro,” 2011.

[196] Y. Zhang *et al.*, “The *MJA–Lancet* Countdown on health and climate change: Australian policy inaction threatens lives,” *Medical Journal of Australia*, vol. 209, no. 11, pp. 474–474, Dec. 2018, doi: 10.5694/mja18.00789.

[197] D. G. Miralles, A. J. Teuling, and C. C. Van Heerwaarden, “Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation,” *Nature Geoscience*, vol. 7, no. 5, 2014, doi: 10.1038/ngeo2141.

[198] MetrixConsulting, “National Fire Danger Rating System and Warnings Social Research Stage 1 Survey Report: Benchmarking Community Understanding and Action.,” Adelaide, South Australia, 2018.

[199] L. Clarke *et al.*, “Knowing What We Know - Reflections on the Development of Technical Guidance for Loss Data for the Sendai Framework for Disaster Risk Reduction.,” *PLoS currents*, vol. 10, Aug. 2018, doi: 10.1371/currents.dis.537bd80d1037a2ffde67d66c604d2a78.

[200] A. Aitsi-Selmi *et al.*, “Reflections on a Science and Technology Agenda for 21st Century Disaster Risk Reduction,” *International Journal of Disaster Risk Science*, vol. 7, no. 1, pp. 1–29, Mar. 2016, doi: 10.1007/s13753-016-0081-x.

[201] B. Merz *et al.*, “Impact Forecasting to Support Emergency Management of Natural Hazards,” *Reviews of Geophysics*, vol. 58, no. 4. Blackwell Publishing Ltd, Dec. 01, 2020. doi: 10.1029/2020RG000704.

[202] P. Davies and P. Meige, “IMPACT-BASED FORECASTING FOR EARLY ACTION THE FUTURE OF FORECASTS,” 2020. Accessed: Jun. 16, 2021. [Online]. Available: https://www.forecast-based-financing.org/wp-content/uploads/2020/09/Impact-based-forecasting-guide-2020.pdf

[203] P. Weyrich, A. Scolobig, D. N. Bresch, and A. Patt, “Effects of Impact-Based Warnings and Behavioral Recommendations for Extreme Weather Events,” *Weather, Climate, and Society*, vol. 10, no. 4, pp. 781–796, Oct. 2018, doi: 10.1175/WCAS-D-18-0038.1.

[204] R. Kaltenberger, A. Schaffhauser, and M. Staudinger, “‘What the weather will do’ – results of a survey on impact-oriented and impact-based warnings in European NMHSs,” *Advances in Science and Research*, vol. 17, pp. 29–38, May 2020, doi: 10.5194/asr-17-29-2020.

[205] AIDR, “Public Information and Warnings Australian Disaster Resilience Handbook Collection,” 2018.

[206] R. E. Morss, J. L. Demuth, A. Bostrom, J. K. Lazo, and H. Lazrus, “Flash Flood Risks and Warning Decisions: A Mental Models Study of Forecasters, Public Officials, and Media Broadcasters in Boulder, Colorado,” *Risk Analysis*, vol. 35, no. 11, pp. 2009–2028, Nov. 2015, doi: 10.1111/risa.12403.

[207] S. H. Potter *et al.*, “The influence of impact-based severe weather warnings on risk perceptions and intended protective actions,” *International Journal of Disaster Risk Reduction*, vol. 30, pp. 34–43, Sep. 2018, doi: 10.1016/j.ijdrr.2018.03.031.

[208] P. Weyrich, A. Scolobig, F. Walther, and A. Patt, “Do intentions indicate actual behaviour? A comparison between scenario-based experiments and real-time observations of warning response,” *Journal of Contingencies and Crisis Management*, vol. 28, no. 3, pp. 240–250, Sep. 2020, doi: 10.1111/1468-5973.12318.

[209] L. C. Ashcroft, A. B. Pezza, and I. Simmonds, “Cold events over southern Australia: Synoptic climatology and hemispheric structure,” *Journal of Climate*, vol. 22, no. 24, pp. 6679–6698, 2009.

[210] D. Mileti and J. Sorensen, “Communication of emergency public warnings: A social perspective and State-of-the-art assessment,” *Landslides*, vol. 1, no. 6, pp. 52–70, 1990, doi: 10.2172/6137387.

[211] Cube Group, “National Review of Warnings and Information: Final Report,” Melbourne, Australia, 2014.

[212] M. A. Casteel, “Communicating Increased Risk: An Empirical Investigation of the National Weather Service’s Impact-Based Warnings,” *Weather, Climate, and Society*, vol. 8, no. 3, pp. 219–232, Jul. 2016, doi: 10.1175/WCAS-D-15-0044.1.

[213] T. Kox, H. Kempf, C. Lüder, R. Hagedorn, and L. Gerhold, “Towards user-orientated weather warnings,” *International Journal of Disaster Risk Reduction*, vol. 30, pp. 74–80, Sep. 2018, doi: 10.1016/j.ijdrr.2018.02.033.

[214] A. S. Tozier de la Poterie, W. E. Jjemba, R. Singh, E. Coughlan de Perez, C. V. Costella, and J. Arrighi, “Understanding the use of 2015–2016 El Niño forecasts in shaping early humanitarian action in Eastern and Southern Africa,” *International Journal of Disaster Risk Reduction*, vol. 30, pp. 81–94, Sep. 2018, doi: 10.1016/j.ijdrr.2018.02.025.

[215] P. O’Donohue and F. Dunstan, “Using community voice to build a new national warnings system for Australia,” 2021.

[216] B. M. Varghese *et al.*, “Heatwave and work-related injuries and illnesses in Adelaide, Australia: a case-crossover analysis using the Excess Heat Factor (EHF) as a universal heatwave index,” *International Archives of Occupational and Environmental Health*, vol. 92, no. 2, 2019, doi: 10.1007/s00420-018-1376-6.

[217] B. Y. Wondmagegn *et al.*, “Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia,” *Science of the Total Environment*, vol. 773, 2021, doi: 10.1016/j.scitotenv.2021.145656.

[218] B. Y. Wondmagegn *et al.*, “Impact of heatwave intensity using excess heat factor on emergency department presentations and related healthcare costs in Adelaide, South Australia,” *Science of the Total Environment*, vol. 781, p. 146815, Aug. 2021, doi: 10.1016/j.scitotenv.2021.146815.

[219] B. M. Varghese *et al.*, “Characterising the impact of heatwaves on work-related injuries and illnesses in three Australian cities using a standard heatwave definition- Excess Heat Factor (EHF),” *Journal of Exposure Science & Environmental Epidemiology 2019 29:6*, vol. 29, no. 6, pp. 821–830, Apr. 2019, doi: 10.1038/s41370-019-0138-1.

[220] S. Williams *et al.*, “Heat and health in Adelaide, South Australia: assessment of heat thresholds and temperature relationships,” *Sci Total Environ*, vol. 414, pp. 126–133, 2012, doi: 10.1016/j.scitotenv.2011.11.038.

[221] S. Williams, M. Nitschke, G. Tucker, and P. Bi, “Extreme heat arrangements in South Australia: an assessment of trigger temperatures,” *Health Promot J Austr*, vol. 22 Spec No, pp. S21-7, 2011.

[222] SA Health, “SA Health Extreme Heat Strategy 2016,” Adelaide, South Australia, 2016.

[223] B. D. Scalley *et al.*, “Responding to heatwave intensity: Excess Heat Factor is a superior predictor of health service utilisation and a trigger for heatwave plans,” *Australian and New Zealand Journal of Public Health*, vol. 39, no. 6, 2015, doi: 10.1111/1753-6405.12421.

[224] S. L. Campbell, T. Remenyi, G. J. Williamson, D. Rollins, C. J. White, and F. H. Johnston, “Ambulance dispatches and heatwaves in Tasmania, Australia: A case-crossover analysis,” *Environmental Research*, vol. 202, p. 111655, 2021, doi: 10.1016/j.envres.2021.111655.

[225] Department of Health and Human Services, “January 2009 heatwave in Victoria: an assessment of health impacts,” 2012.

[226] N. Nicholls, “Do heat alerts save lives?,” *Proceedings of the Royal Society of Victoria*, vol. 131, no. 1, p. 60, 2019, doi: 10.1071/RS19007.

[227] M. Loughnan, N. J. Tapper, T. Phan, K. Lynch, and J. McInnes, *A spatial vulnerability analysis of urban populations during extreme heat events in Australian capital cities*. 2013.

[228] Australian Government, “Physical Environment Analysis Network (PEAN),” 2017. https://www.pean.gov.au/ (accessed Jul. 07, 2021).

[229] B. Varghese *et al.*, “Heatwave-related Mortality in Australia: Who’s impacted the most?,” *European Journal of Public Health*, vol. 30, no. Supplement_5, Sep. 2020, doi: 10.1093/eurpub/ckaa165.377.

[230] B. M. Varghese, M. Beaty, P. Bi, and J. Nairn, “Heatwave-health vulnerability in Adelaide: Analysis of mortality and morbidity outcomes,” in *ISEE Conference Abstracts*, Oct. 2020, vol. 2020, no. 1. doi: 10.1289/isee.2020.virtual.p-0399.

[231] R. M. Beaty, B. Varghese, and J. Nairn, “Social and spatial variation in heatwave-related emergency department visits in Australia,” *ISEE Conference Abstracts*, vol. 2021, no. 1, Aug. 2021, doi: 10.1289/isee.2021.p-378.

[232] B. Varghese, M. Beaty, P. Bi, and J. Nairn, "Impact of Heatwaves on use of health services (GP and Emergency department visits)," *International Journal of Epidemiology*, vol. 50, no. Supplement_1, Sep. 2021, doi: 10.1093/ije/dyab168.680.

[233] S. Williams *et al.*, "Heat-health warnings in regional Australia: examining public perceptions and responses," *Environmental Hazards*, vol. 18, no. 4, 2019, doi: 10.1080/17477891.2018.1538867.

[234] D. Lowe, K. L. Ebi, and B. Forsberg, "Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves," *Int J Environ Res Public Health*, vol. 8, no. 12, pp. 4623–4648, 2011, doi: 10.3390/ijerph8124623.

[235] J. Welsh *et al.*, "Education-related inequalities in cause-specific mortality: first estimates for Australia using individual-level linked census and mortality data," *International Journal of Epidemiology*, Jun. 2021, doi: 10.1093/IJE/DYAB080.

[236] M. Chesnais *et al.*, "Queensland State Heatwave Risk Assessment 2019," Brisbane, 2019. Accessed: Aug. 14, 2019. [Online]. Available: https://www.disaster.qld.gov.au/qermf/Documents/QFES-State-Heatwave-Risk-Assessment-Executive-Summary.pdf

[237] S. L. Campbell *et al.*, "Using Digital Technology to Protect Health in Prolonged Poor Air Quality Episodes: A Case Study of the AirRater App during the Australian 2019–20 Fires," *Fire*, vol. 3, no. 3, p. 40, Aug. 2020, doi: 10.3390/fire3030040.

[238] D. AG. Radford *et al.*, "The creation of heat-resilient infrastructure: A Framework for the mitigation and adaptation from heat-related risk.," *Sustainable Cities and Society*, 2021.

[239] J. Nairn and S. Williams, "Power outages during heatwaves: Predicting mortality burden in Australian cities; a discussion paper ," Adelaide, Australia, 2019. Accessed: Sep. 16, 2021. [Online]. Available: moz-extension://1c9011c8-2b25-4dc8-aea5-e5da87792891/enhanced-reader.html?openApp&pdf=https%3A%2F%2Fwww.aemo.com.au%2F-%2Fmedia%2Ffiles%2Finitiatives%2Fstrategic-partnerships%2F2020%2Fpower-outages-and-mortality-burden-australian-cities.pdf%3Fla%3Den

[240] M. X. TONG *et al.*, "Hospital healthcare costs attributable to heat and future estimations in the context of climate change in Perth, Western Australia," *Advances in Climate Change Research*, vol. 12, no. 5, pp. 638–648, Oct. 2021, doi: 10.1016/J.ACCRE.2021.07.008.

Appendix A: Peer reviewed co-authored journal articles

Collaborative mutli-disciplinary publications listed in Appendix A have played a significant role in establishing the impact credentials for the Excess Heat Factor heatwave index. Partnering with epidemiologists developed data sharing and processing partnerships which secured ethical data privacy and effective spatial interpretation of heatwave data.

Confidence in EHF's exposure relationship to health impacts raised expectations within Australia's health community that a national impact-based heatwave warning system was required and could be delivered. This confidence has been reflected by support from the Australian Health Principal Protection Committee (AHPPC) and the Australia and New Zealand Emergency Management Committee (ANZEMC) for adoption of EHF in the creation and delivery of new heatwave services in Australia.

Recently submitted articles recognize my continuing contribution to cross-disciplinary research required to comprehend how heatwaves currently impact health and infrastructure systems and projected impacts under climate change.

Earlier more significant collaborations ensured partners (meteorological, university, health) correctly interpreted the temporal and spatial characteristics of heatwave severity for epidemiological studies. This included conferences, focus groups and workshops which deepened collaborator understanding of EHF and where I assisted in the design of exposure/impact studies. These collaborations were recognised by the Bureau of Meteorology, where I assumed the role of National Heatwave Project Director, supporting internal development of heatwave services and external engagement with stakeholders in health, emergency services and the wider community. Through this work I was able to introduce the health industry as a new primary partner to the Bureau of Meteorology, inducting health into the Bureau's Vision statement:

"To be an organisation of global standing, that is highly valued by the community for our pivotal role in enabling a safe, prosperous, secure and healthy Australia."

More recent articles focused on how heatwaves impacted the work force and particular forms of morbidity. This includes my role as director for the national "Reducing Illness and Lives Lost from Heatwave" project. Key collaborations with university (including APR Internship), Australian Bureau of Statistics, Australian Institute of Health and Welfare, Geoscience Australia and the Bureau of Meteorology brought diverse data custodians together successfully for the first time. Outcomes from this project extend beyond heatwave, allowing for continuing partnerships with impact data custodians in the development of impact-based warnings and services across other hazard following success with heatwave studies.

Further publications are planned to utilise improving quality of reanalysis data sets and challenging climate change scenarios.

Submitted to Journal: **Science of the Total Environment, August 2021**

M Tong, B Wondmagegn, J Xiang, S Williams, A Hansen, K Dear, D Pisaniello, B Varghese, J Xiao, L Jian, B Scalley, M Nitschke, J Nairn, H Bambrick, J Karnon, P Bi, "Heat-attributable hospitalisation costs in Sydney: current estimations and future projections in the context of climate change"

Submitted Journal: **Urban Climate, August 2021**

M Tong, B Wondmagegn; J Xiang; S Williams; A Hansen; K Dear; D Pisaniello; B Varghese; J Xiao; L Jian; B Scalley; M Nitschke; J Nairn; H Bambrick; J Karno, P Bi, "Heat-attributable hospitalisation costs in Sydney: current estimations and future projections in the context of climate change"

Submitted to Journal: **Sustainable Cities and Society, November 2021**

Michael Tong; Berhanu Wondmagegn; Jianjun Xiang; Susan Williams; Alana Hansen; Keith Dear; Dino Pisaniello; Blesson Varghese; Jianguo Xiao; Le Jian; Ben Scalley; Monika Nitschke; John Nairn; Hilary Bambrick; Jonathan Karnon, "Hospitalization costs of respiratory diseases attributable to temperature in the context of climate change in Australia"

Submitted Journal: **Occupational and Environmental Medicine, November 2021**

B Wondmagegn, J Xiang, Keith Dear, S Williams, A Hansen, D Pisaniello, M Nitschke, J Nairn, B Scalley, A Xiao, L Jian, M Tong, J Karnon, H Bambrick, P Bi, "Understanding Current and Projected Emergency Department Presentations and Associated Healthcare Costs in a Changing Climate"

B. D. Scalley, T. Spicer, L. Jian, J. Xiao, J. Nairn, A. Robertson, T. Weeramanthri, "Responding to heatwave intensity: Excess Heat Factor is a superior predictor of health service utilisation and a trigger for heatwave plans," ***Australian and New Zealand Journal of Public Health***, p. 6, **2015**, doi: 10.1111/1753-6405.12421.

Abstract - Objective: To determine which measures of heatwave have the greatest predictive power for increases in health service utilisation in Perth, Western Australia.

Methods: Three heatwave formulas were compared, using Poisson or zero-inflated Poisson regression, against the number of presentations to emergency departments from all causes, and the number of inpatient admissions from heat-related causes. The period from July 2006 to June 2013 was included. A series of standardised thresholds were calculated to allow comparison between formulas, in the absence of a gold standard definition of heatwaves. - **Results:** Of the three heatwave formulas, Excess Heat Factor (EHF) produced the most clear dose-response relationship with Emergency Department presentations. The EHF generally predicted periods that resulted in a similar or higher rate of health service utilisation, as compared to the two other formulas, for the thresholds examined. - **Conclusions:** The EHF formula, which considers a period of acclimatisation as well as the maximum and minimum temperature, best predicted periods of greatest health service demand. The strength of the dose-response relationship reinforces the validity of the measure as a predictor of hazardous heatwave intensity. - **Implications:** The findings suggest that the EHF formula is well suited for use as a means of activating heatwave plans and identifies the required level of response to extreme heatwave events as well as moderate heatwave events that produce excess health service demand.

E. Jegasothy, R. McGuire, J. Nairn, R. Fawcett, and B. Scalley, "Extreme climatic conditions and health service utilisation across rural and metropolitan New South Wales," ***International Journal of Biometeorology***, vol. 61, no. 8, **2017**, doi: 10.1007/s00484-017-1313-5.

Abstract Periods of successive extreme heat and cold temperature have major effects on human health and increase rates of health service utilisation. The severity of these events varies between geographic locations and populations. This study aimed to estimate the effects of heat waves and cold waves on health service utilisation across urban, regional and remote areas in New South Wales (NSW), Australia, during the 10-year study period 2005–2015. We divided the state into three regions and used 24 over-dispersed or zero-inflated Poisson time-series regression models to estimate the effect of heat waves and cold waves, of three levels of severity, on the rates of ambulance call-outs, emergency department (ED) presentations and mortality. We defined heat waves and cold waves using excess heat factor (EHF) and excess cold factor (ECF) metrics, respectively. Heat waves generally resulted in increased rates of ambulance call-outs, ED presentations and mortality across the three regions and the entire state. For all of NSW, very intense heat waves resulted in an increase of 10.8% (95% confidence interval (CI) 4.5, 17.4%) in mortality, 3.4% (95% CI 0.8, 7.8%) in ED presentations and 10.9% (95% CI 7.7, 14.2%) in ambulance call-outs. Cold waves were shown to have significant effects on ED presentations (9.3% increase for intense events, 95%

CI 8.0–10.6%) and mortality (8.8% increase for intense events, 95% CI 2.1–15.9%) in outer regional and remote areas. There was little evidence for an effect from cold waves on health service utilisation in major cities and inner regional areas. Heat waves have a large impact on health service utilisation in NSW in both urban and rural settings. Cold waves also have significant effects in outer regional and remote areas. EHF is a good predictor of health service utilisation for heat waves, although service needs may differ between urban and rural areas.

J. Xiao, T. Spicer, L. Jian, G.Y. Yun, C. Shao, J. Nairn, R.J.B. Fawcett, A. Robertson, T.S. Weeramanthri, "Variation in population vulnerability to heat wave in Western Australia," ***Frontiers in Public Health***, vol. 5, no. APR, **2017**, doi: 10.3389/FPUBH.2017.00064.
Abstract Heat waves (HWs) have killed more people in Australia than all other natural hazards combined. Climate change is expected to increase the frequency, duration, and intensity of HWs and leads to a doubling of heat-related deaths over the next 40 years. Despite being a significant public health issue, HWs do not attract the same level of attention from researchers, policy makers, and emergency management agencies compared to other natural hazards. The purpose of the study was to identify risk factors that might lead to population vulnerability to HW in Western Australia (WA). HW vulnerability and resilience among the population of the state of WA were investigated by using time series analysis. The health impacts of HWs were assessed by comparing the associations between hospital emergency department (ED) presentations, hospital admissions and mortality data, and intensities of HW. Risk factors including age, gender, socioeconomic status (SES), remoteness, and geographical locations were examined to determine whether certain population groups were more at risk of adverse health impacts due to extreme heat. We found that hospital admissions due to heat-related conditions and kidney diseases, and overall ED attendances, were sensitive indicators of HW. Children aged 14 years or less and those aged 60 years or over were identified as the most vulnerable populations to HWs as shown in ED attendance data. Females had more ED attendances and hospital admissions due to kidney diseases; while males had more heat-related hospital admissions than females. There were significant dose–response relationships between HW intensity and SES, remoteness, and health service usage. The more disadvantaged and remotely located the population, the higher the health service usage during HWs. Our study also found that some population groups and locations were resilient to extreme heat. We produced a mapping tool, which indicated geographic areas throughout WA with various vulnerability and resilience levels to HW. The findings from this study will allow local government, community service organizations, and agencies in health, housing, and education to better identify and understand the degree of vulnerability to HW throughout the state, better target preparatory strategies, and allocate limited resources to those most in need.

Y. Wang, F. Nordio, J. Nairn, A. Zanobetti, and J. D. Schwartz, "Accounting for adaptation and intensity in projecting heat wave-related mortality," ***Environmental Research***, vol. 161, **2018**, doi: 10.1016/j.envres.2017.11.049.

Highlights We propose novel models for intensity of and adaptation to heat waves in projections of heat wave- mortality; The modelling used a large national dataset and the projections used a rich set of climate models and scenarios; Future heat wave-related mortality would be substantially overestimated, if adaptation were ignored; The time trend of future heat wave-related mortality will vary substantially across climate regions.

Abstract - Background: How adaptation and intensity of heat waves affect heat wave-related mortality is unclear, making health projections difficult.

Methods: We estimated the effect of heat waves, the effect of the intensity of heat waves, and adaptation on mortality in 209 U.S. cities with 168 million people during 1962–2006. We improved the standard time-series models by incorporating the intensity of heat waves using excess heat factor (EHF) and estimating adaptation empirically using interactions with yearly mean summer temperature (MST). We combined the epidemiological estimates for heat wave, intensity, and adaptation with the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset to project heat wave-related mortality by 2050.

Results: The effect of heat waves increased with its intensity. Adaptation to heat waves occurred, which was shown by the decreasing effect of heat waves with MST. However, adaptation was lessened as MST increased. Ignoring adaptation in projections would result in a substantial overestimate of the projected heat wave-related mortality (by 277-747% in 2050). Incorporating the empirically estimated adaptation into projections would result in little change in the projected heat wave-related mortality between 2006 and 2050. This differs regionally, however, with increasing mortality over time for cities in the southern and western U.S. but decreasing mortality over time for the north.

Conclusions: Accounting for adaptation is important to reduce bias in the projections of heat wave-related mortality. The finding that the southern and western U.S. are the areas that face increasing heat-related deaths is novel, and indicates that more regional adaptation strategies are needed.

Susan Williams, Kamalesh Venugopal, Monika Nitschke, John Nairn, Robert Fawcett, Chris Beattie, Graeme Wynwood, Peng Bi, "Regional morbidity and mortality during heatwaves in South Australia," ***International Journal of Biometeorology***, pp. 1–16, Aug. **2018**, doi: 10.1007/s00484-018-1593-4.

Abstract Heatwaves can be a common occurrence in Australia, and the public health impacts can be severe. Heat warnings and interventions are being adopted widely to reduce the preventable health impacts. This study examines the effects of heatwaves on morbidity and mortality in different climatic regions in the state of South Australia, to inform the targeting of heat warnings according to regional needs. Heatwaves were defined using the excess heat

factor (EHF), an index based on mean daily temperature indices that quantifies heatwave severity relative to the local climate. In all regions, there were increases in morbidity (daily rates of ambulance call-outs and heat-related emergency presentations and hospital admissions) on heatwave days compared to non-heatwave days, which increased with heatwave severity. This study demonstrates that a consistent measure for heatwave severity, based on EHF, can be used to underpin public health warnings for climatically diverse areas.

Susan Williams, Scott Hanson-Easey, Monika Nitschke, Stuart Howell, John Nairn, Chris Beattie, Graeme Wynwood & Peng Bi, "Heat-health warnings in regional Australia: examining public perceptions and responses," **Environmental Hazards**, vol. 18, no. 4, **2019**, doi: 10.1080/17477891.2018.1538867.

Abstract Heatwaves are an increasing environmental hazard and an important public health issue in Australia. Heat-health warnings are being adopted widely to promote protective behaviours, but there has been limited evaluation of public responses. This study used a household telephone survey to examine public attitudes and responses to heat-health warnings in regional areas in two Australian states, South Australia and Victoria. The results indicate a high level of recall of heat-health warnings and awareness about managing extreme heat. Respondents viewed heat-health warnings positively, but the effects on behaviour change were variable. Our findings suggest that the warnings may be reinforcing existing protective behaviours more than promoting change. Perceptions of heat risks were higher among women than men, but lower in older age groups. Evidence of this nature is important to identify ways to improve heat-health warnings and more effectively address the public health risks.

Matthew Borg, Monika Nitschke, Susan Williams, Stephen McDonald, John Nairn & Peng Bi, "Using the excess heat factor to indicate heatwave-related urinary disease: a case study in Adelaide, South Australia", **International Journal of Biometeorology** volume 63, pages 435–447 (**2019**)

Abstract

The excess heat factor (EHF) is being adopted nationally for heatwave forecasting in Australia, but there is limited research utilizing it as a predictor for heat-related morbidity from diseases of the urinary system (urinary diseases). In this study, the incidence of eight temperature-prone specific urinary disease categories was analyzed in relation to the EHF. Daily data for maximum and minimum temperature and data for metropolitan hospital emergency department presentations and inpatient admissions for urinary disease were acquired in Adelaide, South Australia, from 1 July 2003 to 31 March 2014. An increased incidence for urolithiasis, acute kidney injury (AKI), chronic kidney disease, and lower urinary tract infections was associated with the EHF. Using the Australian national heatwave definition with the EHF, emergency department presentations increased on heatwave days compared to non-heatwave days for total urinary disease (IRR 1.046, 95% CI 1.016–1.076), urolithiasis (IRR 1.106, 95% 1.046–1.169), and acute kidney injury (AKI) (IRR 1.416, 95% CI 1.258–1.594). Likewise, inpatient admissions increased for total urinary disease (IRR 1.090, 95% CI 1.048–1.133) and AKI (IRR 1.335, 95% CI 1.204–1.480). The EHF is a reliable metric for predicting heat-induced morbidity from urinary disease. Climate change-related elevations in temperature can increase morbidity from urinary disease, especially AKI and urolithiasis. Diseases of the urinary system should be highlighted when providing public health guidance during heatwaves indicated by the EHF.

L. Bettio, J. R. Nairn, S. C. McGibbony, P. Hope, A. Tupper, and R. J. Fawcett, “A HEATWAVE FORECAST SERVICE FOR AUSTRALIA,” ***Royal Society of Victoria***, **2019**, doi: 10.1071/RS19006.

Abstract

The Australian Bureau of Meteorology monitors, researches, predicts and communicates Australia’s weather and climate. Australia’s mean temperature has risen by over 1°C since 1910, leading to an increase in the frequency of extreme heat events. Extreme heat can profoundly impact human health, infrastructure and the environment. Research conducted at the Bureau and elsewhere shows that climate change is impacting the intensity and frequency of extreme heat events. One way that the Bureau has responded to this challenge is by providing a forecast service specifically targeted at identifying heatwaves. The heatwave service identifies areas expected to be impacted by three or more consecutive days of unusually high maximum and minimum temperatures on a national map. The service has been developed with clear impact-based categories of heatwave severity. This heatwave service is now available operationally on the Bureau’s website during the heatwave season (nominally November to March) and is proving a valuable tool for engaging the community, including emergency services, with forecasts and warnings of extreme heat.

B. M. Varghese, A. Hansen, M. Nitschke, J. Nairn, S. Hanson-Easey, P. Bi, D. Pisaniello, “Heatwave and work-related injuries and illnesses in Adelaide, Australia: a case-crossover analysis using the Excess Heat Factor (EHF) as a universal heatwave index,” ***International Archives of Occupational and Environmental Health***, vol. 92, no. 2, **2019**, doi: 10.1007/s00420-018-1376-6.

Abstract - Purpose: Heatwaves, or extended periods of extreme heat, are predicted to increase in frequency, intensity and duration with climate change, but their impact on occupational injury has not been extensively studied. We examined the relationship between heatwaves of varying severity and work-related injuries and illnesses. We used a newly proposed metric of heatwave severity, the Excess Heat Factor (EHF), which accounts for local climate characteristics and acclimatization and compared it with heatwaves defined by daily maximum temperature.

Methods: Work-related injuries and illnesses were identified from two administrative data sources: workers' compensation claims and work-related ambulance call-outs for the years 2003-2013 in Adelaide, Australia. The EHF metrics were obtained from the Australian Bureau of Meteorology. A time-stratified case-crossover regression model was used to examine associations between heatwaves of three levels of severity, workers' compensation claims, and work-related ambulance call-outs.

Results: There was an increase in work-related ambulance call-outs and compensation claims during low and moderately severe heatwaves as defined using the EHF, and a non-significant decline during high-severity heatwaves. Positive associations were observed during moderate heatwaves in compensation claims made by new workers (RR 1.31, 95% CI 1.10-1.55), workers in medium-sized enterprises (RR 1.15, 95% CI 1.01-1.30), indoor industries (RR 1.09, 95% CI 1.01-1.17), males (RR 1.13, 95% CI 1.03-1.23) and laborers (RR 1.21, 95% CI 1.04-1.39).

Conclusions: Workers should adopt appropriate precautions during moderately severe heatwaves, when the risks of work-related injuries and illnesses are increased. Workplace policies and guidelines need to consider the health and safety of workers during heatwaves with relevant prevention and adaptation measures. **Keywords:** Case-crossover design; Heatwaves; Occupational health; Worker safety; Workers' compensation claims.

Susan Williams, Scott Hanson-Easey, Monika Nitschke, Stuart Howell, John Nairn, Chris Beattie, Graeme Wynwood &Peng Bi, "Heat-health warnings in regional Australia: examining public perceptions and responses," ***Environmental Hazards***, vol. 18, no. 4, **2019**, doi: 10.1080/17477891.2018.1538867.

Abstract

Heatwaves are an increasing environmental hazard and an important public health issue in Australia. Heat-health warnings are being adopted widely to promote protective behaviours, but there has been limited evaluation of public responses. This study used a household telephone survey to examine public attitudes and responses to heat-health warnings in regional areas in two Australian states, South Australia and Victoria. The results indicate a high level of recall of heat-health warnings and awareness about managing extreme heat. Respondents viewed heat-health warnings positively, but the effects on behaviour change were variable. Our findings suggest that the warnings may be reinforcing existing protective behaviours more than promoting change. Perceptions of heat risks were higher among women than men, but lower in older age groups. Evidence of this nature is important to identify ways to improve heat-health warnings and more effectively address the public health risks.

Keywords: Heatwave, extreme heat, public health, heat-health warnings, prevention

B. M. Varghese, A. G. Barnett, A. L. Hansen, P. Bi, J. Nairn, S. Rowett, M. Nitschke, S. Hanson-Easey, J. S. Heyworth, M. R. Sim & D. L. Pisaniello, "Characterising the impact of heatwaves on work-related injuries and illnesses in three Australian cities using a standard heatwave definition- Excess Heat Factor (EHF)," ***Journal of Exposure Science & Environmental Epidemiology*** *2019 29:6*, vol. 29, no. 6, pp. 821–830, Apr. **2019**, doi: 10.1038/s41370-019-0138-1.

Abstract
Background and Aims:
Heatwaves have potential health and safety implications for many workers, and heatwaves are predicted to increase in frequency and intensity with climate change. There is currently a lack of comparative evidence for the effects of heatwaves on workers' health and safety in different climates (sub-tropical and temperate). This study examined the relationship between heatwave severity (as defined by the Excess Heat Factor) and workers' compensation claims, to define impacts and identify workers at higher risk.

Methods:
Workers' compensation claims data from Australian cities with temperate (Melbourne and Perth) and subtropical (Brisbane) climates for the years 2006–2016 were analysed in relation to heatwave severity categories (low and moderate/high severity) using time-stratified case-crossover models.

Results:
Consistent impacts of heatwaves were observed in each city with either a protective or null effect during heatwaves of low-intensity while claims increased during moderate/high-severity heatwaves compared with non-heatwave days. The highest effect during moderate/high-severity heatwaves was in Brisbane (RR 1.45, 95% CI: 1.42–1.48). Vulnerable worker subgroups identified across the three cities included: males, workers aged under 34 years, apprentice/trainee workers, labour hire workers, those employed in medium and heavy strength occupations, and workers from outdoor and indoor industrial sectors.

Conclusion:
These findings show that work-related injuries and illnesses increase during moderate/high-severity heatwaves in both sub-tropical and temperate climates. Heatwave forecasts should signal the need for heightened heat awareness and preventive measures to minimise the risks to workers.

B. Varghese, M. Beaty, S. Panchuk, B. Mackie, C. Chen, M. Jakab, T. Yang, P. Bi, J. Nairn, "Heatwave-related Mortality in Australia: Who's impacted the most?," ***European Journal of Public Health***, vol. 30, no. Supplement_5, Sep. **2020**, doi: 10.1093/eurpub/ckaa165.377.

Abstract

Background

The impacts of heatwaves on the risk of mortality have been well-documented worldwide. However, impacts are not equally spread across the population with certain subgroups and locations affected more than others, warranting local evidence to guide and improve prevention and adaptation strategies. The objectives of this study were to identify the person and area-level socio-demographic, health, and environmental factors that modify the heatwave-mortality association in Australia.

Methods

Warm-season (October-March) mortality (2007-2017) were obtained from the Australian Bureau of Statistics. Heatwaves were defined using Excess Heat Factor, a normalised metric of heatwave severity. A time-stratified case-crossover design was used to model heatwave-mortality associations at the Statistical Areas 2 (SA2) spatial unit. Effect modification by person and area-level factors was assessed using interaction terms.

Results

Nationally, mortality increased by 2% (Relative Risk-RR 1.02; 95%CI: 1.01-1.03) during heatwaves with 1418 excess deaths (95%CI: 723-2113). But impacts varied with the highest effect observed in Adelaide (RR 1.08; 95%CI: 1.04-1.12) and Regional Tasmania (RR 1.11; 95%CI: 1.04-1.18). A gradient of impact was found within locations, for example, vulnerable SA2s in Adelaide were featured by a higher proportion of people in rental housing, inaccessibilities (vehicle and internet), low vegetation, newer houses, and a prevalence of respiratory and psychological diseases. Person-level factors included those: renting privately, with a low English-speaking ability, with chronic health conditions (diabetes, asthma/chronic obstructive pulmonary diseases) and using antidepressants, anxiolytics and sedative medications.

Conclusions

Our results, leveraging person and area-level linked data, highlight the need to consider contextual and individual risk factors and the importance of developing place-based targeted interventions to reduce heatwave health impacts.

Key messages

- Heatwaves increase mortality in Australia.
- Heatwave-vulnerability is determined by individual and community-level factors.

B. Y. Wondmagegn, J. Xiang, K. Dear, S. Williams, A. Hansen, D. Pisaniello, M.a Nitschke, J. Nairn, B. Scalley, A. Xiao, Le Jian, M. Tong, H. Bambrick, J. Karnon, P. Bi, "Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia," ***Science of the Total Environment***, vol. 773, **2021**, doi: 10.1016/j.scitotenv.2021.145656.

Abstract

Background: A growing number of studies have investigated the effect of increasing temperatures on morbidity and health service use. However, there is a lack of studies investigating the temperature-attributable cost burden.

Objectives: This study examines the relationship of daily mean temperature with hospital admissions, length of hospital stay (LoS), and costs; and estimates the baseline temperature-attributable hospital admissions, and costs and in relation to warmer climate scenarios in Adelaide, South Australia.

Method: A daily time series analysis using distributed lag non-linear models (DLNM) was used to explore exposure-response relationships and to estimate the aggregated burden of hospital admissions for conditions associated with temperatures (i.e. renal diseases, mental health, diabetes, ischaemic heart diseases and heat-related illnesses) as well as the associated LoS and costs, for the baseline period (2010-2015) and different future climate scenarios in Adelaide, South Australia.

Results: During the six-year baseline period, the overall temperature-attributable hospital admissions, LoS, and associated costs were estimated to be 3915 cases (95% empirical confidence interval (eCI): 235, 7295), 99,766 days (95% eCI: 14,484, 168,457), and AU$159 million (95% eCI: 18.8, 269.0), respectively. A climate scenario consistent with RCP8.5 emissions, and including projected demographic change, is estimated to lead to increases in heat-attributable hospital admissions, LoS, and costs of 2.2% (95% eCI: 0.5, 3.9), 8.4% (95% eCI: 1.1, 14.3), and 7.7% (95% eCI: 0.3, 13.3), respectively by mid-century.

Conclusions: There is already a substantial temperature-attributable impact on hospital admissions, LoS, and costs which are estimated to increase due to climate change and an increasing aged population. Unless effective climate and public health interventions are put into action, the costs of treating temperature-related admissions will be high.

Keywords: Climate change; Healthcare cost; Heat-attributable; Hospital admissions; Temperature.

B. Y. Wondmagegn, J. Xiang, K. Dear, S. Williams, A. Hansen, D. Pisaniello, M. Nitschke, J. Nairn, B. Scalley, B. M. Varghese, A. Xiao, Le Jian, M. Tong, H. Bambrick, J. Karnon, P. Bi, “Impact of heatwave intensity using excess heat factor on emergency department presentations and related healthcare costs in Adelaide, South Australia,” ***Science of the Total Environment***, vol. 781, p. 146815, Aug. **2021**, doi: 10.1016/j.scitotenv.2021.146815.

Abstract
Background: The health impacts of heatwaves are a growing public health concern with the frequency, intensity, and duration of heatwaves increasing with global climate change. However, little is known about the healthcare costs and the attributable morbidity associated with heatwaves Objective This study aims to examine the relationship between heatwaves and costs of emergency department (ED) presentations, and to quantify heat-attributable burden during the warm seasons of 2014–2017, in Adelaide, South Australia.

Methods: Daily data on ED presentations and associated costs for the period 2014–2017 were obtained from the South Australian Department of Health and Wellbeing. Heatwave intensity was determined using the excess heat factor (EHF) index, obtained from the Australian Bureau of Meteorology. A distributed lag non-linear model (DLNM) was used to quantify the cumulative risk of heatwave-intensity over a lag of 0–7 days on ED presentations and costs. Effects of heatwaves were estimated relative to no heatwave. The number of ED presentations and costs attributable to heatwaves was calculated separately for two EHF severity categories (low-intensity and severe/extreme heatwaves). Subgroup analyses by disease-diagnosis groups and age categories were performed.

Results: For most disease diagnosis and age categories, low-intensity and severe heatwaves were associated with higher rates of ED presentations and costs. We estimated a total of 1161 (95% empirical confidence interval (eCI): 342, 1944) heatwave-attributable all-cause ED presentations and associated healthcare costs (thousands) of AU$1020.3 (95% eCI: 224.9, 1804.7) during the warm seasons of 2014–2017. The heat-related illness was the disease category contributing most to ED presentations and costs. Age groups 0–14 and ≥ 65 years were most susceptible to heat.

Conclusions: Heatwaves produced a statistically significant case-load and cost burden to the ED. Developing tailored interventions for the most vulnerable populations may help reduce the health impacts of heatwaves and to minimise the cost burden to the healthcare system.

Keywords: ED, Extreme heat, Healthcare spending, Low-intensity heatwave, Severe heatwave

B. Varghese, M. Beaty, P. Bi, and J. Nairn, “Impact of Heatwaves on use of health services (GP and Emergency department visits),” **International Journal of Epidemiology**, vol. 50, no. Supplement_1, Sep. **2021**, doi: 10.1093/IJE/DYAB168.680.

Abstract
Background
Heatwaves are associated with increases in mortality and morbidity (mostly hospitalisations). However, evidence regarding heatwave impacts on the use of frontline health-services such as general practitioner (GP) consultations and emergency department (ED) services is limited. This study quantified the impact of heatwaves on the use of GP and ED services in Adelaide.

Methods
Data on GP services (2011-2016) from the Medicare Benefits Schedule and ED visits (2013-2018) were obtained from the Australian Bureau of Statistics and the Department of Health, respectively. Heatwaves were defined using Excess Heat Factor. Using time-stratified case-crossover models, we modelled heatwave-severity (low, severe/extreme) against the use of GP and ED services in the warm-season (October-March). Effect estimates are reported as relative risks (RRs).

Results
Total GP visits decreased during low-intensity heatwaves and increased during severe/extreme heatwaves (RR 1.14; 95%CI: 1.13-1.15). The highest increases during severe/extreme heatwaves were observed for respiratory (RR 1.36; 95%CI: 1.27-1.45) and psychiatric services. While ED visits decreased overall during low-intensity and severe/extreme heatwaves, those due to heat-light disorders (RR 4.23; 95%CI: 2.98-6.00), volume depletion, and respiratory diseases increased during severe/extreme heatwaves.

Conclusions
There were significant increases in the use of GP and specific ED services during heatwaves in Adelaide. Further research is needed to identify the intrinsic and extrinsic vulnerability factors contributing to these increases in Adelaide and other Australian cities.

Key messages
Impacts of heatwaves extend beyond mortality to include frontline health-services (GP/EDs) that are already challenged. Evidence presented may assist policymakers for resource allocation and healthcare workforce capacity building.

M Tong, B Wondmagegn, S Williams, A Hansen, K Dear, D Pisaniello, J Xiang, J Xiao, L Jian, B Scalley, M Nitschke, J Nairn, H Bambrick, J Karnon, P Bi, ‘Hospital healthcare costs attributable to heat and future estimations in the context of climate change in Perth, Western Australia”, **Advances in Climate Change Research 12 (2021) 638-648** [240]

https://doi.org/10.1016/j.accre.2021.07.008

Abstract Climate change with increasing temperature is making a significant impact on human health, including more heat-related diseases, and increasing the burden on the healthcare system. Although many studies have explored the association between increasing temperatures and negative health outcomes, research on the associated costs of heat-related diseases remains relatively sparse. Furthermore, estimations of future costs associated with heat-attributable hospital healthcare have not been well explored. This study used a distributed lag nonlinear model to estimate heat-attributable hospital healthcare costs in Perth, Western Australia. Using 2006–2012 as the baseline, future costings for 2026–2032 and 2046–2052 were estimated under RCP2.6, RCP4.5, and RCP8.5. Higher temperatures were found to be associated with increased hospital healthcare costs. The total hospital costs attributable to heat over the baseline period 2006–2012 was estimated to be 79.5 million AUD, with costs for mental health hospitalizations being the largest contributor of the heat-related conditions examined. Costs are estimated to increase substantially to 125.8–129.1 million AUD in 2026–2032, and 174.1–190.3 million AUD by midcentury under climate change scenarios. Our findings of a notable burden of heat-attributable healthcare costs now and in the future emphasize the importance of climate change adaptation measures to reduce the adverse health effects of increasing temperatures and heat exposure on the people of Perth.

M Tong, B Wondmagegn, J Xiang, S Williams, A Hansen, K Dear, D Pisaniello, J Xiao, L Jian, B Scalley, M Nitschke, J Nairn, H Bambrick, J Karnon, P Bi, “Emergency department visits and associated healthcare costs attributable to increasing temperature in the context of climate change in Perth, Western Australia, 2012–2019”, **Environ. Res. Lett.** 16 (2021) 065011, **2021**

Abstract Increasing temperature and its impact on population health is an emerging significant public health issue in the context of climate change in Australia. While previous studies have primarily focused on risk assessment, very few studies have evaluated heat-attributable emergency department (ED) visits and associated healthcare costs, or projected future health and economic burdens. This study used a distributed lag non-linear model to estimate heat attributable ED visits and associated healthcare costs from 13 hospitals in Perth, Western Australia, and to project the future healthcare costs in 2030s and 2050s under three climate change scenarios—Representative Concentration Pathways (RCPs)2.6, RCP4.5 and RCP8.5. There were 3697 ED visits attributable to heat (temperatures above 20.5 ◦C) over the study period 2012–2019, accounting for 4.6% of the total ED visits. This resulted in AU$ 2.9 million in heat-attributable healthcare costs. The number of ED visits projected to occur in the 2030s and 2050s ranges from 5707 to 9421 under different climate change scenarios,

which would equate to AU$ 4.6–7.6 million in heat associated healthcare costs. The heat attributable fraction for ED visits and associated healthcare costs would increase from 4.6% and 4.1% in 2010s to 5.0%–6.3% and 4.4%–5.6% in 2030s and 2050s, respectively.
Future heat attributable ED visits and associated costs will increase in Perth due to climate change. Excess heat will generate a substantial population health challenge and economic burdens on the healthcare system if there is insufficient heat adaptation. It is vital to reduce greenhouse gas emissions, develop heat-related health interventions and optimize healthcare resources to mitigate the negative impact on the healthcare system and population health in the face of climate change.

M Tong, B Wondmagegn, J Xiang, S Williams, A Hansen, K Dear, D Pisaniello, B Varghese, J Xiao, L Jian, B Scalley, M Nitschke, J Nairn, H Bambrick, J Karnon, P Bi, "Heat-attributable hospitalisation costs in Sydney: Current estimations and future projections in the context of climate change," **Urban Climate**, vol. 40, p. 101028, Dec. **2021**, doi: 10.1016/J.UCLIM.2021.101028

Abstract The association between heat and diseases has been extensively reported. However, its associated healthcare costs and attributable fraction due to heat were scarcely explored. The aim of this study was to estimate hospitalisation costs attributable to heat in Sydney, and to project future costs under climate change scenarios. Using a distributed lag nonlinear model, this study estimated heat-attributable hospitalisation costs in Sydney; and using 2010–2016 data as baseline, future costs for 2030s and 2050s were estimated under three climate change scenarios depending on greenhouse gas emissions - Representative Concentration Pathway (RCP)2.6, RCP4.5, and RCP8.5. Higher temperatures were found to be associated with increased hospitalisation costs. About 8–9% of the total hospitalisation costs were attributable to heat. The total costs attributable to heat over the baseline period 2010–2016 were estimated to be AU$252 million, with mental health hospitalisation making the largest contribution. Hospitalisation costs are estimated to increase substantially to AU$387–399 million in the 2030s, and AU$506–570 million by mid-century under different climate change scenarios. Urgent action is required to reduce heat-attributable illness in our communities, particularly for mental health conditions. Relevant preparations including healthcare workforce capacity building and resource allocation are needed to deal with these challenges in the context of climate change.

Douglas AG. Radford, Thomas C. Lawler, Brandon R. Edwards, Benjamin RW. Disher, Holger R. Maier, Bertram Ostendorf, John Nairn, Hedwig van Delden and Michael Goodsite, "The creation of heat-resilient infrastructure: A Framework for the mitigation and adaptation from heat-related risk", **Sustainable Cities and Society, 2022,** doi 10.1016/J.SCS.2022.103820

Abstract The rising frequency of heat-related hazards as a result of climate change will increasingly affect heat-sensitive infrastructure assets. Recent studies quantify the heat-related risk to infrastructure, with some exploration of individual mitigation strategies, however missing in literature is an infrastructure sector-transferable and comprehensive framework for analysing future risk and performing evaluation of several options for risk reduction. This paper introduces a generic framework to: quantify heat-related risks to infrastructure assets in a transferable manner; assess the effects of future exogenous systems changes, and; evaluate several practical mitigation strategies. The framework is applied to the asphalt road network in Adelaide, Australia. This case study explores heat-related risk under present and future climate hazard and traffic stressor scenarios and critical evaluation of mitigation strategies. The strategies explored affect both hazard and vulnerability elements of risk, including: asphalt binder materials, reflectivity additives, and traffic volume, loading or speed management. Results indicate up to a 19% increase in risk from 2020 to 2090 as a result of climate change. Road replacement strategies are identified as most effective, reducing risk by up to 33% in 2090. The framework shows value in developing comprehensive and practical strategies for managing heat-sensitive infrastructure assets into the future.

Key Words Climate Change; Heat; Extreme Temperatures; Risk; Resilience; Adaptation; Infrastructure; Road Networks

Appendix B: Poster presented at GLORIOUS project workshop

C3S_422_Lot1_SMHI General Assembly for global Copernicus Climate Change Service

SMHI, Folkborgsvägen 17, Norrköping, Sweden, 16 – 18 September 2018

Moise, Nairn and Hansen, “Heat and Cold Waves in Australia-A Case Study exploring the impact in the Health Sector in New South Wales Spatial extent of Heatwaves is increasing Heat Wave index EHF now operational at the Bureau of Meteorology for Australian seasonal and weekly forecasts,” **GLORIOUS Project Poster, Norrköping, Sweden 2018**

The Australian Bureau of Meteorology (BOM) and the Commonwealth Scientific and Industry Research Organisation (CSIRO) have developed a climate change projections portal through a federal government funded project for the Natural Resource Management sector (see https://www.climatechangeinaustralia.gov.au/en/). This project ended in 2015 and currently provides the most up-to-date climate projections for Australia as well as several 'tools' for the user communities to explore the breadth of the projected changes. Data download is also supported. The global service of GLORIOUS will be used to further develop this national service by adding new CIIs, which are not currently produced in gridded products operationally. The underlying observed climate fields is available at BOM and will be compared to climate projections from the CDS at C3S, by production of CIIs such as: (1) Degree days; (2) SPI (for drought); (3) Heatwave and Coldwave indices; (4) Days above/below thresholds (hot days, frost days, tropical nights); and (5) the Thom discomfort index.

Climate change Impact Indices: • Building on AUS projections expertise • Expanding EHF/ECF to global gridded data set to be applied to GCM output of future scenarios • Engage stakeholders in ongoing dialogue on usefulness of CCII's for their future planning References Heatwave defined as a heat impact event for all community and emergency sectors in Australia.

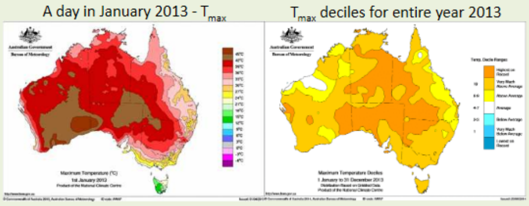
Copernicus Climate Change Service

Heat and Cold Waves in Australia – A Case Study exploring the impact in the Health Sector in New South Wales

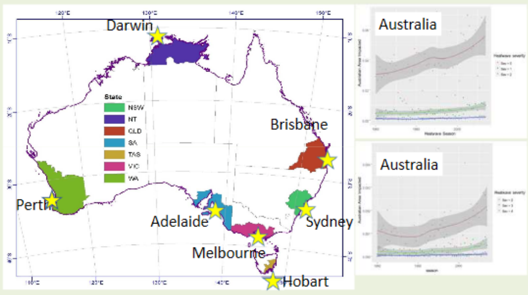
Dr Aurel Moise, John Nairn and Lawson Hanson
Australian Bureau of Meteorology

The Australian Bureau of Meteorology (BOM) and the Commonwealth Scientific and Industry Research Organisation (CSIRO) have developed a climate change projections portal through a federal government funded project for the Natural Resource Management sector (see https://www.climatechangeinaustralia.gov.au/en/). This project ended in 2015 and currently provides the most up-to-date climate projections for Australia as well as several 'tools' for the user communities to explore the breadth of the projected changes. Data download is also supported. The global service of GLORIOUS will be used to further develop this national service by adding new CIIs, which are not currently produced in gridded products operationally. The underlying observed climate fields is available at BOM and will be compared to climate projections from the CDS at C3S, by production of CIIs such as: (1) Degree days; (2) SPI (for drought); (3) Heatwave and Coldwave indices; (4) Days above/below thresholds (hot days, frost days, tropical nights); and (5) the Thom discomfort index.

The Australian "Angry Summer" of 2013-14



Spatial extent of Heatwaves is increasing

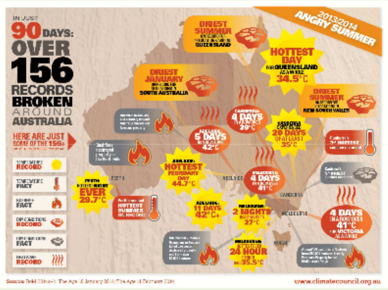


Heatwaves and their projected changes under enhanced greenhouse warming are of particular interest in Australia, where they affect many sectors (health, agriculture, transport, energy, tourism, etc.). Recent results warrant concern over the potential for increased incidence of heatwaves in Australia, noting that further research would be needed to extend this work nationally and refine it to enhance our understanding of the likely extent of future heat events.

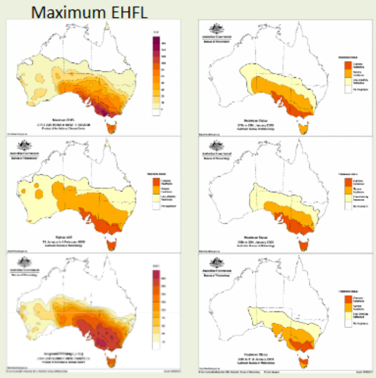
Currently, BOM provides a Heatwave Service for Australia. These heatwave and coldwave indices are demonstrating dose-response skill on three continents with the Excess Heat Factor (EHF; Nairn and Fawcett, 2014) heatwave index being used widely across Australia.

In this case-study we will extend these heatwave and coldwave indices to future climate by using climate projections. The comparison of ensemble projections and observations will advance the scientific understanding and help to communicate confidence of projections to stakeholders with respect to climate change adaptation. For the latter, the national user community in Australia will be queried for feedback and co-design. If deemed useful these CIIs will also be produced globally in the overall GLORIOUS global service, as they are of major global concern affecting many societal sectors, businesses and ecosystems world-wide.

Impact of "Angry Summer" of 2013/14



Heat Wave index EHF now operational at the Bureau of Meteorology for Australian seasonal and weekly forecasts



EHF in action – 2009 heat wave

DEFINITIONS of the indices: EHF and ECF

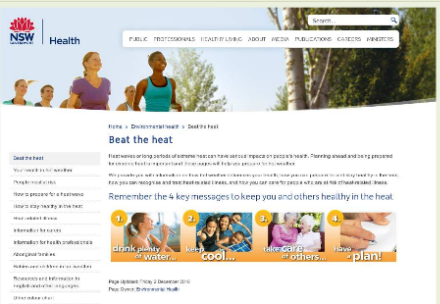
Long term temperature anomaly × (+ve Short term temperature anomaly)
Heatwave detection — Amplifying term

Heatwave (EHF metric) calculations	
EHF:	$EHF = EHI_{sig} \times max(1, EHI_{accl})$
Excess Heat:	$EHIsig = (T_i + T_{i+1} + T_{i+2})/3 - T_{95}$
Heat Stress:	$EHI_{accl} = (T_i + T_{i+1} + T_{i+2})/3 - (T_{i-1} + \dots + T_{i-30})/30$
Coldwave (ECF metric) calculations	
ECF:	$ECF = ECI_{sig} \times max(1, ECI_{accl})$
Excess Cold:	$ECI_{sig} = (T_i + T_{i+1} + T_{i+2})/3 - T_{05}$
Cold Stress:	$ECI_{accl} = (T_i + T_{i+1} + T_{i+2})/3 - (T_{i-1} + \dots + T_{i-30})/30$

Climate change Impact Indices:

- Building on AUS projections expertise
- Expanding EHF/ECF to global gridded data set to be applied to GCM output of future scenarios
- Engage stakeholders in ongoing dialogue on usefulness of CCII's for their future planning

NSW Dept. of Health advisory pages on Heat Waves



Engagement with our stakeholder(s)

- State Departments of Health represented by the NSW Department of Health have a very keen interest in receiving more information on future changes to heat waves
- State Emergency Service (SES) are also indentified as important users
- Seeking feedback on how this information should be provided to the Health departments
- Continued dialogue to evaluate usefulness of CII's

References

Heatwave defined as a heat impact event for all community and emergency sectors in Australia. Nairn 2013. http://www.bushfirecrc.com/resources/research-report/heatwave-defined-heat-impact-event-all-community-and-emergency-sectors-aus

The excess heat factor: A metric for heatwave intensity and its use in classifying heatwave severity, Nairn, J.R., Fawcett, R.J.B. *Int. J. Environ. Res. Public Health* **2015**, *12*(1), 227-253; doi:10.3390/ijerph120100227

Responding to heatwave intensity: Excess Heat Factor is a superior predictor of health service utilisation and a trigger for heatwave plans. Scalley et al. Australian and New Zealand Journal of Public Health 2015

Extending the Bureau's heatwave forecast to multi-week timescales. Hudson, D and Marshall, A.G. 2016. Bureau Research Report, No. 16. Bureau of Meteorology Australia, http://www.bom.gov.au/research/research-reports.shtml

Extreme climatic conditions and health service utilisation across rural and metropolitan New South Wales. Jegasothy et al, 2017. https://link.springer.com/article/10.1007/s00484-017-1313-5

Variation in Population Vulnerability to Heatwave in Western Australia. Jianguo et al. Front. Public Health, 03 April 2017 | https://doi.org/10.3389/fpubh.2017.00064

Heatwaves in Queensland. Nairn and Fawcett. AJEM, 2017. https://ajem.infoservices.com.au/items/AJEM-32-01-11

Publications in Geophysical Research Letters and the Journal of Climate (2012) by Perkins and Alexander (UNSW) have reviewed heatwave indices and utilised EHF (heatwave intensity).

CAWCR 2013 Technical Report 60 co-authored with Robert Fawcett (National Climate Centre then CAWCR with support from the Bushfire CRC).

Using the Excess Heat Factor (EHF) to predict the risk of heat related deaths. Langlois et al. 2013. Journal of Forensic and Legal Medicine. http://www.scopus.com/inward/record.url?eid=2-s2.0-84878902127&partnerID=tZOtx3y1

ON BEHALF OF ECMWF FOR THE EUROPEAN COMMISSION

Australian Government Bureau of Meteorology

Copernicus Europe's eyes on Earth

Figure 127. Copernicus: GLORIOUS project poster.

Appendix C: Oral conference presentations

International Congress of Biometeorology, Durham, UK, September 3 - 7, 2017

Challenges for verifying global heatwave and coldwave forecasts: Can emerging technology help?

Authors: Joanne Robbins[1], John Nairn[2,3], Grant Williamson[4], Amanda Wheeler[4], Sharon Campbell[4], David Bowman[4], Fay Johnston[4]

1. Met Office, Exeter, UK
2. Bureau of Meteorology, Adelaide, South Australia
2. University of Adelaide, Adelaide, South Australia
3. University of Tasmania, Hobart, Tasmania

International Congress of Biometeorology, Durham, UK, September 3 - 7, 2017

Managing increasing heatwave severity, Australia's national heatwave service.

Authors: John Nairn[1,2], Bertram Ostendorf[2], Peng Bi[2]

1. Bureau of Meteorology, Adelaide, South Australia
2. University of Adelaide, Adelaide, South Australia

AFAC/BNHCRC 2018: Extended abstract

Australia's future National Heatwave Forecast and Warning service: operational considerations.

Authors: John Nairn[1,3], Robert Fawcett[2], Linda Anderson-Berry[2], Bertram Ostendorf[3], Peng Bi[3], Chris Beattie[4]

1. Bureau of Meteorology, Adelaide, South Australia, Australia
2. Bureau of Meteorology, Melbourne, Victoria, Australia
3. University of Adelaide, Adelaide, South Australia, Australia
4. State Emergency Service Adelaide South Australia Australia

ISEE Conference 2020, Online, October 2020

Heatwave-health vulnerability in Adelaide: Analysis of mortality and morbidity outcomes

Authors: B. M. Varghese, M. Beaty, P. Bi, and J. Nairn, ISEE Conference Abstracts, vol. 2020, no. 1, Oct. **2020**, doi: 10.1289/isee.2020.virtual.p-0399.

ISEE Conference 2021, Online, August 2021

Towards heat impact forecasts through linked-data and cross-agency collaboration.

Authors: John Nairn, Matt Beaty, Cheng Chen, Tina Yang, Shannon Panchuk, Brenda Mackie

Social and spatial variation in heatwave-related emergency department visits in Australia.

Authors: R. M. Beaty, B. Varghese, and J. Nairn, Abstracts, vol. 2021, no. 1, Aug. 2021, doi: 10.1289/ISEE.2021.P-378.

The author has contributed heatwave insights for the World Meteorological Organisation (WMO) High Impact Weather project's (HIWeather) book, "Towards the "Perfect" Weather Warning: Bridging disciplinary gaps through partnership and communication". The book is being published by Springer, with Open Access in electronic form by December 2021.