DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

NSW Climate Extremes Baseline Assessment

Full report

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Cover photo: Lightning strike at Spectacle Island Nature Reserve. Kelly Nowak/DPIE.

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Report overview

Many of the most significant and earliest effects of climate change are being experienced through changes in extreme weather and ocean hazards that can have severe impacts on New South Wales (NSW) regions. These include relatively common extremes that occur a few times a year on average, as well as rarer extremes with multi-year return periods.

The NSW Department of Planning, Industry and Environment (DPIE) is currently working to catalyse research on climate extremes that will ultimately contribute to reducing the detrimental impacts of climate change on NSW. As part of this effort, in 2017 DPIE commissioned a 'baseline assessment' of the state of scientific research relating to extreme climate events that affect NSW, to guide priorities for further climate science research by DPIE. The baseline assessment project covered the following seven types of extreme climate events:

1. Rainfall: extreme rainfall, flood, snow and drought
2. Temperature: extreme heat/cold, heatwave
3. Unstable atmosphere: dust storm, thunderstorm, hail and lightning
4. Wind: wind gust, storm surge and coastal flooding/tidal inundation
5. Extreme East Coast Lows (ECLs)
6. Fire: bushfire and fire weather
7. Compound or coincident events.

The following three chapters present a concise literature review of research findings on the seven types of extreme events listed above, intended to provide a current baseline for climatological research relating to various atmospheric and oceanic hazards, and available datasets, tools and databases for extreme climate event data and information.

- Chapter 1: Review of extreme climate events research
- Chapter 2: Review of extreme climate events datasets
- Chapter 3: Review of extreme climate events databases and tools.

The accompanying Summary Report[1] provides the key findings from these three chapters.

[1] Department of Planning, Industry and Environment (DPIE) 2020, *NSW Climate Extremes Baseline Assessment: Summary report*.

1. Review of extreme climate events research

1.1 Introduction

Chapter 1 includes research findings on climatological changes and the potential impacts of climate change in relation to these extreme events. The research findings presented are based on data from observations and reanalyses, as well as projected changes from Global Climate Model (GCM) and downscaling simulations of the future climate, rather than the shorter timescales of seasonal-to-decadal variability or much longer timescales of palaeontology (while noting that there is also a considerable amount of literature available covering these other timescales). Literature is summarised with a focus on the overarching conclusions of recent studies for NSW and Australia, as well as globally in some cases. Useful information on these hazards throughout Australia is produced by CSIRO and the Bureau of Meteorology (BoM) and is available on the Climate Change in Australia website. Information specific to NSW is also available on the Publications page of the NSW and ACT Regional Climate Modelling (NARCliM) project.

These hazards can sometimes lead to severe impacts on regions of NSW, dependent on additional factors such as the level of exposure and vulnerability to a particular hazard, while noting that such additional factors are not the focus of this chapter.

1.2 Rainfall: extreme rainfall, flood, snow and drought

1.2.1 Extreme rainfall

Extreme rainfall and associated flooding events in NSW as well as other regions of the world can cause extensive damage to the built and natural environments, as well as loss of life and productivity. There is a large degree of natural variability in the physical processes and large-scale drivers that influence rainfall characteristics in NSW (such as in relation to the El Niño Southern Oscillation (ENSO) (Risbey et al. 2009; King et al. 2014; Dowdy et al. 2015a)), making observed trends in extreme rainfall both difficult to detect and sensitive to analysis methodology in some cases. Extreme rainfall is often caused by significant weather systems such as thunderstorms, frontal systems and cyclones, including East Coast Lows (ECLs) in coastal NSW (Pepler et al. 2014; Kiem et al. 2016; Dowdy & Catto 2017). Changes in weather systems such as these (as detailed in subsequent sections) are likely to lead to future regional and seasonal changes in extreme rainfall in NSW.

Some studies show that long-term climatological trends in rainfall rates can be different depending on the duration of rainfall events examined, including for NSW regions. For example, in the Greater Sydney region, an increase in observed short duration rainfall (less than two hours) has been identified, while for durations of three or more hours a decrease was found to be more likely (Bates et al. 2015a; Zheng et al. 2015). Results such as these are similar to evidence more broadly apparent throughout Australia that a higher proportion of total annual rainfall in recent decades has come from heavy rainfall events based on daily totals, as shown by CSIRO and BoM (2015) for heavy rainfall (defined as above the 90th percentile). There is substantial physical understanding in support of an increase in the intensity of some extreme rainfall events, given that global warming can have a direct influence on heavy rainfall potential by increasing the maximum amount of available moisture in the atmosphere, as the atmospheric moisture capacity increases with temperature by about 7% per degree (the Clausius–Clapeyron relationship). Global analyses based on satellite, balloon and surface observations all show increased absolute humidity broadly consistent with the observed global warming trends (Trenberth et al. 2007). Furthermore, an increase in maximum annual 1-day precipitation has been observed for many regions of the world (Westra et al. 2013) including most of NSW from 1911–2014 (see Fig. 3.17 in Evans et al. 2014). Some studies indicate that the intensity of heavy rainfall events is increasing at a rate of about 7% per degree of warming, while noting that short-duration events (e.g. sub-daily rainfall extremes), as produced by thunderstorms or tropical cyclones, could increase by about double that rate (including due to the additional effect of stronger convective processes such as shown by Lenderink et al. (2008) and Westra and Sisson (2011)).

Heavy rain events based on daily totals are generally projected to become more intense in the future across most of Australia (CSIRO & BoM 2015; Alexander & Arblaster 2017). GCMs and some downscaling projections suggest future increases in rainfall intensity for the wettest day of the year throughout most of NSW, as well as in the likelihood of extreme rainfall events of intensities that are currently rare (e.g. 1-in-20-year events) (CSIRO & BoM 2015). For the eastern seaboard region, an increase in 1-day precipitation is projected to occur during summer with little change indicated for other seasons including based on considering potential seasonal changes to ECLs and thunderstorms (CSIRO & BoM 2015; Dowdy et al. 2015a), as is also discussed in subsequent sections here on unstable atmosphere (Section 1.4) and ECLs (Section 1.6). However, an analysis of the maximum seasonal and annual 1-day precipitation based on model output from NARCliM downscaling did not find significant changes at the 95% confidence level for NSW regions (Evans et al. 2017a). Despite difficulties associated with characterising historical observed trends, as well as some differences between results from different modelling approaches, there is a substantial degree of confidence in future projections of more intense extreme rainfall events, in part due to the physical understanding based on the Clausius–Clapeyron relationship, coupled with the very high confidence in projections of future temperature for various greenhouse gas emissions scenarios.

Projections of sub-daily rainfall extremes have a higher degree of uncertainty about them, noting that they are generally produced by phenomena that are difficult to represent in GCMs such as thunderstorms. This can be important for impacts such as damages caused by flash flooding. As noted above in relation to observations, it is plausible that increases in rainfall extremes will significantly exceed (e.g. double) the scaling rates per degree of warming as indicated by the Clausius–Clapeyron relationship. There is some indication of this from modelling for regions of NSW based on the NSW Government's NARCliM downscaled climate projections of daily rainfall extremes (Bao et al. 2017).

Regional downscaling efforts, such as NARCliM (Bao et al. 2017; Evans et al. 2017a), can provide greater resolution of some rainfall characteristics than GCMs, such as around geographic features that may not be resolved by GCMs (including details of the Great Dividing Range and eastern seaboard orography), as well as provide insight into extremes such as for intensity–frequency–duration (IFD) analysis (Willgoose et al. 2014; Evans & Argüeso 2015). Future projections from NARCliM indicate some increases in the magnitude of precipitation extremes in NSW, while noting that although the projected future changes are similar to some observed changes there is not a high degree of statistical significance in the projected changes in rainfall extremes, in part due to considerable differences in results between models within the NARCliM ensemble. For example, Evans et al. (2014) note that in projections for 2020–2039 all increases are within the inter-annual variability and are therefore not statistically significant, and in projections for 2060–2079 this remains true for most indices and regions.

Significant differences are apparent in rainfall projections for NSW between different downscaling efforts, including differences between downscaling results and other methods of examining future changes, as detailed in studies such as Bates et al. (2015a), Dowdy et al. (2015a) and Grose et al. (2015). For example, projections can be assessed based on a consideration of multiple lines of evidence in addition to modelling, including physical understanding of the processes that cause extreme rainfall (e.g. in relation to weather phenomena such as thunderstorms and cyclones, as well as large-scale drivers such as ENSO) and based on observed trends, as discussed in CSIRO and BoM (2015). Current developments in convection-permitting modelling may help reduce some uncertainty in projections of rainfall extremes particularly at sub-daily scales, while noting that differences in results between different modelling efforts will likely remain as well as uncertainties remaining associated with larger-scale conditions (e.g. relating to ENSO), highlighting the benefit in considering multiple lines of available evidence as well as considering a broad range of different modelling efforts.

1.2.2 Floods

The extent and severity of flooding is influenced by a range of factors, including the timing, spatial distribution, intensity and duration of rainfall, as well as the antecedent and background climate conditions (such as soil moisture and storage levels). For a recent review on this see Johnson et al. (2016) and references therein, noting that *Australian rainfall and runoff* (Engineers Australia 1987) provides guidance on best-practice methods around flood estimation. There is also considerable variability in the occurrence of the weather systems that can sometimes cause widespread heavy rainfall, such as cyclones and fronts, as well as localised heavy rainfall such as thunderstorms that can cause flash flooding. The complex interaction of these factors, coupled with the large inter-annual variability and relatively short length of comprehensive flood records, make it difficult to confidently assess significant trends in the frequency or magnitude of observed flood events in Australia (as noted by Johnson et al. (2016) and references therein). However, there are some regional exceptions to this, with a significant increase in observed flooding frequency identified for coastal south-east Australia since the mid-19th century (Power & Callaghan 2016), as well as decreases indicated in some regions (including south-east Australia) by Ishak et al. (2013) while noting considerable uncertainties in understanding the causes of the trends (e.g. climate change and/or other influences).

There is considerable uncertainty based on modelling as to how flood severity and frequency could change in the future at a catchment level, including due to considerable uncertainties in future rainfall projections (e.g. the influence of drivers such as ENSO) as well as uncertainties in currently available hydrological models. However, extreme rainfall is projected to increase significantly in many regions of Australia, including NSW (Section 1.2.1), which could contribute to an increased risk of flooding in some cases. Additionally, a potential increase in flash flood risk is also plausible, due to potential changes in short-duration convective rainfall events (Westra et al. 2014). However, in general there is a relatively limited number of studies examining climatological flood risk in Australia based on projections from climate models, and although flood hazard in Australia is expected to change in the future it is not currently possible to even universally predict the direction of these changes (Johnson et al. 2016).

For many coastal and estuarine regions, projected changes in extreme rainfall suggest that flooding will likely increase in frequency and magnitude particularly when combined with rising sea levels (as an example of a compound event, discussed in Section 1.8), while sea level rise can also lead to an increased risk of ‘nuisance tidal flooding’ through the combination of high astronomical tides and elevated sea level alone, in the absence of a major weather event (Sweet & Marra 2016). Further detail on coastal flooding is provided in Section 1.5.2.

1.2.3 Snow

Various observational studies have reported downward trends in snow cover for Australia, including NSW regions, while noting a considerable degree of inter-annual variability in various different snow conditions and little research to date on the potential influence of climate change on extreme snowfall events. Satellite remote sensing observations indicate a reduction in snow cover in the Australian Alps including NSW regions from 2000–2014 (Thompson 2016). Fiddes et al. (2015a,b) found that maximum snow depth as well as total snow accumulation have declined over the last 25 years, based on long-term observations from a number of ski resorts, and that these snow conditions were highly related to maximum temperatures, indicating the role of climate change in reducing snow cover. Pepler et al. (2015) reported some influence on snow depth from large-scale drivers such as ENSO and the Indian Ocean Dipole (IOD). Downward trends were also reported by earlier studies on the impact of climate change on snow conditions in mainland Australia (Hennessy et al. 2003, 2008a; Pickering & Buckley 2010; Bhend et al. 2012), which similarly found snow depths at various alpine sites have declined since the 1950s and variability in snow depth is related to maximum temperatures.

Future projections of snow in Australia have been produced based on GCMs as detailed in CSIRO & BoM (2015). As shown in their section 7.2.4, there is very high confidence that as warming progresses there will be a decrease in snowfall as well as an increase in snowmelt, and thus reduced snow season length, particularly at low elevations. These projections have larger reductions in snow conditions for higher emissions pathways than lower emissions pathways, indicating the anthropogenic influence on snow conditions. These results show some similarities to previous studies mentioned above, including recent studies such as Fiddes et al. (2015a) and Timbal et al. (2016).

Downscaling projections also indicate a likely reduction in snowfall and snow cover, with Di Luca et al. (2017) finding that the snowpack decreases by about 15% by 2030 and 60% by 2070 under a high emissions scenario relative to 2000. Additionally, a decrease in the frequency of suitable snowmaking conditions for the Australia Alps has also been projected to occur (Ji et al. 2017).

1.2.4 Drought

Drought can be defined in a number of ways, including a general definition as a deficit of water compared to the mean. Numerous variations exist for aspects of the definition of drought, such as discussed in Kiem et al. (2016), with meteorological drought focused on here. This can be defined as extent and severity of drought in terms of deficits in precipitation from average conditions, possibly combined with increased potential evapotranspiration. Drought is a feature of the NSW climate, characteristic of the substantial spatio-temporal variability that can occur in contributing factors (including rainfall) throughout Australia (Hennessy et al. 2008b). The occurrence of rainfall can be influenced in NSW by large-scale atmospheric and oceanic modes of variability such as ENSO, the IOD and the Southern Annular Mode (SAM), as well as the subtropical ridge and atmospheric blocking, which can influence regional rainfall and other environmental conditions in the state and the weather phenomena that cause rainfall (e.g. cyclones, fronts and thunderstorm systems) (Risbey et al. 2009; Gallant et al. 2013; Maher & Sherwood 2014; Dowdy et al. 2015a).

Long-term climatological changes in observed drought conditions in Australia are difficult to determine with a high degree of confidence, given the substantial degree of variability that naturally occurs in contributing factors including rainfall. Australia has experienced three major dry periods over the last century or more, including the Federation drought (1895–1903), the World War II drought (1939–1945) and the Millennium Drought (1996–2010), all of which had severe impacts for NSW, including economic losses from agriculture. For example, the severity of the recent Millennium Drought, which resulted in significant reductions in groundwater storage (van Dijk et al. 2013), has been attributed in part to multi-decadal variability combined with anthropogenic greenhouse warming (Cai et al. 2014; Ummenhofer et al. 2009), exacerbated by land–atmosphere coupling such as vegetation coverage and albedo (Evans et al. 2017b).

There is relatively low confidence in projections for future changes to large-scale drivers such as ENSO, thereby adding uncertainty to understanding likely changes in drought for NSW in the future. However, the Walker Circulation shows signs that it has weakened during the 20th century (Power & Kociuba 2011) and due to an increase in moisture availability it is likely that ENSO-related precipitation variability on regional scales will intensify (Chapter 12 in IPCC 2013). Coupled Model Intercomparison Project phase 5 (CMIP5) models are generally better at representing ENSO than CMIP3 (phase 3) models (Guilyardi et al. 2009), while noting that current GCMs still have considerable limitations such as in their ability to represent rainfall teleconnections in some regions including NSW (Watanabe et al. 2012). As discussed in CSIRO and BoM (2015), there is considerable uncertainty in representing potential changes in the characteristics of future ENSO variability based on GCMs, also noting that these large-scale variations associated with atmospheric and oceanic modes such as ENSO are not able to be corrected with fine-scale downscaling techniques.

Measures of meteorological drought based on indices such as the Standardised Precipitation Index (SPI) were applied to GCM projections of future climate, as detailed in CSIRO and BoM (2015), indicating an increased risk of drought in eastern Australia, including an increased amount of time spent in drought and a greater frequency of severe droughts. Recent downscaling results using the Weather Research and Forecasting (WRF) model also indicate that capturing feedbacks related to vegetation and albedo changes may be important to consider in relation to understanding drought based on climate model output (Evans et al. 2017b).

1.3 Temperature: extreme heat/cold, heatwaves

1.3.1 Extreme heat/cold

Extreme temperature events can pose significant risks to human health, the environment and the economy (Coates et al. 2014). Average temperatures across Australia have increased by about 1°C since 1900, with the dominant cause of this warming being anthropogenic greenhouse gas emissions (Reisinger et al. 2014; CSIRO & BoM 2015). This has also been demonstrated in various attribution studies, such as presented by Dittus et al. (2016). The warming has led to an increase in the number of extreme heat events that have occurred on a range of timescales, including both day- and night-time temperatures as well as fewer cold extremes in NSW and other regions of Australia (BoM & CSIRO 2016; Alexander & Arblaster 2017).

There is high confidence in projections of future temperature, including extremes, and it is virtually certain that climate change will continue to worsen the impacts of extreme heat events with more frequent extremely hot days in regions of Australia (including NSW), as well as temperatures beyond anything in the historical record for many regions. Although continued warming in the next couple of decades is now practically inevitable, greenhouse gas emissions during these decades will help determine the magnitude and rate of future warming towards the end of this century, with higher emissions scenarios causing faster rates of warming than lower emissions scenarios. GCM projections for eastern Australia indicate that for mid-range emissions scenarios later this century, some areas could experience two to three times the average number of days above 35°C (CSIRO & BoM 2015). Extremely cold days and frosts are also projected by GCMs to become less frequent and less intense (CSIRO & BoM 2015). Downscaling projections for NSW also indicate future changes broadly consistent with GCMs projections, including warmer maximum and minimum extreme temperatures (CSIRO & BoM 2015; Wang et al. 2016; Gross et al. 2017), while noting the additional small-scale details that can be indicated by downscaling.

1.3.2 Heatwaves

Heatwaves can cause severe impacts in NSW and other regions of Australia and the world, including large loss of life as discussed by Coates et al. (2014), with climate change likely to significantly influence these impacts. Multi-day heatwave events have increased in intensity, frequency and duration based on observations across many regions of Australia including NSW, and it is virtually certain that climate change will continue to increase these heatwave characteristics (CSIRO & BoM 2015).

Analysis from forced and unforced climate model simulations shows that increasing greenhouse gases caused a five-fold increase in the odds of Australia recording the extreme temperatures experienced in January 2013 (Lewis & Karoly 2013). That summer of 2012–13 included Australia’s area-averaged hottest month, hottest week and hottest day on record, as well as the longest and most spatially extensive national heatwave on record at that time, associated with near-surface air temperatures and regional sea-surface temperatures for the December to February period that were the highest on record for Australia (BoM 2013). Additionally, Black et al. (2015) showed that heatwave events have increased in severity due to anthropogenic global warming through an attribution study of the extreme heatwave that occurred in January 2014. A recent assessment of heatwaves in NSW is presented in the report by Argüeso et al. (2015b) based on NARCliM downscaling, finding that heatwave intensity, duration and frequency are generally all projected to increase and, in almost all cases, these increases are statistically significant across all of NSW.

Heat stress on people in urban areas is also likely to be greater than in rural areas, particularly overnight. This is due to urban heat island effects that can add to the broader regional-scale warming trend (Fischer et al. 2012), as shown for individual cities such as for Sydney as reported by Argüeso et al. (2013; 2015a).

As noted by Perkins-Kirkpatrick et al. (2016), relationships between atmospheric heatwaves and large-scale and synoptic variability have been identified, including for a number of recent extreme events in NSW, as well as more broadly spanning across other regions of Australia. However, more research is required to further our understanding of the dynamical interactions of heatwaves, particularly with the land surface and physical drivers (e.g. synoptic-scale phenomena such as high-pressure systems as well as larger-scale models of variability).

1.4 Unstable atmosphere: dust storm, thunderstorm, hail and lightning

1.4.1 Dust storm

Dust storms are important phenomena in NSW due to associated impacts such as human health risks, environmental degradation, infrastructure damages and economic losses, such as occurred for recent events including the 2009 dust storm that impacted on Sydney and other NSW regions (Leys et al. 2011; Tozer & Leys 2013; Aryal et al. 2015). They can have a relatively large spatial scale (synoptic) and relatively short temporal (~1 day) scale and are created by wind erosion often associated with frontal passages (e.g. Strong et al. 2011). An overview of many aspects of dust production and transport mechanisms as well as observational techniques is presented in McGowan and Soderholm (2012), including providing improved estimates of dust plume loads and noting the importance of having improved confidence in modelling dust emissions and impacts in a changing climate. Similarly, as noted by De Deckker et al. (2014) and references therein, a greater understanding of the potential impact of climate change on dust storms is important for a number of reasons, including human health.

Various research efforts have examined case studies of observed dust storms in Australia; for example, Wain et al. (2006) presented a case study of a dust storm from October 2002 (one of the largest to have occurred in recent decades), finding that strong wind speeds associated with a frontal system and dust transport could be modelled for this event using numerical weather prediction (NWP) systems. Leslie & Speer (2006) found that dust storms in NSW and other regions of central eastern Australia are generally associated with cold fronts.

Dust storms in Australia have also been examined from a climatological perspective in various studies; for example, Speer (2013) found that dust storms in eastern Australia are influenced by a combination of conditions including the occurrence of strong, frontal westerly winds and antecedent dry conditions. The long-term changes examined for that study indicate a trend towards more dust storms in spring and summer over the period from 1957 to the mid-1970s, due to both anomalously strong, southerly winds existing on the western side of a cyclonic anomaly adjacent to the east Australian coast, reported to result from the state of the Pacific climate system, and an anti-cyclonic anomaly at the top of the Great Australian Bight. O'Loingsigh et al. (2014) developed a dust storm index in relation to broad-scale wind erosion in Australia, intended for long-term regional examinations, and found that it provided an accurate representation of observed wind erosion activity including for various NSW locations.

The different studies on dust storms described here show some similarities to each other, particularly in relation to identifying the drivers of dust storms as wind erosion with frontal activity to transport the dust, often from large distances west of NSW. Although various research efforts have examined case studies or the observed climatology of dust storms in Australia, there remain considerable uncertainties in long-term climatological changes in dust storm risks. This is in part due to a relatively limited number of studies that have examined this particular topic, while also noting that projected changes to future dust storm characteristics is a significant gap in the literature. However, a consideration of projected changes to conditions associated with dust storms indicates considerable uncertainties in future changes to dust storm activity in Australia, including due to substantial uncertainties in future changes for drought conditions, strong wind events and ENSO, as summarised in various sections of this chapter. Consequently, based on a synthesis of the currently available knowledge, there is a high degree of uncertainty in future changes to dust storms, including for regional changes within NSW.

1.4.2 Thunderstorms, hail and lightning

Thunderstorms are relatively small-scale weather systems, characterised by strong convective updrafts, including the occurrence of hazards such as lightning, hail, tornados, and extreme winds and rainfall. These hazards can result in severe impacts in NSW, including loss of life, damage to property and disruption to power networks, while lightning can also ignite bushfires and directly cause human injury and death (Allen & Allen 2016). Thunderstorm asthma is another phenomenon that can have significant impacts in NSW, as well as other regions of Australia and the world (D'Amato et al. 2007), with examples including Wagga Wagga in 1997 and Melbourne in 2017. Consequently, they are of importance to many sectors, including insurance, health and emergency services. For example, severe thunderstorm events such as the Sydney hailstorm of 1999 rank among the most expensive weather events ever recorded in Australia in terms of insurance losses (Coleman 2002).

As noted in the recent review paper of Allen and Allen (2016), there is a research need for improved observational or proxy climatologies of severe thunderstorms and associated hazards in Australia, including how they respond to climatological drivers of variability. Some climatological studies have been based on reports of thunderstorm hazards, including for hail in the Sydney region (Rasuly et al. 2015); however, observations of thunderstorms and associated hazards (including hail and tornados) are generally not spatially or temporally homogenous in Australia, as is the case for ground-based lightning detections systems (such as that of GPATS Australia Pty Ltd). Consequently, satellite observations of lightning activity have been used to provide a homogenous climatology for Australia (Dowdy & Kuleshov 2014) and for examining the influence of large-scale modes of variability on thunderstorm activity including in relation to ENSO, IOD and SAM (Dowdy 2016). There have also been some recent developments in the ability to produce homogenous climatologies of observed thunderstorm characteristics based on radar data, as presented by Soderholm et al. (2017) for an 18-year hail climatology for south-east Queensland.

Long-term trends in severe thunderstorms and their associated hazards (such as observed hailstorms as well as extreme winds from downbursts or tornado events) are difficult to determine due to their small spatial and temporal scale as well as infrequent occurrence (e.g. Walsh et al. (2016) and references therein). However, lightning observations based on station records show some indication of a recent decrease in frequency for southern Australia during the winter months (Bates et al. 2015b), while noting some uncertainty around whether the changes in lightning characteristics are associated with anthropogenic or natural influences.

Currently available modelling techniques (including climate downscaling as well as finer-scale NWP models) are not able to directly examine thunderstorm activity due to the small spatio-temporal scales required to model some convective processes, such that parameterisation is generally applied, including for assessing associated hazards such as lightning characteristics. Future projections have been produced based on assessing changes in larger-scale indicators of atmospheric conditions favourable to thunderstorm occurrence (e.g. Convective Available Potential Energy: CAPE). Future increases in CAPE are projected to occur in some regions, including in relation to a potential increase in the frequency of severe thunderstorm environments for parts of eastern Australia (Allen & Karoly 2014). Large-scale projection methods such as these need to be explored further to determine if they produce robust results in relation to various thunderstorm hazards, given the wide range of factors influencing convective processes as well as the limitations of available observations and modelling capabilities. Similar to the case for extreme rainfall, current developments in convection-permitting modelling may help reduce some uncertainty in projections of thunderstorms and associated hazards (including potentially for lightning, tornados and hail), while noting that considerable uncertainties will remain for some aspects (e.g. as is the case for operational NWP-scale predictions with data assimilation of observations included), such that considering additional lines of available evidence will likely remain important given the very fine scales of some convective processes (including microphysical aspects).

1.5 Wind: wind gust, storm surge and coastal flooding/ tidal inundation

1.5.1 Wind gust

Extreme speeds of wind gusts in NSW and other regions of Australia are typically caused by convective phenomena such as tornados and severe thunderstorms (including associated downbursts), or larger-scale phenomena such as tropical cyclones in more northern regions as well as ECLs in eastern and south-eastern Australia. Observations of extreme wind events are generally concentrated around population centres in Australia (i.e. spatially inhomogeneous). There is also a relative lack of long-term temporally homogenous observations of wind speed in Australia, as well as inherent limitations of reanalyses for representing extreme winds (e.g. current reanalyses have coarser resolution than is required for resolving convective processes), making it difficult to examine long-term changes in their climatology (Jakob 2010; Walsh et al. 2016).

Given the lack of long-term homogenous wind speed observation, as well as the many uncertainties around modelled changes in extreme convective phenomena such as tornados and severe thunderstorms (as discussed in Section 1.4.2), there is significant uncertainty in the climatology of wind gusts in Australia. This includes for observed trends, as well as for projected future changes in their characteristics; however, some indication of future changes in extreme wind events can be obtained based on a consideration of the storms that cause them. For example, for the eastern seaboard of NSW, extreme winds can sometimes be caused by ECLs, particularly during the cooler months of the year. Consequently, the projected decrease in the frequency of ECLs suggests the potential for fewer extreme wind events, as well as associated extreme waves, during winter for these regions (Dowdy et al. 2014). The advent of convection-permitting reanalyses (e.g. the 'BARRA' reanalysis product currently in production within BoM, as well as other recent international developments, as discussed in Chapter 2) and dynamical downscaling methods, has the potential to lead to significant improvements in the ability to project changes in extreme winds associated with convective systems.

1.5.2 Storm surge and coastal flooding/tidal inundation

Elevated sea levels are related to a number of factors including tides and storms (such as ECLs in coastal NSW; detailed in Section 1.6), as well as variations at seasonal-to-inter-annual timescales associated with ENSO, while variations at longer timescales (e.g. historically observed or projected future changes in 30-year mean values) are dominated by rising sea levels due to anthropogenic global warming including along the NSW coast (CSIRO & BoM 2015). Intense low-pressure systems (e.g. tropical or extratropical cyclones) and periods of prolonged strong winds can also contribute to extreme sea level and storm surge events, with large waves also being associated with hazards such as coastal erosion and flooding (McInnes et al. 2016).

Anthropogenic global warming is causing sea levels to rise due to the combined effects of melting glaciers and thermal expansion of the oceans (IPCC 2013). Due to this sea level rise, the frequency and magnitude of coastal flooding is expected to increase significantly this century, regardless of changes in storm events. Sea level rise can also lead to 'nuisance tidal flooding', defined as the combination of high astronomical tides and elevated sea level alone (i.e. in the absence of a major weather event), and although this is not yet widely documented in Australia there have been marked recent increases in this type of flooding affecting major urban centres in the USA (Sweet & Marra 2016). Sea level rise will also increase the intensity of riverine floods, by slowing the drainage of water from low-lying areas and increasing overall water heights in tidal-zone rivers and drains.

Globally, sea level rose at about 1.7 mm/year during the 20th century, with similar trends in Australia (CSIRO & BoM 2015). The average rate of relative sea level rise from observations along the Australian coast was 1.4 ± 0.3 mm/year from 1966 to 2010, and 1.6 ± 0.2 mm/year when the sea level variations associated with the ENSO are accounted for (White et al. 2014). Sea level rise has accelerated in recent decades, with a global increase of 2.6–2.9 mm/year from 1993 to mid-2014 (Watson et al. 2015).

The likely global sea level rise by 2081–2100 relative to 1986–2005 is 32–63 cm for mid-range emissions scenarios, and 45–82 cm for high emissions scenarios. Overall projected sea level rise for the Australian coastline is similar to the global average (McInnes et al. 2015); however, the strengthening of the subtropical gyre circulation of the South Pacific Ocean is projected to lead to larger increases off the south-eastern Australian coastline (McInnes et al. 2015; Zhang et al. 2017a,b). Specific details on NSW sea levels, including for a number of different locations along the coast, are provided in CSIRO & BoM (2015), including regionally specific reports and datasets. For example, a regionally specific report covering the northern portion of the NSW eastern seaboard (Dowdy et al. 2015b) notes that there is very high confidence that sea level will continue to rise during the 21st century. This includes results for the near future (2030) for which the projected range of sea level rise for the cluster coastline is 0.08–0.18 m above the 1986–2005 level (with only minor differences between RCPs), as well as for 2090 with RCP4.5 giving a rise of 0.30–0.65 m and RCP8.5 giving a rise of 0.44–0.88 m. These NSW sea level projections are broadly similar to Australia-wide projections (e.g. 26–55 cm for RCP2.6 and 45–82 cm for RCP8.5 by 2090 (CSIRO & BoM 2015)).These projections do not fully capture the potential contribution to sea level rise from the large ice sheets (Greenland and Antarctica), whose response to global warming is uncertain and possibly underestimated (Vermeer & Rahmstorf 2009; DeConto & Pollard 2016), with rises exceeding 2.4 m being physically possible later this century as listed in a recent US Government synthesis report (USGCRP 2017).

An increase in mean sea level will result in a larger increase in the frequency of extreme inundation events. For Australia, to maintain the current level of exposure of coastal assets to extreme sea levels, protective barriers would need to be raised by at least 0.7–1.0 m by 2100 for a high emissions scenario (CSIRO & BoM 2015). Further specific details for NSW locations in relation to sea level rise as well as heights for raising protective barriers are available in CSIRO and BoM (2015), including for the central east coast region of Australia. Taking into account the nature of extreme sea level along the east coast coastlines and the uncertainty in the sea level rise projections, an indicative extreme sea level ‘allowance’ is provided (i.e. the minimum distance required to raise an asset to maintain current frequency of breaches under projected sea level rise). For the east coast in 2030, the vertical allowances along the coastline are in the range of 13–15 cm for all RCPs. By 2090 they are 55–63 cm for RCP4.5 and 78–89 cm for RCP8.5 (Dowdy et al. 2015b).

In addition to mean sea level rise, changes in characteristics of weather and storms (including ECLs discussed in the next section) such as their frequency, intensity, spatial extent, duration and timing may also influence the frequency and intensity of extreme sea levels and their impacts (McInnes et al. 2016). The key drivers of extreme sea levels in NSW include ECLs, cold frontal systems and tropical cyclones that track southwards towards NSW latitudes (McInnes et al. 2016). Colberg and McInnes (2012) studied changes to extreme sea levels based on hydrodynamic simulations forced by CMIP3-forced GCMs and Regional Climate Models (RCMs), finding small (within ±0.1 m) changes in 95th percentile surface height along the NSW coast and large inter-model differences, based on comparing the late-20th century to the late-21st century climates. Furthermore, simulations of future waves along eastern Australia using wave models forced by RCMs (Hemer et al. 2013) and statistical wave models forced by an ensemble of CMIP5 models (Dowdy et al. 2014) indicated a robust decrease in the frequency of large wave events later this century (i.e. stronger decreases for later years and for more emissions, including due to fewer ECLs around the cooler months of the year). Potential changes such as these to storm systems therefore should be considered in combination with other factors such as sea level rise when considering the influence of climate change on coastal impacts, noting that the relative importance of such factors for particular impacts is a current knowledge gap in the literature.

1.6 Extreme East Coast Lows

Various definitions and sub-types of ECLs (also sometimes called east coast cyclones) have been presented in the literature, with a common aspect of these definitions being that ECLs are cyclones that occur near the central and south-east regions of Australia’s east coast, often causing severe coastal hazards in extreme cases (including severe winds, precipitation, flooding, lightning, ocean waves and erosion). This can result in impacts such as loss of life, as well as large insurance losses, as has occurred for some recent events such as the June 2007 storm that grounded the *Pasha Bulker* in the region around Newcastle (Mills et al. 2010). It is also noted that they can have beneficial impacts, including providing heavy rainfall that can contribute significantly to catchment inflows important for water supply in NSW population centres (Pepler & Rakich 2010), as well as snow in some cases (Fiddes et al. 2015b). They can sometimes intensify rapidly, with some satisfying the ‘bomb’ criterion described by Sanders & Gyakum (1980), sometimes referred to as explosive cyclogenesis, with extreme ECLs typically characterised by a distinctive upper-tropospheric signature (e.g. Mill et al. 2010). They can occur at any time of year (unlike tropical cyclones near Australia) with many of the most extreme cases occurring during the cooler months of the year, while noting they can sometimes occur as a result of tropical cyclones transitioning to be more baroclinically driven. Additionally, it is not uncommon for several ECLs to occur within a short period of time, as was the case in June 2007 when five individual ECLs had notable impacts on various parts of the NSW coast.

Most definitions of ECLs to date have been based on closed contours of surface pressure, but with a range of different requirements added, varying from study to study. For example, Hopkins & Holland (1997) defined an east coast cyclone as any system with closed cyclonic circulation at sea level which forms in a maritime environment from 20–40°S within 500 km of the east coast, additionally requiring movement parallel to the coast at some stage of its lifetime and a pressure gradient of at least 4 hPa per 100 km. Speer et al. (2009) examined various types of maritime cyclones by manually checking synoptic charts of mean sea level pressure (MSLP) for the region around NSW, with application of an operational ECL definition used in NSW Regional Office of the BoM that included requiring ECLs to have formation and/or intensification in a maritime environment within the vicinity of the east coast. A number of subsequent studies have examined ECLs based on considering cyclones that occur in the vicinity of the central and south-east Australian coast using systematic methods applied to gridded data (using reanalyses and/or model output) based on cyclonic vorticity measures at various different levels of the troposphere (Dowdy et al. 2011, 2014) as well as based on closed contours of pressure at the surface (Pepler & Coutts-Smith 2013; Di Luca et al. 2015; Browning & Goodwin 2016).

ECLs have large inter-annual variability in their occurrence frequency, overshadowing any trends in their characteristics based on observations or reanalysis data which show no clear trend in the frequency of ECLs in recent decades (Speer et al. 2009; Dowdy et al. 2013; Ji et al. 2015; Browning & Goodwin 2016; Kiem et al. 2016; Pepler et al. 2016a). It is also noted that Alexander et al. (2011) found a decline in the frequency of ‘storminess’ (based on winds calculated from pressure data) in south-east Australia between 1885 and 2008, and Power & Callaghan (2016) found a long-term increase in the observed frequency of ECLs associated with widespread coastal flooding based on a longer time period using a range of different information sources (including newspaper clippings and shipping records).

ECL case studies examined the underlying physical processes behind extreme cases, such as the May 1974 Sygna storm, the 1998 Sydney to Hobart yacht race event and the June 2007 *Pasha Bulker* event, finding a common set of ingredients associated with extreme ECL events (including a clearly-defined cyclone vorticity signature in the middle and upper troposphere) (Mills 2001; Mills et al. 2010). Building on the results of such case studies, Dowdy et al. (2011) produced a systematic climatology of ECL activity based on a range of mid- and upper-tropospheric environmental conditions, including comparisons in relation to the Speer et al. (2009) database of synoptic surface pressure lows. The findings showed that strong cyclonic values of geostrophic vorticity at 500 hPa is a good indicator of the risk of ECL occurrence, with application of that method to GCMs indicating fewer ECLs in the future, particularly during the cooler months of the year (Dowdy et al. 2013, 2014). Recent projections based on dynamical downscaling for surface pressure indicators of ECL activity (Pepler et al. 2016b) also indicate a decline in the frequency of ECLs, particularly during the cool season, with the decline being most robust for lows located east of the coastline. Pepler et al. (2016c) found that changes in the East Australian Current (EAC) do not have a strong influence on the risk of extreme ECLs, including not being related to changes in upper-tropospheric vorticity which is strongly associated with the development of extreme ECLs, broadly consistent with the results of previous studies examining the role of the EAC in relation to extreme ECLs such as the *Pasha Bulker* case (Chambers et al. 2014).

Although fewer extreme ECLs are projected to occur in general, rising sea levels in the future are likely to increase the impacts of large waves on coastal regions in some cases, as well as noting the projected increase in the upper limit of extreme rainfall (as discussed in Section 1.2.1), which could lead to changes in ECL rainfall-related impacts on NSW regions. Changes in storm characteristics (such as the intensity, frequency and duration of associated extreme wind and wave events, as well as noting wave direction as an important factor for some coastal processes) can have significant influences on various coastal processes. For example, storm characteristics in eastern Australia have been linked with changes in wave energy flux in NSW regions, including a directional shift in wave power reported to likely result in future changes to sediment transport (Mortlock & Goodwin 2015; Goodwin et al. 2016; Harley et al. 2017).

There is considerable scope for improved projections of ECL activity. Further development of ECL research capability is likely to further improve our understanding of the risks associated with these systems and their associated hazards, including in relation to the advent of convection-permitting downscaling. For example, some extreme ECL events such as the *Pasha Bulker* case in June 2007 were associated with substantial convection, with evidence of strong and deep convection for that event being clearly shown by the large amount of lightning observed clustered near the storm centre (Chambers et al. 2014; Dowdy & Kuleshov 2014). The interrelationship between cyclones and thunderstorms in this region was also highlighted by Dowdy & Catto (2017), who found that extreme winds and rainfall near coastal NSW are often caused by a type of triple storm characterised by the simultaneous occurrence of a cyclone, front and thunderstorm (with further details on compound storm types provided in Section 1.8). Furthermore, the potential influence of expanding tropics and intensification of the subtropical ridge in this region could potentially influence the relative contributions of different energetic components driving ECL formation, as is currently being examined in the Extreme Weather Projections project of the National Environmental Science Program (NESP) Earth Systems and Climate Change Hub. This new research includes examining various subtypes of ECLs based on different combinations of tropical and extra-tropical contributions to ECL characteristics, as has been observed for cyclone activity in various subtropical regions of the world, including as shown previously for some cases along the central east coast of Australia (Pezza et al. 2014; Yanase et al. 2014).

1.7 Fire: bushfire and fire weather

Bushfires can have severe impacts in NSW including loss of life and large economic costs (Clarke et al. 2016). This includes through the direct impacts of the fires, as well as through smoke and other products of combustion. Anthropogenic climate change is influencing the frequency and severity of dangerous fire conditions in Australia and other regions of the world, including through influencing temperature, environmental moisture, weather patterns and fuel conditions (Cary et al. 2012; Mathews et al. 2012; CSIRO & BoM 2015; Abatzoglou & Williams 2016; Boer et al. 2016; Dowdy 2017). Fire activity is dependent on a range of factors in addition to weather and climate, many of which have large uncertainties around quantifying the climatological trends in their characteristics (e.g. for ignition and suppression activities, as well as fuel state). However, many climatological studies have focused on the weather conditions that influence fire activity, given the ability to quantify long-term changes in many of these factors with a useful degree of confidence, including for historical trends as well as for future projected changes.

Fire weather conditions have become more severe in recent decades, in part due to increasing temperatures, with observed trends towards more dangerous conditions apparent in some regions of Australia, including some regions of NSW, based on considering individual observing station locations (Clarke et al. 2013) as well as based on gridded analysis of observations (Dowdy 2017), noting that the magnitude of the changes depends on region and season, as well as some differences between trends in mean and extreme conditions. The fire season has also lengthened particularly in parts of temperate Australia (including some NSW regions (Clarke et al. 2013; Dowdy 2017)), associated with a spring increase in the number of severe fire weather days. In addition to influencing bushfire activity, seasonal and regional changes in fire weather conditions could also influence planned burning (as well as associated smoke impacts), although little research has been done on this in relation to the influence of climate change.

Fire weather is projected to increase in severity for many regions of Australia, including due to more extreme drought and/or heat events. In particular, there is high confidence that fire weather will increase in severity in southern and eastern Australia based on GCM projections (CSIRO & BoM 2015). Downscaling projections for NSW regions also indicate an increase in the severity of fire weather conditions due to increasing atmospheric greenhouse gas concentrations, including potential changes to fuel load (Clarke et al. 2016). Further details on climate change impacts on bushfire risk in NSW are provided in Clarke (2015) and references therein.

There is considerable uncertainty in climatological trends in observed fire activity, given the large number of factors that influence fire occurrence (including changes in fuel management and planned burning practices, as well as ignition and suppression variations). In relation to fire ignition, there is some indication that climate change could influence the risk of dry-lightning (i.e. lightning that occurs without significant rainfall), while noting large uncertainties in currently available model representations of this phenomenon (Dowdy 2015).

Pyroconvection can occur when the heat and moisture released from a fire modifies the air in the fire plume, resulting in convectively unstable conditions. There has recently been a number of devastating fire events in Australia associated with extreme pyroconvection (including thunderstorm development in fire plumes), as occurred for the 2003 Canberra fires and the 2009 Black Saturday fires (Mills & McCaw 2010; McRae et al. 2015; Dowdy et al. 2017). However, the influence of climate change on pyroconvection is currently not well understood. Consequently, there are substantial research gaps remaining relating to the factors that influence climatological variations in fire activity in Australia including regions within NSW, particularly given the current knowledge on projected future changes in ignition sources as well as fire–atmosphere feedback processes (such as those associated with pyroconvection). However, there is some indication of a trend towards more dangerous conditions for pyroconvection in parts of NSW, particularly in some regions away from the coast during summer (Dowdy & Pepler 2018). Projections for the future climate provide an indication of an increase in some pyroconvection risk factors for an area-averaged region of south-east Australia (Sharples et al. 2016).

1.8 Compound or coincident events

Dangerous conditions can sometimes be associated with the simultaneous occurrence of more than one type of event. These compound events can include the combined influence of different extremes, such as a storm surge combining with flooding from extreme rainfall in a coastal region, or the coincident occurrence of various different storm types in a given region (e.g. a cyclone, front and/or thunderstorm occurring at the same time in the same region) (Dowdy & Catto 2017). A compound event can also be caused by events which may not be extreme in isolation, but which may combine or interact leading to an impact referred to as a 'compound event'. This can include various combinations of events including in relation to bushfires, heatwaves, droughts, floods and storms, as well as associated extreme weather and physical processes. Additionally, natural hazards can intersect with other existing problems, such as international socioeconomic issues, thereby intensifying the impacts of disasters.

The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (Seneviratne et al. 2012) defines three types of compound events: (1) two or more extreme events occurring simultaneously or successively; (2) combinations of extreme events with underlying conditions that amplify the impact of the events; or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined, based on contributing events that can be of similar (clustered multiple events) or different type(s). Additionally, a framework for considering compound events was presented by Leonard et al. (2014), which also considers the combinations of conditions that may not be extreme individually but result in a combined impact that can be extreme, concluding that there is benefit in considering multivariate approaches to analyses associated with compound events given the complexities and inter-relationships between different physical processes.

Storm surge combined with flooding from extreme rainfall is an example of a compound event of importance for coastal NSW regions. The complex interaction of factors that influence flooding, coupled with the short length of comprehensive flood records and large inter-annual variability, make it difficult to confidently assess significant trends in the frequency or magnitude of observed flood events (as discussed in Section 1.2). However, for many coastal and estuarine regions, projected changes in extreme rainfall suggest that flooding in some coastal regions will likely increase in frequency and magnitude particularly when combined with rising sea levels, given the high degree of confidence in projected increases in sea level in the future, as well as noting the strong dependence between extreme rainfall and storm surge in the coastal zone (Zheng et al. 2013; Wu et al, 2018). Additionally, as noted in Section 1.6, Power and Callaghan (2016) have reported a long-term increase in the observed frequency of ECLs associated with widespread coastal flooding.

Although ECLs are generally characterised by cyclonic conditions at various different levels of the atmosphere, they can also be associated with other atmospheric conditions that can sometimes exacerbate their impacts, including thunderstorms and frontal activity (Speer et al. 2009; Chambers et al. 2014; Dowdy & Kuleshov 2014). Furthermore, as highlighted by a recent systematic assessment of compound storm types, extreme precipitation and extreme wind events along the east coast of NSW are often associated with a type of triple storm characterised by the simultaneous occurrence of a cyclone, front and thunderstorm (Dowdy & Catto 2017). It is currently not known how the coincident occurrence of such storms might or might not change in the future, while noting that work on this is currently underway as part of the Extreme Weather Projections project of the National Environmental Science Program (NESP) Earth Systems and Climate Change Hub.

A relatively common type of compound event in Australia is the coincidence of a drought and a heatwave, which can often lead to dangerous conditions for bushfire activity, as well as have impacts on a range of different sectors (e.g. agriculture, as well as dust storm risks). There is relatively high confidence that the coincidence of hot and dry conditions in NSW will increase in frequency and intensity due to increasing atmospheric greenhouse gas concentrations, including as represented in indices for representing fire weather (CSIRO & BoM 2015; Clarke et al. 2016; Dowdy 2017).

There are large knowledge gaps associated with compound events, as relatively little research has focused on them to date, noting that there is a vast array of combinations of events that can occur between atmospheric and non-atmospheric processes (e.g. thunderstorms and pollen leading to asthma risk). Additionally, data on extremes are typically very sparsely available, suggesting potential benefits could be obtained from the application of modelling approaches in some cases. Furthermore, the multivariate nature of compound extremes means that longer periods of data may be needed for observation-based assessments as compared to single types of extreme events. Consequently, there is generally a large uncertainty in understanding the climatology of compound extremes, including in relation to drivers of variability and long-term changes. Another notable research gap is on compound extremes that may be simultaneous in time but occur in different regions of Australia, such as fires in south-east Australia coinciding with extreme weather from a tropical cyclone in northern Australia (Parker et al. 2013), potentially leading to response challenges for emergency services capabilities. Consequently, there is a research need to help address the currently very low confidence in observed climatologies and trends, as well as future projections, for various different types of compound extreme events.

1.9 Conclusions

Table 1.1 below presents a general summary of the literature reviewed here on the influence of climate change on weather and ocean hazards. The results are based on observations as well as model projections for this century, including some changes that have already occurred as well as those that are likely to occur in coming decades. The changes for some types of events are more uncertain than for other types of events, while noting that an increase in uncertainty may be important to consider for managing potential changes to the impacts of these events. For example, knowing there is increased uncertainty in the characteristics of an event (such as its intensity, frequency or duration) may be important for decision-makers in relation to improving preparedness, adaptation and disaster risk reduction efforts.

Table 1.1 General summary of the literature reviewed here on the influence of climate change on weather and ocean hazards

Extreme weather and ocean events	Summary of climate change influences
Rainfall: extreme rainfall, flood, snow and drought	Likely to have more extreme rain events, less snow cover, potential increases in rainfall-related drought risks and larger uncertainties for other types of drought as well as for flood risks
Temperature: extreme heat/cold, heatwave	More frequent and intense extreme heat events and heatwaves, with the converse for extreme cold events
Unstable atmosphere: dust storm, thunderstorm, hail and lightning	Potential increases in some thunderstorm hazards including convective rainfall extremes, with larger uncertainties for tornadoes, wind extremes, hail and lightning, as well as larger uncertainties for dust storms
Wind: wind gust, storm surge and coastal flooding/tidal inundation	Larger uncertainties for extreme wind gusts; sea levels will continue to rise, increasing storm surge and inundation risk
Extreme East Coast Lows (ECLs)	Fewer but potentially more intense ECLs and associated severe weather impacts, including potential increases in the intensity of associated extreme rainfall
Fire: bushfire and fire weather	More dangerous bushfire risk factors, including fire weather conditions in some regions and seasons
Compound or coincident events	Large knowledge gaps, but growing interest in the importance of compound or coincident events

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A.1 Acronyms used in Chapter 1

BARRA	Bureau of Meteorology Atmospheric Regional Reanalysis for Australia
BoM	Bureau of Meteorology
CAPE	Convective Available Potential Energy
CMIP	Coupled Model Intercomparison Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EAC	East Australian Current
ECL	East Coast Low
ENSO	El Niño Southern Oscillation
GCM	Global Climate Model
IOD	Indian Ocean Dipole
MSLP	mean sea level pressure
NARCliM	NSW/ACT Regional Climate Modelling project
NWP	numerical weather prediction
RCM	Regional Climate Model
SAM	Southern Annular Mode
WRF	Weather Research and Forecasting model

2. Review of extreme climate events datasets

2.1 Introduction

Datasets relating to extreme climate events can be of two forms: those that provide information on extreme events directly without further processing (e.g. incidence of East Coast Lows; count of days over a temperature threshold), or datasets that with further processing would produce information on extreme events (e.g. extraction and analysis of relevant variables from ERA-Interim reanalyses to provide information on extreme events such as drought, or synoptic conditions conducive to East Coast Lows). In this chapter we have termed these 'Tier 1' and 'Tier 2' datasets, respectively. Tier 1 datasets are discussed in detail, including data format, resolution, spatio-temporal scales, strengths and considerations (where applicable). There are many Tier 2 datasets, so we include only those considered to have the potential to add value. Information on Tier 2 datasets is constrained to the name, access (direct download or contact author), dataset type (historic or projected), the extreme event type it could potentially provide information on, and how it could add value. To facilitate easy reference, a brief summary of which datasets provide information on each type of extreme event is provided in Table 2.1.

Our definition of dataset includes: (i) observational data, (ii) reanalyses, and (iii) data derived from Global or Regional Climate Models (GCMs or RCMs). Observational data sources include the Bureau of Meteorology (BoM) station and gridded products, satellites, tide gauges and wave buoys.

Chapter 2 begins with a description of Tier 1 extreme events datasets (Section 2.2) and various Tier 2 datasets (Section 2.3). Section 2.4 summarises overall conclusions and gaps.

Table 2.1 Overview of the type of extreme event (described in Chapter 1) covered by each dataset*

Dataset	Section	Time		Extreme event type						
		Historic	Projected	Rainfall	Temperature	Unstable atmosphere	Wind	Extreme ECLs	Fire	Compound/ coincident
NARCliM	2.2.1	X	X	X	X	X	X	X	X	
Climate Change in Australia	2.2.2	X	X	X	X		X		X	
ETCCDI and ET-SCI indices	2.2.3	X	X	X	X					
BoM observational data	2.2.4	X		X	X	X	X	X	X	
weather@home Australia-New Zealand	2.2.5	X	X	X	X					
Australian Rainfall and Runoff	2.2.6	X	X**	X						X
BoM radar datasets	2.2.7	X		X		X				
SILO	2.2.8	X		X	X					
BoM Severe Storm Archive	2.2.9	X		X		X	X			
BoM Gridded Average Lightning Flash Density and Thunder Days	2.2.10	X				X				
CAWCR wave hindcast	2.2.11	X					X			
CAWCR wind-wave climate projections	2.2.12		X				X			
Australian Baseline Sea Level Monitoring	2.2.13	X			X		X			
Manly Hydraulics Laboratory	2.2.14	X		X			X			
BoM MATCHES ECL data	2.2.15	X		X			X	X		
Speer et al. (2009) dataset of low pressure systems	2.2.16	X						X		

Dataset	Section	Time		Extreme event type						
		Historic	Projected	Rainfall	Temperature	Unstable atmosphere	Wind	Extreme ECLs	Fire	Compound/ coincident
Projected future change in ECLs	2.2.17		X					X		
Baird Stochastic ECL model	2.2.18	X		X			X	X		
BoM FFDI	2.2.19	X							X	
FIRMS	2.2.20	X							X	
DustWatch	2.2.21	X				X				

* Included are: (i) datasets that provide information on extreme events directly without further processing, and (ii) datasets that have the potential to provide information on extreme events, but may need further processing and analysis, and/or to be used in conjunction with data from other sources. See text in the relevant section for acronym definition and full dataset description.

** Datasets providing climate change factors.

2.2 Tier 1 datasets

Tier 1 datasets are defined as datasets that provide direct information on extreme climate events without further processing.

2.2.1 NARCliM

The NSW Government's NSW and ACT Regional Climate Modelling (NARCliM) dataset provides dynamically downscaled climate projections for south-east Australia at a horizontal resolution of approximately 10 km. The domain includes NSW, the ACT, Victoria, and parts of Queensland and South Australia, and its eastward extent (169.16°E) was selected to capture offshore climate events such as storms generated from East Coast Lows (ECLs).

NARCliM data come from three configurations of the Weather Research and Forecasting (WRF) RCM, with each configuration forced with output from four CMIP3 GCMs (MIROC3.2; ECHAM5/MPI-OM; CGCM3.1; CSIRO-MK3.0) resulting in a total set of 12 simulations. Additionally, the three WRF configurations were forced with National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalyses. The GCM-forced simulations were run for three time periods (1990–2009; 2020–2039; 2060–2079), and the reanalyses-forced simulations were run for the period 1950–2009. A business-as-usual emissions scenario was simulated: Special Report on Emissions Scenarios A2 (IPCC 2000). The model selection process used in NARCliM was somewhat ground-breaking as it incorporated consideration of model independence and the RCM selection process incorporated assessment of model performance at simulating extreme storms (Evans et al 2013, 2014; Fita et al 2017; Luca et al 2016).

A large amount of data are available for free via webtools (see below and Chapter 3), including static and interactive maps of multi-model mean change and output from individual model simulations, plus the facility to extract point and gridded data for individual model simulations.

The databases include:

1. Static and interactive maps of multi-model mean change relative to a baseline (1990–2009) are available for the two future periods (2020–2039 and 2060–2079) for extremes including:
    - annual mean number of hot days (days with temperatures >35°C)
    - annual mean number of cold nights (nights with temperatures <2°C)
    - annual and seasonal Forest Fire Danger Index (FFDI) (mean and severe)
    - annual and seasonal mean daily maximum and minimum temperature.

    The static multi-model mean regional maps are available for the whole of NSW as well as separately for 10 regional areas, in JPEG and ASCII formats. The interactive maps enable the user to select the variable and future time period, and to select regions within NSW.

2. Selected data from individual model simulations at 10 km resolution are available for download from the Climate Data Portal. Data can be extracted for point locations (in comma-separated values format) or gridded data (individual grids or spatially continuous polygons) in GIS-readable ASCII or NetCDF format on a regular latitude–longitude grid. While the model simulations generated data for more than 100 meteorological variables, 11 are available for download from the Climate Data Portal as a time series with daily and monthly values:
    - precipitation accumulation (including bias-corrected data)
    - mean surface air temperature
    - mean surface pressure
    - mean surface specific humidity

  - mean near-surface (10-m) wind speed
  - mean surface evaporation flux
  - mean soil moisture content
  - mean sea surface temperature
  - mean downward shortwave radiation
  - mean downward longwave radiation
  - mean upward longwave radiation.

These data can be considered to be Tier 2 datasets as they require further processing to extract extremes data. These data are directly available from the Climate Data Portal, however it should be noted that other Tier 2 NARCliM datasets that could provide further information on extremes (e.g. sub-daily data for levels through the atmosphere) are freely available by contacting the NSW Department of Planning, Industry and Environment (DPIE) via narclim@environment.nsw.gov.au. Also available are NARCliM rainfall-related ETCCDI (Expert Team on Climate Change Detection and Indices) and heatwave-related data.See Section 2.2.3 and note that FFDI data and Morton’s APET data are available, which have relevance for drought research.

NARCliM also simulated the entire COordinated Regional Climate Downscaling EXperiment (CORDEX) Australasia domain at 50 km. This is potentially useful for comparing with the 10 km dataset to assess the benefits of higher resolution for simulating extremes.

There is also a dataset of 2 km climate simulations over Sydney for 1990–2009 and 2040–2059. A number of research papers have used these data (Argüeso et al. 2013, 2014; Evans & Argüeso 2015; Li et al. 2015, 2017a, 2017b). This dataset is available from NSW DPIE on request via email.

NARCliM data have been used in various studies including investigation of daily rainfall extremes (Bao et al. 2017), snowfall and snow cover (Di Luca et al. 2017), heatwaves (Argüeso et al. 2015; Gross et al. 2016), and drought (Evans et al. 2017).

Strengths:

- Host GCMs selected based on independence and ability to provide projections that span a wide range of plausible futures.
- Downscaled using RCMs (different configurations of WRF) that NARCliM project leaders identified as performing well at simulating mean climate and extreme storms in that geographic region, particularly in terms of ‘effectively simulating temperature and rainfall and providing a good representation of local topography and coastal processes’ (see the NARCliM site for more details on model selection).
- Each data folder contains metadata describing the naming conventions used in the file name.
- Good description of available data.
- Data provided as maps in two formats (JPEG and ASCII) and also the entire model output from individual model simulations, as well as ability to extract the raw data for individual points, grids or polygons.
- Bias-corrected dataset available for temperature and precipitation, which is important for threshold-based extremes (e.g. see Gross et al. 2016).

Considerations:

- CMIP3 GCMs were used in the IPCC 4th Assessment (2007) so they are at least 10 years old. CMIP5 models were used in the IPCC 5th Assessment (2013) and in a number of Australian datasets, such as Climate Change in Australia. National and international climate research centres are currently undertaking model runs for CMIP6. There would be value in updating NARCliM with CMIP5 or CMIP6 data or participating in a nationally coordinated and consistent dataset that is downscaled from CMIP5 or CMIP6 GCMs. The use of CMIP5 models for expanded and enhanced NARCliM projections is underway at present (see NARCliM1.5 below).

- Simulations used a single mid-range emissions scenario (A2), which has now been superseded by Representative Concentration Pathways (RCPs) used in the IPCC 5th Assessment, including both strong mitigation scenarios (e.g. RCP2.6) as well as high emissions scenarios (RCP8.5).
- Two future time periods encompass the near term (2020–2039) and longer term (2060–2079), but nothing for the end of the century or beyond. Furthermore, 20-year periods are not long enough to analyse some rare extremes and account fully for multi-decadal climate variability.
- The host GCMs selected do not include a representative of any of the CMIP5 models that project a much hotter future in south-east Australia.

NARCliM1.5

In 2020, DPIE will release additional regional climate projections, NARCliM1.5, to complement the original NARCliM dataset released in 2014. NARCliM1.5 can be summarised as follows:

- three CMIP5 GCMs downscaled to two RCMs each, creating six regional projections. These two RCMs are two of the three WRF configurations used in the original NARCliM
- the six regional projections will be available for the same south-eastern Australia 10 km and the CORDEX-Australasian 50 km domains as in the original NARCliM. Each projection is 150 years long (1950–2100)
- two future scenarios are projected for the two domains: a medium (RCP4.5) and high (RCP8.5) emissions future. The three selected GCMs (CSIRO0-BOM-ACCESS1.0, CSIRO-BOM-ACCESS1.3 and CCCma-CanESM2) project a warmer future than the four GCMs used in the original NARCliM
- bias-corrected data will be available for at least minimum and maximum temperature and for precipitation
- the NARCliM1.5 dataset includes ERA-Interim reanalysis-driven regional projections for the two RCMs for the 1979–2013 period
- both NARCliM1.5 and NARCliM1.0 data will be freely accessible for at least NetCDF, ASCII and .csv formats with supporting documentation via an upgraded NSW Government climate data portal
- the modelling is undertaken both by NSW DPIE and by UNSW.

2.2.2 Climate Change in Australia

Climate Change in Australia (CCIA) provided projections for natural resource management (NRM) regions grouped into climatologically similar clusters. Numerous historical and projected future datasets are available via the CCIA website, including temperature, rainfall, relative humidity, solar radiation, evapotranspiration, and mean wind speed. Ocean data are also available including sea surface temperature and salinity, pH, and sea level. Summary information on cyclones, snow, and soil moisture is available via the Technical Report (access via the CCIA website).

Two types of projections data are available:

- projected future change relative to a baseline (IPCC reference period of 1986–2005) based on CMIP5 GCMs judged to perform well over Australia, plus dynamic and statistical downscaling where appropriate. The spatial resolution of these GCMs is approximately 200 km[2]

- ‘application-ready’ future climate data, where the projected future change has been applied to 30 years (1981–2010) of observational data and so is at the resolution of the observational dataset (Australian Water Availability Project (AWAP) data at 0.05° resolution for temperature and rainfall; ERA-Interim reanalyses for humidity, wind speed, and solar radiation; CSIRO Land and Water 0.05° data for evapotranspiration). Application-ready data are available for a subset of eight CMIP5 models (described below), selected because they provide the range of projected possible future climates for Australia.

Datasets can be visualised and downloaded using the Extremes Data Explorer, Thresholds Calculator, Map Explorer Tool, Gridded Data and Station Data Download Tools (require registration through CCIA website), and the Marine Explorer Tool.

The Extremes Data Explorer allows you to visualise and download the projected future seasonal change in four measures of climatic extremes for four future periods (20-year periods centred on 2030, 2050, 2070 and 2090) and two emissions scenarios (RCP4.5 and RCP8.5). Climate extremes include:

- coldest night
- hottest day
- wettest day (average of the wettest day each year over a 20-year period) and 1-in-20 year wettest day (estimate, using Generalised Extreme Value analysis, of the 20-year return value of the annual maximum daily rainfall – see CCIA Technical Report for further details).

Once the user has selected an NRM cluster, a bar-plot is automatically produced showing the results from all available GCM simulations. The bar-plot can be saved as a PNG file and the underlying data can be downloaded as a comma-separated values (.csv) file.

The Thresholds Calculator provides data on the number of days above or below a threshold for maximum and minimum temperature for an historic dataset (AWAP) and eight GCM models (CanESM2, CNRM-CM5, ACCESS1.0, MIROC5, HadGEM2-CC, NorESM1-M, GFDL-ESM2M, CESM1-CAM5) for two emissions scenarios (RCP4.5 and RCP8.5) and four future time periods centred on 2030, 2050, 2070 and 2090. The user can choose from annual, seasonal, wet/dry season, or individual months, and can select maximum temperature thresholds ranging from 35–44°C in 1°C increments (e.g. number of days with a maximum temperature >35°C), and minimum temperature thresholds ranging from 0–8°C (e.g. number of days with a minimum temperature <0°C) and 25–29°C (e.g. number of days with a minimum temperature >25°C). Data are available as a gridded map (0.05° resolution) with the option to select a particular location (>80 in NSW), which then provides a table of historic and future values for the selected location. Location data are obtained from the nearest grid cell, not calculated from station data. The projected data for each model is the average difference between a 20-year baseline (1986–2005) and the 20-year future period (calculated separately for annual, seasonal or monthly), which is then applied to a 30-year historical daily time series (AWAP) and analysed for days above or below the selected threshold. This method, known as the delta change or change factor method, preserves the historical spatial patterns but does not account for any future change in natural variability. Data can be downloaded in five formats: NetCDF; comma separated values; comma separated ASCII; html table; JSON.

[2] CCIA, Climate model resolution

Projections of time in meteorological drought (based on the Standardised Precipitation Index; SPI) (CSIRO & BoM 2015) are available via the Climate Futures Tool.

A summary of historic and projected FFDI is available for 40 national BoM stations (nine in NSW) via the Station Data Download Tool. The dataset is an Excel spreadsheet containing summary (average annual cumulative FFDI) and threshold (average days per year of High, Very High, Severe, Extreme and Catastrophic fire danger) FFDI data for three CMIP5 GCMs (CESM1-CAM5; GFDL-ESM2M; MIROC5) for two emissions scenarios (RCP4.5 and RCP8.5) for 20-year periods centred on 2030, 2050, 2070 and 2090, as well as historic data.

The CCIA website provides two types of data on wind speed:

- gridded datasets of future projected wind speed from 34 GCMs for four emissions scenarios and for 20-year periods centred on 2030, 2050, 2070 and 2090; annual, seasonal, and monthly datasets are available
- ‘application-ready’ gridded datasets of wind speed, where projected future change in wind speed from eight CMIP5 models (interpolated from GCM native grid to 0.05° grid) was applied to ERA-Interim reanalyses of wind speed (also interpolated from ERA-Interim 0.75° grid to 0.05° grid) for four emissions scenarios and four future time periods.

CCIA also provides data via two tools that would provide information on extremes with further processing (strictly a Tier 2 dataset using this report’s terminology, but included here for completeness):

1. The Time Series Explorer provides a continuous time series of historic and future climates as simulated by ~40 CMIP5 and CMIP3 GCMs, with the option of superimposing the results from an individual model onto the full set of results. Data are available for temperature (mean, maximum and minimum) and rainfall, for an NRM cluster, sub-cluster or super-cluster. The user has the option of selecting annual, seasonal, wet/dry seasons or individual months.
2. The Map Explorer Tool allows visualisation and download of datasets for:
    - four future time periods: 20-year periods centred on 2030, 2050, 2070 and 2090
    - two emissions scenarios: RCP4.5 and RCP8.5
    - eight variables: humidity, rainfall, solar radiation, wind speed, evapotranspiration, and mean, maximum and minimum temperature
    - eight CMIP5 models: CanESM2, CNRM-CM5, ACCESS1.0, MIROC5, HadGEM2-CC, NorESM1-M, GFDL-ESM2M, CESM1-CAM5
    - annual, seasonal, warm/cool season
    - data type: change relative to baseline; application-ready
    - region: cluster, super-cluster or sub-cluster (option to specify latitude and longitude range is available when user selects option to download the data). Downloadable data are not regional averages, but are gridded datasets, at the resolution of the GCM native grid, comprised of grids that lie within or intersect the boundary defining the region
    - download data format: NetCDF; comma separated values; comma separated ASCII; html table; JSON.

Sea level data are accessible via the Marine Explorer tool, which provides 10th, 50th, and 90th percentile maps derived from the range of GCMs. Data can be downloaded for 27 coastal regions in a comma-separated values file giving values for 20-year periods centred on 2030, 2050, 2070 and 2090 for three emissions scenarios (RCP2.6, RCP4.5 and RCP8.0).

Strengths:

- Developed through a comprehensive user consultation and testing process, with annual user surveys.
- Projected future changes are provided for four future time periods, four RCPs and up to 40 CMIP5 GCMs, consistent with IPCC 5th Assessment (i.e. credible, relevant and comprehensive).
- Application-ready data from eight GCMs means users can apply the data directly in impact models (but see point below regarding natural variability).
- Numerous datasets available in different formats, which can be downloaded directly.
- Precipitation is quantile-scaled, not mean change, so captures future changes in extreme rainfall (e.g. no change in mean but significant increase in extreme values).
- Provides drought information.
- Provides climate science information.
- Much guidance material.
- Examples available in Impacts and Adaptation section of tool.
- Data free for non-commercial purposes; licence fee for commercial users after completing a simple licence form.
- Still being maintained and datasets added.
- Data request service.

Considerations:

- Application-ready data has future change applied to historical observational dataset, which means the dataset does not capture GCM-simulated changes in future variability.
- Can't specify a postcode and extract all relevant data.

2.2.3 ETCCDI and ET-SCI indices

The Expert Team on Climate Change Detection and Indices (ETCCDI) and Expert Team on Sector-specific Climate Indices (ET-SCI) provide a set of consistent climate extreme indices (see below). ETCCDI data are freely available via the CLIMDEX web tool, and ET-SCI are available through a downloadable R-software package, climpact2, that calculates a wide range of sector-specific climate indices. Both the ETCCDI and ET-SCI have been calculated for AWAP and NARCliM data using the climpact2 software and data are available by contacting DPIE via narclim@environment.nsw.gov.au.

The ETCCDI data freely available from CLIMDEX includes a range of station and gridded land-based global datasets of indices for extremes derived from daily temperature and precipitation data. The CLIMDEX web tool provides access to raw data and indices, trend maps, time series and uncertainty estimates in ASCII and NetCDF format. Station-based indices are calculated from datasets such as the Global Historical Climatology Network (GHCN-Daily), and European Climate Assessment and Dataset (ECA&D), and global gridded datasets include HadEX2 (3.75° longitude x 2.5° latitude grid; available from 1901 to 2010), GHCNDEX (2.5° x 2.5° grid; 1951 to present), and HadGHCND (3.75° longitude x 2.5° latitude grid; 1951 to present) (see website for full dataset description). The start and end date of the gridded datasets varies among datasets, and the time period covered by the station data varies according to the operational coverage of individual stations.

CLIMDEX is maintained by UNSW and is in collaboration with the University of Melbourne, Environment Canada, and the US National Oceanic and Atmospheric Administration (NOAA).

Twenty-seven climate extreme indices are available through CLIMDEX including:

- annual count of days when daily maximum/minimum temperature <0°C
- annual count of days when daily maximum temperature >25°C
- annual count of days when daily minimum temperature >20°C
- monthly maximum (and minimum) value of daily maximum/minimum temperature
- cool nights and cool days: percentage of days when daily maximum/minimum temperature <10th percentile centred on a 5-day window for the base period 1961–1990
- warm nights and warm days: percentage of days when daily maximum/minimum >90th percentile centred on a 5-day window for the base period 1961–1990
- warm/cold spell duration indices
- monthly mean difference between daily maximum and minimum temperature
- monthly maximum 1-day and consecutive 5-day precipitation
- simple precipitation intensity index
- annual count of days when precipitation is greater than a defined threshold (mm)
- maximum length (days) of dry/wet spell
- count of 'very wet' and 'extremely wet' days
- annual total wet-day precipitation.

Strengths:

- Widely used.
- Highly relevant data provision for extremes.
- Easily accessible datasets in formats commonly used by researchers and data analysts.

2.2.4 BoM observational data

The BoM has numerous observational datasets and products relating to observed weather and climate extremes. These include:

- Australian Climate and Weather Extremes Monitoring System which has tables, maps (0.05° resolution), and graphs of daily, monthly, seasonal and annual extremes of rainfall and temperature. The tables can be downloaded as a text file and the data behind the graphs are also provided in a table format that can be copied and used in an Excel spreadsheet for example. Also available are maps of extreme rainfall or temperature events in terms of the average amount of time in years that one would expect such an event to occur again, based on the past climate record and assuming no change in the future climate.
- Climate Change Tracker webpages with maps and trends in extremes including 18 temperature-related extremes (e.g. trend in number of very hot days) and 11 rainfall-related extremes (e.g. trend in number of heavy rain days). Data behind the time series graphs can be downloaded directly as a text file. The Tracker uses Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) dataset (temperature) and high-quality BoM station datasets for the other variables (rainfall, cloud amount and pan evaporation).
- Climate and oceans data and analysis service where a wide range of historic weather and climate data can be obtained. Many datasets are free and can be downloaded directly; others will require submission of a particular data request that may incur a fee.

Strengths (Climate Change Tracker):

- Good data description and guidance on use.
- High-quality station data has been temporally homogenised.

2.2.5 weather@home Australia–New Zealand

This project, weather@home Australia–New Zealand, is focused on conducting regional climate simulations to investigate the cause of recent heatwaves and drought in Australia and New Zealand. It uses public volunteers' home computers to run a global atmospheric model (1.25° longitude by 1.875° latitude) with a nested regional model (0.44° × 0.44° resolution) over the Australasian region, thereby generating numerous simulations of possible weather under various climate scenarios. The project has generated very large ensembles (multi-thousand members) for selected years over the period 1985–2016 and is currently performing experiments for future climate scenarios (i.e. select years within the 2030s). The combination of large ensemble sizes with high spatial resolution enables investigation of extreme events. The regional data are archived at a daily time-step, and all data generated by the project are freely available to the broader research community. Further details are provided in Black et al. (2016).

2.2.6 Australian Rainfall and Runoff

Australian Rainfall and Runoff (ARR) is published by Engineers Australia and provides information, guidelines and approaches for practitioners and policy-makers involved in water management in Australia. ARR was updated in 2016 (the first update since 1987) and provides data standards to provide a consistent approach to collecting, analysing and managing flood information. The 2016 revision is based on Australian data, where previously it was based on US data. Software and data that enable and support the guidelines are available for download and can be accessed from the ARR Guidelines webpage. Two datasets are available:

- Design Rainfalls – the 2016 Rainfall Intensity–Frequency–Duration (IFD) Data System is hosted by the BoM and, once the user has entered a latitude and longitude, provides IFD design rainfall depth (mm) for durations ranging from one minute to 168 hours, and annual exceedance probability (AEP) ranging from 1–63.2%. Data are derived for the selected location from values at the nearest grid point on the 0.025° grid.
- ARR Data Hub – the user can enter the latitude and longitude of a point location or upload a shapefile and retrieve data (.txt or .pdf file formats) on the design inputs required to undertake flood estimation in Australia. Data available include:
    - name and characteristics of the river region
    - areal reduction factor[3] parameters
    - temporal patterns
    - IFD values
    - Interim Climate Change factors – values for change in temperature (°C) and percentage increase in rainfall for RCP4.5, RCP6.0 and RCP8.5 for 10-year intervals from 2030 to 2090 inclusive (change factor of 5% increase per degree of warming, based on Clausius–Clapeyron equation).

Data are copyright of the Commonwealth of Australia (Geoscience Australia) and are published under CC BY 4.0. API requests can also be sent to the server directly through the URL.

The ARR data, in conjunction with sea level and waves datasets, could facilitate investigation of coincident events (e.g. heavy rainfall, flooding and tidal inundation). This approach has been used in studies (currently undergoing peer review) using hydrodynamic models to incorporate tide gauge data and catchment flow, because with rising sea levels, it may need a less severe heavy rainfall or runoff event and a lower tidal state to cause coastal inundation compared with the present day.

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[3] ratio of the mean areal rainfall to the mean point rainfall for the same duration and return period in the same area

2.2.7 BoM radar datasets

Weather radars can detect precipitation such as rain and hail. The BoM has a national network of weather radars, including seven within NSW. Archived radar data are available for a fee via the BoM Data Services. Radar images are available in PNG, shapefile and raw polar data formats. For NSW, basic volumetric radar data are available from 2009 onwards, and the quantitative radar-based precipitation estimate dataset (‘Rainfields’) is available for four radars (Sydney Terrey Hills, Sydney Kurnell, Wollongong and Newcastle) from 2014 onwards.

Strengths:

- Provides one of the very few hail-relevant datasets.
- The optimal coverage area from an individual radar extends to approximately 200 km from the radar. The locations of NSW radars provide coverage over much of the east coast (Figure 2.1).

Considerations:

- Radar coverage can be restricted due to hills and mountains on the horizon, and tall trees or buildings in the local area. This is known as ground ‘clutter’. Sea clutter can also occur when there is reflectivity off the sea surface. Also, at some wavelengths the radar beam is not fully reflected when passing through very heavy rain or hail, which can reduce the echo intensity further out from the radar.
- At the current time, in Australia, only the Darwin radar has been fully calibrated to enable the long-term hail dataset to be used. The same calibration process would be required for the NSW radar datasets to facilitate long-term investigation of hail from these datasets.

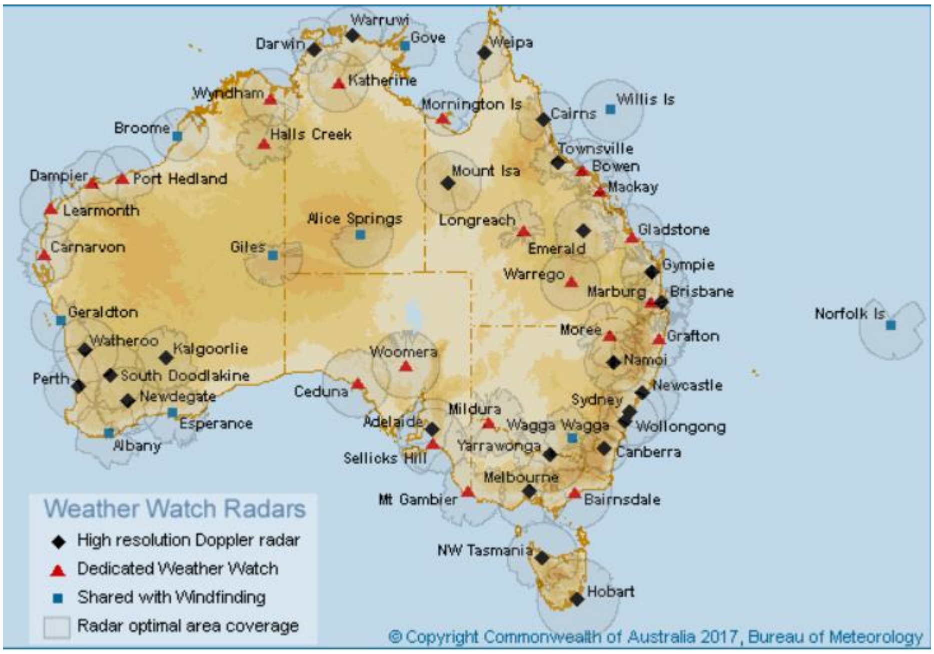

Figure 2.1 Map showing the optimal radar coverage area for radar images available from the Bureau of Meteorology website[4]

[4] BoM 2019, Optimal Radar Coverage Areas

2.2.8 Scientific Information for Land Owners (SILO)

The Scientific Information for Land Owners (SILO) offers free-of-charge a large number of historical (from 1889 to the present) climate-related primary and derived datasets including temperature, rainfall, evaporation and frost days. Three types of data are available: interpolated gridded datasets (0.05 × 0.05 degrees resolution); daily time series at BoM stations supplemented by interpolated estimates for missing observations; and a daily time series at any location, obtained by interpolated estimates from the gridded dataset.

There are some differences between SILO and BoM station and gridded products. BoM station data may have missing values if observational data were not reported on a particular day, whereas SILO data include interpolated estimates for missing observations. SILO and AWAP gridded products use similar interpolation techniques and result in similar biases although there are also some differences. Further details are provided in SILO's Comparison of Bureau of Meteorology and SILO climate datasets (PDF 285).

2.2.9 BoM severe storms archive

BoM's Severe Storms Archive contains data relating to recorded events in Australia dating back to the 18th century. The datasets can potentially (depending on specific event, time and/or location) provide a considerable amount of important information for seven storm-associated features:

- Rain
  - intense precipitation amount and period
  - total precipitation and duration
- Wind
  - maximum gust speed and direction
  - maximum mean wind speed and direction
  - path length, width and direction
- Hail (size)
- Lightning
  - maximum current
  - flash rate
  - powerline deaths
- Tornado
  - maximum and minimum speed
  - path width and direction
- Water spout (duration and number)
- Dust devil
  - severity
  - duration
  - path length, width and direction.

In addition to the above, the following four attributes are potentially available for all of the seven events listed above: damage total ($), insurance payout ($) and the number of injuries and deaths.

Data can be displayed in a table or downloaded in comma-separated values file format containing data for all of the attributes listed above.

Strengths:

- Information is provided for multiple weather extremes potentially for the same extreme event (i.e. an extreme event on a particular day could have potentially involved rain, hail, wind and lightning, and data may be available for all types).

Considerations:

- BoM highlights that the data are for recorded events and cover a long period, which means there is an artificial increase in observed events over time (due to increases in population and in the number and range of observation systems), and the distribution of events is influenced by population density. It is advisable to read the information on the About Severe Storms Archive link on the site, which provides a clearly written overview of caveats and considerations.

2.2.10 BoM gridded average annual thunder-day and lightning flash density

The BoM has gridded maps of the average annual number of thunder-days based on observed thunderstorm activity at approximately 300 recording stations across Australia over a 10-year period (1990–1999). An objective analysis technique was applied to the station annual averages to produce a regular gridded dataset covering Australia. Gridded maps are also available of annual average lightning total flash density and lightning ground flash density across Australia using satellite-derived data over an 18-year period (1995–2012). Also provided are climatologies of lightning ground flash density for the warm season (November – April) and cool season (May – October).

Both the thunder- and lighting-related datasets are available for a fee for individual states or any rectangular grid area by contacting the BoM Climate Data Service. Data are provided in ASCII or Arc/Info grid interchange (.e00) file formats.

2.2.11 CAWCR wave hindcast (1979–2010; 2011–2014)

Waves were not explicitly included in the seven types of extreme events but are an important aspect in influencing the magnitude of coastal inundation for some regions. The Collaboration for Australian Weather and Climate Research (CAWCR) wave hindcast dataset is an ocean wave hindcast for 1979–2010 which used the WaveWatch III v4.08 wave model forced with NCEP Climate Forecast System Reanalysis (CFSR) hourly surface winds and sea ice. The dataset contains spectral wave output at 3683 points, as well as gridded outputs (in NetCDF format) on a global 0.4 degrees (24 arcminute) grid (~50 km), with nested Australian and western Pacific subgrids of 10 and 4 arcminutes resolution (~18 km and ~7 km respectively). Gridded parameters output includes wind speeds and numerous wave characteristics (e.g. significant wave height; mean wave length, period and direction; wave energy flux). The dataset is freely available via the CSIRO Data Access Portal, as are two further datasets extending the hindcasts for 2011–2013 and 2013–2014.

While the data can be downloaded directly from the CSIRO Data Access Portal, the wave hindcast dataset can also be visualised and extracted using the Australian Renewable Energy Mapping Infrastructure (AREMI). Options include extraction and visualisation of a 30-year time series, annual and monthly wave rose showing wave direction and return period levels. Data format options include comma-separated values, PDF and PNG image. AREMI is funded by the Australian Renewable Energy Agency (ARENA) and developed by CSIRO Data61 in partnership with Geoscience Australia and the Clean Energy Council.

2.2.12 CAWCR global wind-wave 21st century climate projections

Global wind-wave projections are available from the CSIRO Data Access Portal. Simulations were conducted using a 1° global implementation of WaveWatch III forced with surface winds and sea-ice concentration fields from two CMIP3 GCMs (ECHAM5 and CSIRO Mk3.5) dynamically downscaled to 60 km using the Cubic Conformal Atmospheric Model (CCAM) and from eight CMIP5 GCMs (ACCESS1.0, CNRM-CM5, HadGEM2-ES, INMCM4, BCC-CSM1.1, MIROC5, GFDL-ESM2M, MRI-CGCM3). Simulations were conducted for two future periods (2026–2045 and 2080–2099) under RCP4.5 and RCP8.5 emissions scenarios. Archived variables are in monthly NetCDF files for all simulations, and include significant wave height, mean wave period and direction. Further details are outlined in Hemer et al. (2013) and Hemer and Trenham (2016).

2.2.13 Australian Baseline Sea Level Monitoring (ABSLM)

The BoM Australian Baseline Sea Level Monitoring (ABSLM) project monitors sea level around the Australian coastline using a network of 14 standard stations that measure sea level very accurately and record meteorological parameters. There is one station within NSW, at Port Kembla, and data from 1991 to the present in the form of plots and tables can be downloaded directly from the BoM site for monthly sea levels, barometric pressure, water and air temperature. Hourly data of the same parameters with the addition of wind speed, direction and gust are also freely available in comma-separated values format.

2.2.14 Manly Hydraulics Laboratory (MHL)

The Manly Hydraulics Laboratory (MHL) is a business unit within the NSW Government. The majority of data presented online by MHL has been collected under the NSW Coastal Data Network Program managed by DPIE. Available data include: wave height, period and direction (seven Waverider buoys); tides (18 recording stations); water levels (>500 recording stations); and rainfall (>300 recording stations). Data are available for a fee by submitting an online request on the MHL website.

2.2.15 BoM MATCHES ECL database and updated ECL dataset

Maps and Tables of Climate Hazards on the Eastern Seaboard (MATCHES) is an online database of ECLs passing through a region bounded by the Australian east coast, 161°E, 24°S and 41°S. The aim of the MATCHES online tool was to provide a relatively broad database of low pressure systems and allow the user to filter for those that are of impact, so the dataset includes many more systems than those typically thought of as ECLs. The user can filter by setting thresholds for wind, rainfall and ocean state (waves and water level). Wind and rainfall data are from BoM, and ocean state data are from the Manly Hydraulics Laboratory. ECLs were identified from the surface pressure field from NCEP1 reanalysis, which has 6-hourly 2.5° pressure data, and tracked using the Jones and Simmonds (1993) version of the Murray and Simmonds (1991) tracking scheme. The database shows the tracks of each weather system for the period specified (maximum of one year), and data for a particular event can be downloaded (in comma-separated values format) by clicking on the track for that event.

The MATCHES database covers the period 1950 to 2008, and access is via registration with the BoM MATCHES support staff (email: matches@bom.gov.au). Users of the database should acknowledge BoM and NSW DPIE/Eastern Seaboard Climate Change Initiative (ESCCI). The database was created primarily as a tool to enable linkage of ECLs to weather impacts but was not made operational and has not been updated since 2008; however, on request the MATCHES support staff can provide an updated ECL dataset (in comma-separated values format) which extends to 2016. The updated version contains the date, time, position (latitude and longitude), mean sea level pressure (MSLP; hPa) and Laplacian (represents the curvature of the MSLP and provides an indicator of the strength of a cyclone) of each identified ECL from 1950 to 2016.

Users of MATCHES include: emergency services; NSW Government health, planning and environment departments; universities (researchers and students); CSIRO; BoM; consultants; insurance/reinsurance companies; local governments.

Strengths:

- Automated tracking system has been verified against 'manually' identified datasets (e.g. Speer et al. 2009) and found to perform well (Pepler et al. 2015).
- Can download important weather impact data (rainfall, wind, waves and water level) directly relevant to the ECL data and which is from highly credible and well-regarded institutions (BoM; Manly Hydraulics Laboratory).
- Easy access to data after registration with BoM MATCHES support staff.

Considerations:

- Webtool has not been updated since 2008 and no intention to do so at the present time; has not been funded to turn it into an operational product.
- Existence of MATCHES may not be widely known outside of the research community.

2.2.16 Speer et al. (2009) dataset of low pressure systems

A dataset identifying low pressure systems off the NSW coast is described in Speer et al. (2009) and is available from the authors. Weather systems were manually identified (as opposed to the automated tracking systems used in MATCHES) from the manual MSLP chart archives based on meteorological expertise within the BoM. Weather systems were categorised as one of six types according to the MSLP synoptic patterns in which the lows formed (inland trough lows; easterly trough lows; ex-tropical cyclones; lows forming on a wave on a front; decaying front lows; westerlies lows). Detailed information is available from Speer et al. (2009).

2.2.17 Projected future change in ECLs

Pepler et al. (2016a) provided an assessment of projected future ECL activity using regional model outputs from NARCliM (see Section 2.2.1) and several methods of identifying ECLs. Full results are provided in Pepler et al. (2016a) and the authors could be contacted to discuss accessing the raw data.

2.2.18 Baird Australia stochastic ECL model

Baird Australia has developed a stochastic ECL multi-hazard model for south-eastern Australia. Data are available for a fee from Baird, and include:

- ECL database based on synoptic analysis (time/track position/synoptic type/intensity) for the period 1970–2016
- 10,000-year synthetic event set of ECL events (time/track position/synoptic type/intensity) based on Monte Carlo modelling, as well as their rainfall, wind and coastal inundation hazard footprints
- ECL hindcast of significant events (those generating above threshold rain/wind/waves) from 1979 to the present
- ECL wave hindcast from 1970 to the present.

The domain covers NSW and south-east Queensland. The wind and rainfall footprints are specified at 5 km resolution. The rainfall hazard is based on AWAP. The wind hazard is based on measured winds and sea winds. The coastal inundation hazard is based on Baird's wave and storm surge modelling, and inundation footprints are mapped at 20 m resolution using LiDAR. The data can be formatted in any required format, but is currently available in .csv files, with average recurrence interval surfaces also in .kmz format.

2.2.19 BoM derived historical fire weather dataset (stations and gridded)

BoM have a derived historical fire weather dataset for 77 Australian stations (17 in NSW) for the period 1973 to 2017, which can be purchased via their online data service. The dataset includes FFDI, Grassland Fire Danger Index (GFDI), maximum temperature, 3pm relative humidity, 3pm wind speed and direction, drought factors/indices related to fire (e.g. Keetch-Byram Drought Index) and daily rainfall. Considerations regarding use of the data are explained fully in Lucas (2010).

A gridded FFDI dataset from 1950 onwards at 0.05° resolution (Dowdy 2017) is also available via BoM using their Data Requests and Enquiries service. The input variables for calculating FFDI values were obtained from a gridded analysis of AWAP observations, with the exception of wind which came from the 6-hourly NCEP/NCAR reanalysis.

2.2.20 Fire Information for Resource Management Systems (FIRMS)

The NASA Fire Information for Resource Management System (FIRMS) distributes near real-time (NRT) active fire data within three hours of satellite overpass from both the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS). Each MODIS active fire location represents the centre of a 1 km pixel that is flagged by the algorithm as containing one or more fires within the pixel. Archive data in three formats (shapefiles, comma-separated files and JSON files) are also available by submitting a data request. Temporal coverage is from November 2000 to the present for MODIS data and from January 2012 to the present for VIIRS 375m.

2.2.21 DustWatch

Community DustWatch is a citizen-science program coordinated by NSW DPIE to gather data about dust storms to monitor wind erosion. Community volunteers record data and observations about dust in their local area and send them to DPIE who analyses and shares the data with the community, researchers and government agencies. The project started in 2002. There are 40 monitoring stations of relevance to NSW. The database classifies the aerosols into fog, smoke and dust. A webtool enables visualisation of data for individual stations by selecting the time period and dust level (moderate or severe; dust storm or haze). Alternatively, DustWatch data can be accessed by registration via the website.

2.2.22 Coincident events

There are very few Tier 1 datasets of coincident events readily available, although data may be accessible through contacting data authors. For example, recently analyses have been conducted on the drivers of extreme rainfall and winds in relation to the coincident occurrence of cyclones, thunderstorms and fronts (Dowdy & Catto 2017). The data are not directly available to external groups because of licence agreements associated with parts of the dataset; however, the data can be used through research collaboration with BoM, with enquiries directed to the journal authors. The compound storm data consists of six-hourly values from 2005–2015 at 0.75 degrees latitude and longitude grid, based on combinations of cyclone, front and thunderstorm events.

2.3 Tier 2 datasets

Tier 2 datasets are defined as those that with further processing could produce information on extreme events. There are numerous Tier 2 datasets that with additional processing by the user could potentially provide information on extreme events relevant to NSW. Details of these are provided briefly below. The datasets fit into three broad categories: reanalyses; distributors of numerous large datasets; and others. Extreme events by their very definition are rare, sitting at the upper and lower ends of the probability distribution. This fundamental feature limits what information can be extracted from existing datasets, both observed and projected. In the case of projected data, the research community finds itself on the horns of a dilemma; many of the extreme events have their genesis in the physics of convection and synoptic scale processes. These require high resolution models; such models have been used to create 20-year future windows, but it is hard to detect a 1-in-20-year event in such a dataset. Much longer time windows would be required to adequately characterise many types of extreme events and coincident/compound events.

Although a number of subject matter experts (SMEs) held differing views, this study concluded that Tier 2 datasets often have the potential to provide information for more than one extreme event type, and for coincident events (e.g. reanalyses), but it should be noted that these, in particular the projections datasets, will be critically limited in many areas.

2.3.1 Reanalyses

ERA5 reanalysis

Reanalyses are used for a wide range of purposes including extraction of variables and synoptic characteristics relevant to extreme events. ERA-Interim is a widely used global atmospheric reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim is 10 years old and is being replaced by a new reanalysis, ERA5, which will have greater spatial and temporal resolution. ERA5 will span 1950 onwards and will provide hourly estimates of atmospheric, land and oceanic parameters including those pertinent to extremes including surface air temperature, pressure, wind, rainfall, soil moisture and sea surface temperature (SST), at a resolution of about 31 km worldwide. ERA5 will also include information on wave height over the global oceans. ERA5 has several benefits over using ERA-Interim including the improved spatial and temporal resolutions, observations assimilated using the 4D-Var data assimilation technique, the use of CMIP5 radiative forcing, a consistent historical dataset for SST and sea ice cover, and other improved datasets.

Data for 1979 to the present (five days behind real time) is publicly available from the Copernicus Climate Change Service (CCCS).

Strengths:

- Widely used.
- Freely available and ongoing maintenance and support.
- CCCS Climate Data Store will include a toolbox allowing users to perform custom-made manipulations in the cloud without having to download large datasets.
- Secure dataset.
- Useful for regions and variables where station-based data may be sparse or incomplete.

Considerations:

- ERA5 will comprise a massive dataset and need considerable resources infrastructure to archive these data in Australia. Ongoing discussions with major data holders (e.g. NCI, BoM) to determine how this can be best achieved.

ERA-20C

ERA-20C is ECMWF's atmospheric reanalysis of the 20th century from 1900–2010. A coupled atmosphere-land surface-ocean waves model assimilates observations of surface pressure and surface marine winds only. The horizontal resolution is approximately 125 km. Daily (3 or 6-hourly) and monthly mean data are available directly from the ERA-20C ECMWF Public Datasets web interface.

NOAA/CIRES Twentieth Century Global Reanalysis Version 2

The NOAA/CIRES Twentieth Century Global Reanalysis is a reanalysis dataset that spans 1851 to 2014. The reanalysis assimilates surface observations of synoptic pressure, monthly sea surface temperatures and sea ice distribution. An Ensemble Filter data assimilation method is used which provides each six-hourly analysis as the most likely state of the global atmosphere, and also estimates uncertainty in that analysis. Data (3 and 6-hourly, daily average and monthly) on a 2 × 2 degree global latitude–longitude grid can be accessed directly from the NCAR Research Data Archive after a straight-forward registration process.

This reanalysis product has been used in studies of extreme events, such as analysing long-term trends and variability of ECLs (Pepler et al. 2016b).

BoM Atmospheric high-resolution Regional Reanalyses for Australia (BARRA)

The BoM Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) is a new reanalysis dataset developed specifically for Australia. BARRA is based on the Australian Community Climate Earth System Simulator (ACCESS) model. The reanalysis over the Australian domain is at a resolution of approximately 12 km with 70 atmospheric levels. For a small number of subdomains (e.g. Sydney, Melbourne), the 12 km reanalysis is downscaled to a resolution of 1.5 km. Other subdomains could potentially be downscaled to the 1.5 km resolution, through future collaborative agreements. The reanalysis produces outputs at hourly (and some at 10-minute) intervals for about 100 parameters including many (e.g. temperature, precipitation, wind speed and direction, evaporation and soil moisture) that will assist studies focused on extreme events such as historic bushfires, ECLs, heatwaves, drought and flood.

The reanalysis dataset will cover the 25-year period from 1990 to 2016, and data will be released publicly in six-year blocks every six months, with data for 2010–2015 already released to 'early adopters'. Questions around licensing and processing are still being decided; however, collaborative agreements that seek to use the data can be discussed at any time with the BoM Project Leader (Doerte Jakob). A sample dataset is available for direct download from the BoM BARRA information site, which contains the full set of parameters for the 12 km resolution over the Australian continent and the 1.5 km high-resolution over the Tasmania domain for a 24-hour period on 7 February 2015.

Bluelink ReANalysis (BRAN)

The Bluelink ReANalysis (BRAN) is a multi-year integration of the Ocean Forecasting Australia Model (OFAM) that assimilates observations using an Ensemble Optimal Interpolation (EnOI) data assimilation system called BODAS (Bluelink Ocean Data Assimilation System). BRAN data comprise gridded (0.1 degrees resolution) daily-average fields of temperature, salinity, velocity and sea level for the years 1993 to 2010. Bluelink is a collaboration involving CSIRO, BoM and the Royal Australian Navy. Data can be accessed via registration with CSIRO, and is subject to acceptance of licence agreements by users, with options for commercial or non-commercial licences.

NCEP/NNRP Reanalysis Project

The NCEP/NCAR Reanalysis Project (NNRP or R1) archived data from a global Reanalysis Model at T62 (209 km) resolution with 28 vertical sigma levels, at 6-hour intervals from 1948. There are over 80 different variables in several different coordinate systems, such as 17 pressure levels on 2.5 x 2.5 degree grids, 28 sigma levels on 192 x 94 Gaussian grids, and 11 isentropic levels on 2.5 x 2.5 degree grids. In addition to analyses, diagnostic terms (e.g. radiative heating, convective heating) and accumulative variables (like precipitation rate) are available. The input observations are archived with quality and usage flags in WMO BUFR format. Most of the project outputs are stored in WMO GRIB format.

2.3.2 Distributors of numerous large Tier 2 datasets

Earth System Grid Federation (ESGF) – repository of CMIP data

The Coupled Model Intercomparison Project Phases 3 (CMIP3) and 5 (CMIP5) provided a structured approach to conducting GCM runs and model output. Data are freely available via the Earth System Grid Federation (ESGF) nodes (e.g. esgf-node.llnl.gov/projects/esgf-llnl), and includes GCM outputs for numerous atmosphere, land and ocean variables at the grid resolution of the native GCM.

Currently institutions around the world are conducting GCM runs for the next phase, CMIP6 (Eyring et al. 2016), with 21 CMIP6-endorsed model intercomparison projects (MIPs) including those focused on: high-resolution modelling; land surface, snow, and soil moisture; and ocean modelling.

Strengths:

- Comprehensive datasets that enable extensive analysis of data for numerous purposes, including addressing extremes; often require subsequent downscaling (dynamical or statistical) to be useful in investigating extreme events.
- Highly consistent experiments and data formats because this is a key requirement for participating in CMIP.
- Very secure dataset (can always download data from individual institutions if ESGF ever failed).

Considerations:

- CMIP6 will generate huge amounts of data, and there are ongoing discussions with major data holders as to how best to organise the download and storage of these CMIP6 datasets for use by Australian researchers and data users.

CORDEX

The Coordinated Regional Climate Downscaling Experiment (CORDEX) provides a framework for conducting regional downscaling experiments aimed at addressing climate information needs at the regional level. The CORDEX framework facilitates the production of a coordinated set of regional projections worldwide. Data are available via the ESGF infrastructure. With international groups currently undertaking GCM modelling for CMIP6, plans are underway to produce the second phase, CORDEX-II, which will use CMIP6 model outputs for regional downscaling. The proposed resolution is 20 km but this has yet to be finalised and confirmed by the CORDEX Science Advisory Team. More information for the Australian region can be found on the CORDEX-AustralAsia wikipage.

Strengths:

- Internationally coordinated, best practice, high credibility.

Considerations:

- No funding other than a modest travel budget to attend meetings. Relies on research agencies funding model development, assessment, simulations and analysis.

NCI data holdings

The National Computational Infrastructure (NCI) is Australia's largest research data repository. NCI data holdings can be viewed and downloaded via the data catalogue. Datasets of relevance to extreme events include BoM observational data, BoM Oceans-Marine Reference data, CCIA data (see Section 2.2.2) and ESGF data (CMIP5, CORDEX).

Australian Ocean Data Network

The Australian Ocean Data Network (AODN) portal provides access to available Australian marine and climate science data and provides the primary access to data collected through the Integrated Marine Observing System (IMOS). Datasets are available relating to sea level, waves, sea temperature and salinity, and are sourced from satellites, radar, tide gauges, wave buoys (including data from the Manly Hydraulics Laboratory Waverider buoys), gliders, Argo floats, permanent moorings and ships.

CSIRO Data Access Portal

The CSIRO Data Access Portal provides freely available access to numerous climate, land, atmospheric and ocean datasets including those relating to: FFDI; mean sea level (e.g. monthly reconstructed global mean sea level time series for 1980 to 2009 as described in Church and White (2011)); wave hindcasts.

NSW DPIE data portal: Sharing and Enabling Environmental Data (SEED)

SEED provides access to a variety of data including those relating to vegetation cover, digital elevation maps, and wave and sea level data, and a link to NARCliM data. The DPIE air quality monitoring site also provides archived (hourly and 1–2 minute average data dating back to 1993), hourly and daily data on air quality and meteorological variables including air temperature, rainfall, wind speed and direction, and relative humidity.

Geoscience Australia

Geoscience Australia (GA) hosts a range of datasets relating to numerous hazards including bushfire, flood and severe wind. GA also hosts the National Exposure Information System (NEXIS), which provides comprehensive and nationally consistent information on exposure to risk, and is produced by sourcing the best publicly available information, statistics, spatial and survey data about buildings, demographics, community infrastructure and agricultural commodities.

Land cover data

Land cover indices provide a measure of the amount of live green vegetation available, which could be used to assess the amount and type of vegetation available when considering bushfire risk. Two key repositories of land cover datasets of relevance to NSW are:

- BoM – provides a freely available gridded product, the Normalised Difference Vegetation Index (NDVI). The index provides a measure of the amount of live green vegetation available and is derived from satellite data processed initially onto a 0.01° grid and then averaged to a 0.05° grid. Maps can be downloaded as GIF images or in PDF format for individual states including NSW/ACT (combined). Monthly NDVI grids in ASCII format suitable for ingestion into GIS can also be downloaded. The NDVI average and anomaly are available for periods of one, three or six months. Maps are available from April 1992 (with a gap from October 1994 to January 1995), and gridded data are available from July 2008.
- TERN AusCover – provides earth observation data and products that describe important land-surface and environmental characteristics derived using satellite and airborne imagery. For example, the site hosts MODIS vegetation fractional cover datasets that represent the exposed proportion of green, non-green and bare cover within each pixel of the MODIS satellite data. Both eight-day and one-month composites are available for Australia at 500 m resolution from 2000 to the present. Data are updated fortnightly and can be freely accessed directly via the TERN AusCover portal. Other datasets include the Landsat seasonal fractional cover dataset, which provides seasonal vegetation data at 30 m resolution from 1989 to the present.

The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) (see Section 2.3.3) also provides a land-use mapping tool at the national scale and catchment scale.

Paleoclimate data providers

Climate reconstruction through the use of paleoclimate data provides the potential to investigate historical extreme events. There are three key paleoclimate data providers with datasets of relevance to Australia (Dixon et al. 2017):

- The NOAA National Centers for Environmental Information (NCEI) offers search and download of paleoclimatic proxy data and paleoclimate reconstructions from the NOAA/World Data Service for Paleoclimatology archives. Datasets are derived from various sources such as tree rings, ice cores, corals, and ocean and lake sediments. Of the >10,000 datasets available, there are five datasets currently available for the NSW region (e.g. Upper Murray 300-year stochastic rainfall reconstructions; Upper Snowy Mountains 6500-year dust deposition data). Data can be downloaded directly as a single compressed file, and metadata in JSON format is available via a web service.
- The Neotoma database covers the Pliocene-Quaternary part of the geologic record, and for NSW holds four datasets relating to pollen.
- The Pangaea data publisher has five datasets relating to NSW palaeontology including datasets on foraminifera isotopes and pollen.

The supplement (PDF; large file:129MB) to Dixon et al. (2017) also provides a list of references with paleoclimate data of relevance to NSW.

Terrestrial Ecosystem Research Network (TERN)

The Terrestrial Ecosystem Research Network (TERN) is focused on Australian ecosystems research and datasets, including the impact of weather and climate extremes on terrestrial ecosystems. The site hosts ecosystem-related data and research outputs related to the impacts of fires, cyclones, droughts, dust storms, heatwaves and floods, including datasets relevant to NSW.

2.3.3 Other sources of Tier 2 datasets

Australian Water Availability Project (AWAP)

The Australian Water Availability Project (AWAP) datasets use BoM station observations to create a national gridded dataset at 0.05 × 0.05 degrees resolution for minimum and maximum daily temperature (from 1911 to the present), daily rainfall (from 1900 onwards), solar exposure (from 1990) and 9am and 3pm vapour pressure (from 1971). Monthly products include these variables as well as the Normalised Difference Vegetation Index (NDVI) (from 1992). Station data, gridded maps, and data can be accessed directly from the BoM Maps of recent, past and average conditions webpage, in Arc/Info grid and ASCII data formats.

AWAP data are widely used; for example, Climate Change in Australia uses the AWAP temperature and rainfall datasets to produce 'application-ready' datasets, and BoM uses AWAP data to map rainfall deficit for drought.

Strengths:

- Widely used.
- Freely available.

Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT)

The Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) dataset provides a daily record of Australian temperatures over the last 100 years. The dataset is produced and managed by BoM. The ACORN-SAT network comprises 112 observation locations across Australia (25 in NSW) that were selected to maximise both the length of record and network coverage. Minimum and maximum temperature data for each station are directly available in text file format from the ACORN-SAT BoM site.

Strengths:

- The data are robust and comparable through time, enabling investigation into the frequency of heat and cold extremes.

Consistent Climate Scenarios

The Consistent Climate Scenarios project was undertaken by the Queensland Government Department of Science, IT and Innovation with CSIRO to produce climate change projections data for 2030 and 2050 for all of Australia in a format suitable for input to biophysical models such as pasture and crop modelling. Available datasets are daily projections of rainfall, evaporation, minimum and maximum temperature, solar radiation and vapour pressure deficit for individual locations (BoM stations) as well as a 0.05° gridded product. The projections were based on 19 CMIP3 GCMs, and later updated through the addition of data from 28 CMIP5 GCMs and the use of the Linear Mixed Effect State Space projection method in addition to the change factor and quantile matching methods. Data are available through the SILO database, and more detail on methodology is available from the State of Queensland Department of Science (2016).

Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)

The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) provides a Weekly Australian Climate, Water and Agricultural Update that summarises recent climatic conditions, notable weather events and their impact on agriculture, water storage levels and irrigation allocations. The archive of weekly reports extends back to 2010. It is included here because the report brings together data from numerous sources (e.g. BoM, public and private water trading and water data sources and industry), and is used by end-users interested in agricultural drought.

Contacting dataset creators directly

Several SMEs highlighted that many creators of datasets that are not publicly available may be amenable to sharing their data through a research collaboration, and this could be especially relevant in the case of, for example, reading a journal article that potentially contained a pertinent dataset (see Chapter 1 of this report).

2.4 Conclusions

The datasets reviewed in this chapter are summarised in Table 2.2 below, divided into climate extreme type.

1. There are three types of datasets applicable to extreme events relevant to NSW:

1. Tier 1 datasets that have already been processed and provide data directly on extreme events (e.g. FFDI, temperature thresholds and drought, via CCIA and NARCliM)
2. Tier 2 datasets that have the potential to provide data on extreme events but require further processing to do so; these datasets are freely available and can be downloaded via a web portal
3. datasets as in 2. above, but knowledge of them may be limited to researchers working in that field and access is by contacting the authors/creators of the datasets.

With some exceptions (e.g. NARCliM, CCIA), many Tier 1 datasets contain data for only one or two extreme event types, and few provide direct information on coincident or compound events. In contrast, Tier 2 datasets often have the potential to provide information for more than one extreme event type, and for coincident events.

Both Tier 1 and Tier 2 datasets are generally in a format easily and commonly used by regular analysers of data (e.g. NetCDF, JSON), and many subsets of data are also available as comma-separated values and GIS-readable ASCII. While less technical end-users probably cope with these latter two types, many probably struggle with using NetCDF files and in using scripts to download large volumes of Tier 2 data.

4. There are numerous good quality Tier 2 datasets available for looking at extreme events in NSW; however there are many more historic Tier 2 datasets than projected. In contrast, Tier 1 datasets include both historic and projected datasets.

Updates and improvements are ongoing for key Tier 2 datasets, including: GCMs through CMIP6; CORDEX through CORDEX-II; and reanalyses through ERA5 and BARRA. Updates are also ongoing for some Tier 1 datasets including CCIA.

The least amount of data is available for hail and coincident events, which represents big gaps in the extreme event types investigated here.

Interviews with SMEs indicated there is a strong atmosphere of collaboration and sharing in Australia that hugely facilitates use and sharing of datasets and encourages the practice of contacting data creators directly to ascertain whether their data are available. Similarly, this review process identified a relevant dataset available for a fee from a consultant (Baird; see

Section 2.2.18) and it is likely there are other datasets held by other consultancies that could be of relevance to NSW.

Gaps:

- Accessibility to end-users of datasets used by researchers and described in peer-reviewed papers; translation of technical/scientific publications to end-users regarding the datasets.
- Analysis of the underlying utility of existing Tier 2 projections to provide robust and reliable extremes information.
- Exclusion of marine heatwaves from the list of extreme event types, even though they are important for NSW.
- Least amount of data on hail and coincident events.
- Lack of climate services to support the uptake of datasets in research and decision-making.

Table 2.2 Summary of the datasets reviewed on climate extremes

Extreme event type	Overview of datasets reviewed
Rainfall: extreme rainfall and snow, drought and flood	Many historic and projected datasets provide data directly on extreme rainfall and drought (e.g. CCIA; NARCliM; CLIMDEX; BoM), but none identified for NSW-relevant snow; ARR provides detailed information on flood analysis but few datasets readily available on flood events
Temperature: extreme heat/cold, heatwave	Many historic and projected datasets provide data directly on extreme temperatures (e.g. CCIA; NARCliM; CLIMDEX; BoM)
Unstable atmosphere: dust storm, thunderstorm, hail and lightning	Historic datasets on thunderstorms, hail and lightning available through BoM; dust storm data available through DustWatch; forthcoming calibration of radars in NSW will provide valuable hail and precipitation dataset
Wind: wind gust, storm surge and coastal flooding/ tidal inundation	Historic and projected wind speed available through CCIA and NARCliM; other historic wind datasets provided through BoM (e.g. Severe Storm Archive) and MHL; storm surge and coastal inundation reliant on coastal inundation maps, Tier 2 datasets (e.g. providers of waves, water levels, sea level rise) and modelling (e.g. Baird; forthcoming projects)
Extreme East Coast Lows (ECLs)	MATCHES online database provides highly relevant historic data on ECLs and associated rainfall, winds, waves and water levels to 2008; projected data available via request to data authors; other modelled (e.g. Baird) and historic data (e.g. Speer et al. 2009) also available
Fire: Bushfire and fire weather	Historic and projected data on FFDI available through multiple sources (e.g. NARCliM; CCIA; BoM); historic fire activity data are available from Geoscience Australia and state fire authorities
Compound or coincident events	Very few datasets available on compound events, but increasing focus in this area suggests data will become available in the future (e.g. work on synoptic features that create extreme ECLs; work on impact of extreme rainfall, sea level, and storm surge and low-lying coastal areas)

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A.2 Subject matter experts who contributed directly to Chapter 2

Subject matter experts (SMEs) interviewed by phone or in person prior to the workshop

- Hamish Clarke (University of Wollongong)
- John Clarke (CSIRO)
- Jason Evans (UNSW)
- Doerte Jakob (BoM)
- David Karoly (University of Melbourne)
- Dewi Kironi (CSIRO)
- Todd Lane (University of Melbourne)
- Chris Lucas (BoM)
- Kathy McInnes (CSIRO)
- Acacia Pepler (BoM)
- Andy Pitman (UNSW)
- Tony Rafter (CSIRO)
- Seth Westra (University of Adelaide)

SMEs who provided input at/following the workshop held on 19 February 2018

- Joanna Aldridge (Baird Australia)
- Lisa Alexander (UNSW)
- Mitchell Black (BoM)
- Jason Evans (UNSW)
- Michael Grose (CSIRO)
- David Hanslow (DPIE)
- Ningbo Jiang (DPIE)
- Anthony Kiem (University of Newcastle)
- Todd Lane (University of Melbourne)
- John Leys (DPIE)
- Acacia Pepler (BoM)
- Mahesh Prakash (CSIRO)
- Seth Westra (University of Adelaide)

A.3 Acronyms used in Chapter 2

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ACORN-SAT	Australian Climate Observations Reference Network – Surface Air Temperature dataset
AREMI	Australian Renewable Energy Mapping Infrastructure
AWAP	Australian Water Availability Project
BARRA	Bureau of Meteorology Atmospheric Regional Reanalysis for Australia
BoM	Bureau of Meteorology
CAWCR	Collaboration for Australian Weather and Climate Research
CCIA	Climate Change in Australia
CFSR	Climate Forecast System Reanalysis
CMIP	Coupled Model Intercomparison Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ECL	East Coast Low
ECMWF	European Centre for Medium-Range Weather Forecasts
ESGF	Earth System Grid Federation
ET-SCI	Expert Team on Sector-specific Climate Indices
ETCCDI	Expert Team on Climate Change Detection and Indices
FFDI	Forest Fire Danger Index
GCM	Global Climate Model
MATCHES	Maps and Tables of Climate Hazards on the Eastern Seaboard
MSLP	mean sea level pressure
NARCliM	NSW and ACT Regional Climate Modelling project
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCI	National Computing Infrastructure
NetCDF	Network Common Data Form
NOAA	US National Oceanic and Atmospheric Administration
NRM	natural resource management
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SME	subject matter expert
SPI	Standardised Precipitation Index
WRF	Weather Research and Forecasting model

3. Review of extreme climate events tools and databases

3.1 Introduction

Many of the most significant and earliest effects of climate change are being experienced through changes to extreme weather and ocean hazards, which can have severe impacts on NSW regions, including relatively common extremes that occur a few times a year on average, and rarer extremes with multi-year return periods.

Data on extreme climate events can be found on different types of information systems, ranging from simple web portals that provide nothing more than a link to a soft copy of a specific report through to virtual computers running on national mainframes. This report defines a 'database' as a large collection of data specially organised for rapid search and retrieval, and an information 'tool' as a user-driven piece of software specifically linked to a database that can be used to define and conduct the search and retrieve data from that database. This definition excludes the type of web portal (or sub-portal) that merely provides a link to a report and the wide array of purely code/software/algorithms/tools that are used in academic research.

Many of the information systems on extreme climate events are **tools/databases** that are built upon **datasets**. The work in this chapter therefore analyses the tool/database attributes of a given system, commenting on aspects such as the user interface, structure and accessibility. The dataset attributes have been covered in Chapter 2. The definition of dataset used in Chapter 2 includes (i) observational data, (ii) reanalyses, and (iii) data derived from Global or Regional Climate Models (GCMs or RCMs). Observational data sources include the Bureau of Meteorology (BoM) station and gridded products, satellites, tide gauges and wave buoys.

One of the challenges in the work was to clearly differentiate between systems that provided functionality on extreme **climate** rather than extreme weather. A number of information systems were identified that provided warnings of imminent extreme weather and associated risks. These were excluded from the research on the basis that their content was based on forecasts and not projections. Examples of this include BoM's Heatwave Service for Australia and the NSW Rural Fire Service's Fires near me web portal.

The global re-insurance industry is known to run sophisticated natural hazard tools/databases. Examples of this would be the CatNet® tool provided to clients of Swiss Re and Munich RE's NatCatSERVICE; however, these tools are not accessible other than through service subscription and could not be examined directly in this research. The research report *Catastrophe Modelling and Climate Change* published by the global insurance firm Lloyds of London examined the issue of how well the current generation of catastrophe models deal with climate change risks. The report stated:

> Climate change trends may be implicitly built into catastrophe models, given the heavy use of historical data in constructing them; however, these trends are not necessarily explicitly incorporated into the modelling output. Uncertainties associated with the estimation of the extent and frequency of the most extreme events means that the climate change impact can be difficult to account for in risk models.

And concluded:

> The catastrophe model case studies illustrate a wide range of approaches used in the industry. The impact of climate change is mostly not explicitly reflected in the catastrophe models, but all contributors note that any climate changes to date will be implicitly included in the recent data they use to create their models.

> Within a time horizon of much less than a decade an empirical recent databased approach appears sound, as natural variability is expected to dominate over the underlying trend. Nevertheless if longer time horizons are required then climate model projections will need to be more relied upon. These climate change projection based approaches are required for those making long-term commitments, for example, insuring or investing in infrastructure. The reduction of greenhouse gases remains an essential and urgent requirement to limit the risks and the inevitable cost of managing them.

This is evidence that these catastrophe models do include some projections of extreme climate events based upon recent observations, but not GCMs.

Chapter 2 identified that datasets relating to extreme climate events, both historical and future, can be of two forms: those that provide information specific to extreme events without further processing (e.g. incidence of East Coast Lows; Forest Fire Danger Index; count of days over a temperature threshold), and those datasets that would require further processing (e.g. extraction and analysis of relevant variables from ERA-Interim reanalyses to provide information on extreme events such as drought, or synoptic conditions conducive to East Coast Lows). Chapter 2 has termed these ‘Tier 1’ and ‘Tier 2’ datasets respectively. This chapter takes the same approach when discussing tools and databases. Subject matter experts engaged to support content in this chapter are listed in Appendix A.4.

The scope of the research includes the coverage of the seven separate types of extreme climate event as stated in the Overview, and Chapter 3 presents the findings on the type-by-type basis. It is noted however, that the more extensive and sophisticated information systems cover many (but not all) of the seven types of event types. These systems are:

- Bureau of Meteorology (BoM) web portal
- Climate Change in Australia (CCIA)
- NSW and ACT Regional Climate Modelling (NARCliM) project
- CLIMSystems – SimCLIM.

Section 3.2 provides an overview of these systems, and the types of extreme climate events they cover.

3.2 Findings for information systems of historical extreme climate events – BoM

The Bureau of Meteorology (BoM) is the lead organisation in Australia in the collection, processing and dissemination of climatic information in the form of weather forecasts. It has a key role in the national infrastructure and many of its activities are closely integrated into both Commonwealth and state government functions. Its extensive and detailed observational records of historical weather events are a very important component of Australia’s capability to manage climate variability and change. This report includes a review of the BoM website to the extent that it provides tools/databases of observed historical extreme climate events. One advantage of the observations is that they can provide information on complex and synoptic-scale extreme events such as thunderstorms and lightning that may not be well-represented in climate model simulations.

The BoM website is Australia’s top tier information system on weather and overall water availability and the primary point of access to detailed databases of historical records of hundreds of types of climatic and geophysical variables and all types of extreme climate events for which observational records exist. It is funded by the Australian Government, developed and maintained by BoM, presented in English, free to access and specific to the Australian mainland and Tasmania, with links to global weather information systems. As weather information is used by all of Australian society, the website is extensive with a very detailed architecture, embedded tools and high quality graphical and database functionality.

The BoM website is under copyright with some provision for Creative Commons use but with an extensive number of caveats and conditions attached. These include limitations on any commercial use. Additional access and licence agreements can be made with BoM for application outside of its default terms of use. There is an extensive free-of-charge facility for directly downloading data either in graphical files or file formats compatible with spreadsheet use. In addition to the free and immediate download function there is also a data-on-request service where fees apply to cover the cost of BoM staff extracting the data. (Tested in the research by initiating a request for a dataset of 17 years of minute-by-minute wind speed from East Sale, Victoria.)

The areas of content on the BoM website of direct relevance to this report are State of the Climate, Climate Data Online, Climate change – trends and extremes, Drought and the Severe Storms Archive. It is noted that the web architecture has these interlinked. The content of *State of the Climate* is linked directly to the text report of the same title and presents the information and analysis on the key aspects of climate change and the observations up to the end of the previous calendar year. As it is neither a tool nor a database it is not commented on any further here.

The functionality of *Climate Data Online* is based on the dataset Australian Data Archive for Meteorology (PDF 446KB) (ADAM) and allows users to search for and download datasets for rainfall, air temperature and solar exposure as far back as the records exist for either a point location (BoM station) or area. The content of *Climate change – trends and extremes* is extensive and allows the user to define and download datasets, design and display trends, filter for extreme climate event by duration, frequency and intensity. As the key variables are temperature and precipitation, the database is able to provide information on most types of extreme climate events either directly via an editable search or by downloading datasets and subsequent processing. The content of *Climate change – trends and extremes* does not cover aspects such as unstable weather (covered by the Severe Storms Archive, see below) or bushfire and fire weather.

The functionality of *Drought* is confined to the provision of an archive of monthly drought maps consisting of national coverage at (0.05° resolution) of short and long-term monthly rainfall deficiencies, and lower level (10–100 cm) soil moisture. These maps cover the period 1900 to the present day; in three-month periods up to 12 months, then in six-month intervals up to 48 months. The maps are licenced under Creative Commons and are available as images only with no access to the underlying databases.

The Severe Storms Archive allows users to select from a database of storm types covering: rain, hail, wind, tornado, lightning, waterspouts and dust devils. The information content not only covers climatic metrics such as rainfall duration and intensity but also socioeconomic metrics such as number of deaths, damage total quantity of insurance pay-outs. The dataset generated can be downloaded in a spreadsheet compatible file format.

The BoM system does not appear to have any tools or direct functionality relating to compound or coincident events; however, it is noted that the extensive level of detail in the underlying datasets would allow this to be done as a separate data-mining activity.

3.3 Findings for information systems covering projections of multiple extreme climate event types

3.3.1 Climate Change in Australia (CCIA)

The CCIA web portal is Australia’s top tier information system on climate change and most types of extreme climate events, covering both future projections and historical climate. It is funded by the Australian Government, CSIRO and BoM. It was developed and is maintained by CSIRO, presented in English, free to access and specific to the Australian mainland and Tasmania. The CCIA research and website was guided by a user panel and has been designed for the natural resource management (NRM) stakeholders. The regional cluster classifications (see the case study below) reflect NRM regions with options to collate data by sub-cluster, by state and by specific location (typically BoM stations). The CCIA portal is maintained, enhanced and supported by training/webinars through Project 2.6 of the National Environmental Science Program Earth Systems and Climate Change Hub, but resources are very limited.

CCIA has deep and extensive read-only content (50+ pages), encompassing training, guidance, a filterable database and a number of scenario building tools where the end-user can set up known system sensitivities (i.e. decrease in annual rainfall and increase in temperature) for a particular location and then search for the relevant climate projections and plausible futures. It also provides the user with the functionality to download both location/variable specific data points and area wide gridded datasets in a number of common file formats (spreadsheet compatible .csv format and NetCDF .nc format) and sizes (smallest only a few kB, largest download observed to be around 2MB).

The underlying datasets are built upon a suite of CMIP5 GCMs (selected for their 'skill' in simulating the Australian climate) combined with observed data using various statistical methods. An important feature of CCIA is that it encompasses the four emissions scenarios (RCPs) from the 2013 IPCC Fifth Assessment Report (AR5), which start to diverge around 2020. The databases cover historic values using both a 1986–2005 baseline (consistent with IPCC) and a separate time series baseline of 1981–2010 as well as future values, both as change factors and time series, out to the year 2100. The use of both historical and projection data is required to allow for changes to be expressed and to allow for the 'set-up' in a number of natural system models such as DairyMod. An example of the set-up would be a historical baseline of 30 years of temperature and precipitation input into a farm model that establishes the appropriate present day level of soil carbon and nitrogen prior to introducing future projected changes in those parameters.

When it comes to extreme climate events, CCIA has a number of specific tools and databases based primarily on two types of data, projected climate change data and application-ready data. The former is based on the data, at native grid resolution (nominally 150 × 150 km), from a suite of eight CMIP5 GCMs that have been shown to perform well for Australia, with projected regional changes spanning most of the changes from the full set of GCMs. The latter is based on a statistical modification, such as multi-quantile scaling for rainfall, of the projected changes with observed data at a resolution of 5 × 5 km; it is described as a synthetic future.

In terms of CCIA's functionality for extreme climate events from the projected data domain, it provides access to datasets that include extreme rainfall and wind speeds (expressed as a 1-in-20-year event) and extreme sea level rise ('caused by a combination of factors including astronomical tides, storm surges and wind-waves, exacerbated by rising sea levels'[5]), all on an annual area average basis.

The CCIA assembly of tools and databases has a number of limitations. These include:

- no search function for either text or numeric values
- a lack of downloadable datasets for certain climate variables such as rainfall at a station-by-station basis
- an inflexible/fixed structure of setting up the metadata for downloading data, e.g. the need to start back at each variable and repopulate the selector boxes makes data retrieval clunky and slow

[5] CCIA, Coastal and marine projections, 'Sea level allowances and extreme sea levels'

- users with requirements for larger datasets quickly reach the limitations of the download functionality
- no virtual machine, cloud-based functionality that would allow the large NetCDF datasets to be interrogated remotely
- legal and copyright constraints on the website and a lack of clarity over what data can be used for commercial or business research purposes
- the 'many truths' approach where the user is left to determine the most appropriate 'future' from the range of datasets provided – although this is more of a limitation for basic users. Guidance material is provided via the Climate Campus webpage
- the inability to address the increased demand for 'finer-scale' resolution that can deal with the observed variation in specific locations such as may be found on a farm or vineyard.

Extreme climate events

The CCIA assembly does include a specific functionality for accessing databases of certain types of extreme climate events. The database (analogous to a Tier 1 dataset described in Chapter 2) includes projected change values (relative to a 1986–2005 baseline) expressed on a seasonal basis (summer, etc.) for three different RCPs and four different time series, each of 20 years and centred on 2030, 2050, 2070 and 2090 for the following variables:

- coldest night and 1-in-20-year coldest night
- hottest day and 1-in-20-year hottest day
- wettest day and 1-in-20-year wettest day.

CCIA also includes tools that allow the user to define threshold levels and then both view the output from the database search graphically and download the dataset. The webpage instructions describe functionality for both temperature (max. and min.) and rainfall; however, at the time of writing only the temperature variables were accessible. For example, the annual number of days over 40°C can be calculated for over 400 sites for different combinations of years, emissions and GCMs.

Given the extent of the databases that CCIA is designed to access, the research concluded that it would be feasible to develop an understanding of a number of types of extreme climate events such as extreme rainfall, drought, heatwaves, bushfires and fire weather. It was noted that CCIA is able to provide information on drought on an annual areas average using the Standardised Precipitation Index (see discussion on drought definitions below). It may also be possible to analyse the databases to identify ECLs, sufficient data on daily atmospheric pressure exists, although it is understood this would require a specific type of tracking algorithm to be used (see the discussion on ECLs below).

The observation about the use of algorithms is important in the discussion of research gaps and directions. As climate datasets become ever larger and the types of searches become more specific, the use of virtual machines, cloud-based functions and code library resources will become more important.

The research identified that the CCIA information system does not include functionality within its tools/ databases for the following extreme climate events:

- unstable atmospheres
- wind gusts[6], coastal flooding and inundation
- compound or coincident events.

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[6] Functionality relates to maximum daily wind speed and 20-year return level of maximum daily wind speed.

CCIA case study – Extremes

The work on climate change adaptation planning carried out by a number of catchment management authorities in North Eastern Victoria provides an effective example of the use of CCIA that includes the consideration of extreme climate events. The published reports for the North-East Climate Ready Strategy[7] and the Climate Change Adaptation Plan[8] for the Goulburn Broken Catchment, both from 2016, made extensive use of temperature and rainfall data from the CCIA databases and NRM cluster reports. The reports include narrative on extreme climate event such as:

> Projections resulting in generally hotter and drier conditions, with increased frequency and intensity of extreme events: fire, flood, heatwave, drought.

However, without access to the underlying work it has not been possible to determine the extent to which the tools/databases on extreme climate events have been used.

This climate data was integrated into a spatial assessment tool and informed the exposure component of the assessment of the vulnerability of the natural resources.

3.3.2 NSW and ACT Regional Climate Modelling (NARCliM) Project

The NSW Government's Climate Data Portal, and the accompanying AdaptNSW website, all presented in English and free to access, is the primary information system on future climate change and most types of extreme climate events applicable to NSW and the ACT.

NARCliM was funded by the NSW and ACT governments and developed in conjunction with UNSW and multiple other agencies. The target end-users are those in the NSW and ACT communities attempting to plan for the range of likely future changes that will affect services such as state transport, water and emergency services. End-users were heavily involved in the design of NARCliM through stakeholder workshops and consultation. Many NSW public bodies were involved through being partners in the NARCliM consortium, or contributing funding, expertise and opinions to the design.

The portal presents a reasonable amount (15+ pages) of read-only content including an overview of the modelling approach, a description of the most commonly used meteorological variables (out of the 100+ contained in the overall datasets), an explanation of the concept of uncertainty, and links to technical reports. The copyright for NARCliM is one of Creative Commons Attribution; this applies to the datasets but not to any source code or the databases. In practice, this would allow specific datasets such as daily precipitation data to be copied and integrated in other applications, but it would not allow the applications to interact with the databases directly. NARCliM data are freely available via various avenues (e.g. the data portal serves data for selected variables in ASCII format, all variables are available from DPIE on request, and all data are freely available in NetCDF format).

At the core of the NARCliM system are the databases from three configurations of the Weather Research and Forecasting (WRF) RCM, with each configuration forced with output from four CMIP3 GCMs (MIROC3.2; ECHAM5/MPI-OM; CGCM3.1; CSIRO-MK3.0)[9] resulting in a total set of 12 simulations (four GCMs × three downscaling runs with different RCM configurations) for the time periods 1990 to 2009 (recent climate baseline), 2020–2039 (near future) and 2060–2079 (far future). The model selection process incorporated an

[7] North East Catchment Management Authority 2016, North-East Climate Ready Strategy

[8] Goulburn Broken Catchment Management Authority 2016, Climate Change Adaptation Plan for natural resource management in the Goulburn Broken Catchment, Victoria

[9] NARCliM model selection

assessment of model skill, model independence and the spanning of uncertainty in future climate changes. The IPCC SRES A2 (mid-range) emissions scenario is used.

A key function of the NSW Climate Data Portal for basic users is the interactive maps (with zoom functions) of projected changes, based on the 12 multi-model mean in the climate variables ‘temperature, hot days and cold nights, rainfall, and severe Forest Fire Danger Index (FFDI)’[10]. For more sophisticated end-users, the main functionality is the ability to specify metadata and then download the data (file size range from Kb to Gb), both site-specific and gridded, for a wide range of variables of direct relevance to the downstream data tools used in agriculture and water catchment management for individual NARCliM simulations. The relatively high resolution of the downscaled data (10 km) makes NARCliM very sophisticated from a climate impacts perspective. NARCliM also simulated the entire CORDEX Australasia domain at 50 km and the data from these simulations are available. This is potentially useful for comparing with the 10 km dataset to assess the benefits of higher resolution for simulating extremes.

While the NARCliM tool provides access to the databases of the climate variables at the surface level, additional databases of the same variables at different heights in the atmosphere are not available via the tool, but these data are available on request from NSW DPIE via email: climate.admin@environment.nsw.gov.au.

The NARCliM system has a number of limitations:

- The use of the single A2 (mid-range) emissions scenario from the 2007 IPCC Fourth Assessment Report has been superseded by the four RCPs used in the 2013 IPCC Fifth Assessment Report.
- The databases are based on GCMs from the CMIP3 generation and as such have been superseded by the more recent CMIP5 generation of models. Nevertheless, planners and decision-makers are using the NARCliM data (and the Tasmanian Climate Futures data), based on downscaling CMIP3 GCMs.
- The presentation of a 12-model ensemble, while reflecting good climate science, is conceptually challenging to users not familiar with the underlying principles and/or who lack literacy in probabilistic approaches to risk analysis. It is noted that the converse approach, of providing a value from the multi-model mean, can give misleading information for variables such as precipitation where the models do not agree in the sign, positive or negative, of the change.

Extreme climate events

The AdaptNSW website provides ready-made ‘snapshots’ and more detailed technical reports on changes in severe fire weather, hot days (>35°C) and cold nights (<2°C) that can be downloaded directly (Tier 1 type datasets). Due to its high spatial and temporal resolution, the NARCliM databases can be used, with further processing, to characterise the extent, frequency and intensity of many types of extreme climate events. These include:

- drought, extreme rainfall and snow[11]
- temperature extremes, heatwaves
- East Coast Lows
- fire weather.

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[10] NSW Climate Change Downloads

[11] Snow is considered as precipitation below a certain temperature threshold.

ETCCDI/ET-SCI

The Expert Team on Climate Change Detection and Indices (ETCCDI) and Expert Team on Sector-specific Climate Indices (ET-SCI) provide a set of consistent climate extreme indices associated with temperature and rainfall (see Section 2.2.3). Both the ETCCDI and ET-SCI have been calculated for NARCliM data using the climpact2 software and data are available by contacting DPIE via narclim@environment.nsw.gov.au.

The NARCliM information system is not capable of providing functionality on:

- unstable atmospheres
- wind gusts, storm surge and coastal flooding and inundation
- compound or coincident events.

These limitations were also noted for CCIA (see Section 2.2.2). It was noted that it was possible to obtain datasets of wind speed at 10 m above ground surface on an hourly time step but not 10-second wind gusts.

NARCliM case study – Extremes

This author had direct experience of data on extremes for temperature and rainfall being used by an Australian bank in the development of its strategic approach to managing climate change risk across its operations. The information used was in the form of the indices reports for precipitation[12] and heatwaves/ temperature[13]. The key insight the NARCliM data provided was on the relative difference in the frequency of extreme climate events for coastal and inland locations. This level of granularity was sufficient to allow the bank to understand that it could, in theory, implement risk weightings for certain types of lending based on the proximity to the eastern seaboard. It is not possible to provide any further details as they are commercially confidential.

3.3.3 CLIMSystems – SimCLIM

The SimCLIM software tool designed and distributed by the New Zealand company CLIMSystems is one of the few commercial climate data mapping and manipulating tools available. It is entirely commercial and requires a licence to use; commercial licences cost US$6997 and an educational licence is US$3374. The tools and operating manual are protected by commercial copyright. The SimCLIM product website describes the tool as providing functionality to perform:

- spatial scenarios (user chosen year, emissions scenario, climate sensitivity and GCM)
- site-specific scenario (given location, emissions scenario, climate sensitivity and GCM)
- site-specific sea level rise (with/without vertical land movement)
- site data (import, browse, analytics)
- extreme events (analytics, with/without climate change)
- supports ensembles of GCMs.

The SimCLIM system is known to have been designed for commercial end-users across the resource, planning and infrastructure sector. A number of large property companies and coastal councils in Australia are known to have had climate impact studies done by engineering consultancies using SimCLIM.

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[12] AdaptNSW, Floods and Storms

[13] AdaptNSW, Heatwaves

The website states that the underlying database has global coverage through the use of ‘all of AR5’ which includes:

- global included (0.5° × 0.5° or 50 × 50 km; sea level rise 0.25° × 0.25° or 25 × 25 km)
- all countries/regions/subregions available (resolution dependent on country area, most 1 × 1 km)
- specific countries with states available on request
- some continents available on request.

In terms of climate variables, the tool includes datasets of the monthly averages of:

- precipitation (mm)
- mean temperature (°C)
- minimum temperature (°C)
- maximum temperature (°C)
- on request – solar (W/m^2); relative humidity (%); wind speed (m/s).

The author of this report has had some insight into the SimCLIM system and this, along with anecdotal evidence from environmental consultants who have used it, led to the initial observation that SimCLIM is a ‘black box’ and that it may be difficult for end-users to achieve full transparency and traceability.

The key features of the tool are described as:

- AR5 – support for the four key representative concentration pathway scenarios: RCP2.6; 4.5; 6.0; and 8.5
- climate scenarios including minimum, maximum and mean temperature available with 40 GCMs to choose from and to apply in ensembles for virtually any place on Earth
- CORDEX Regional Climate Model (RCM) data available for nearly all the CORDEX regions of the world. Their inclusion with SimCLIM 4.0 supplements the 40 GCMs already available and can be used individually, as a group or combined with the GCMs in a master ensemble. The user has complete control over the mix of GCMs and RCMs that can be applied
- flexible Windows-based program that can apply a wide range of previously downscaled data at virtually any scale (local to global) so that ‘what if’ scenarios can be rapidly developed
- scientifically robust methods are applied that are based on IPCC guidelines, the latest climate science and an expert panel of advisors
- climate data are presented in formats that are easily understood and transparent
- downscaled data that are derived from virtually any statistical or dynamical method can be post-processed and added to SimCLIM so it can drive the generation of spatial scenarios as a member of a multi-model ensemble
- outputs can be exported to GIS programs such as ArcGIS and tabular data can be quickly exported to Excel for further analysis and graphing
- extreme daily precipitation analysis AR5 dataset now with 22 general circulation model patterns.

This information suggests that SimCLIM has some degree of interactive capability where user defined data can be added; however, overall it is not clear how the tool works with all of the extreme climate events that are the subject of this report.

3.4 Findings for extreme climate events by type

3.4.1 Rainfall-related extremes: extreme rainfall and snow, drought, flood

The research work in Chapter 2 identified extensive datasets on rainfall and drought both historical and projected. The scope of the work was to look at 'rainfall-related extremes'. This aligns with the definition of meteorological drought. In terms of tools and databases, BoM, CCIA and NARCliM were identified as being able to provide the main functionality for the rainfall-related extreme events, noting the limitations described in the relevant sections above. In addition to these, a number of other tools and databases were identified for examination.

It was noted that 'extreme snow' was something of a special case as it is not an extreme climate event in its own right, but the co-incidence of extreme precipitation below a certain temperature threshold.

The BoM tools and databases were able provide functionality on 'accumulated convective snowfall' through a specialist application of ACCESS-R:

> A number of raw and post-processed NWP products are available as outputs from the Australian Community Climate Earth-System Simulator (ACCESS) suite of Numerical Weather Prediction models which are run routinely by the Bureau National Operations Centre (BNOC).[14]

The NSW Government's Climate Data Portal housing NARCliM states that the models provide data on metrological variables including snow amount. While snow was not a variable listed in the guidance on what could be downloaded, snow data are available by emailing: climate.admin@environment.nsw.gov.au.

CCIA's Extremes data explorer tool does not cite snowfall as a variable.

While a number of tools and databases were found to provide functionality on the drought aspects of rainfall-related extreme events it is noted that drought as an extreme event is a vastly more complex topic than just the meteorological aspects. The scope of this work was to look at 'rainfall-related extremes' and consequently it has not been possible to assess tools and databases that may provide functionality on hydrological, agricultural and socioeconomic drought.

Australian Rainfall and Runoff

The Australian Rainfall and Runoff (ARR) information system is an extensive resource for a wide range of policy decision and infrastructure projects. The web portal, managed by Geoscience Australia, is free to access, presented in English and specific to the Australian mainland and Tasmania. The stated use of ARR is:

> the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:
>
> - infrastructure such as roads, rail, airports, bridges, dams, storm water and sewer system;
> - town planning;
> - mining;
> - developing flood management plans for urban and rural communities;
> - flood warnings and flood emergency management;
> - operation of regulated river systems; and
> - estimation of extreme flood levels.

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[14] BoM, ACCESS-R

The ARR system, originally established in 1987, underwent a significant upgrade in 2016 to incorporate advances in the understanding of rainfall runoff practices. It was also made publicly available and free of charge to use. The web portal and associated content is copyrighted to the Commonwealth and is under a Creative Commons Attribution licence.

The web portal provides access to published guidelines, software and data. The guidelines, A Guide to Flood Estimation, are available as an online reference or a downloadable document. These are extensive, consisting of nine books and numerous chapters. The topic of climate change is dealt with in Book 1, Chapter 6 and the coverage includes detailed examples of how to adjust expected flooding levels for climate change projections. The source of the climate data is referenced as CCIA (see Section 2.2.2); however, it is noted that the text states:

> Given the uncertainty in rainfall projections and their considerable regional variability, an increase in rainfall (intensity or depth) of 5% per °C of local warming is recommended.

And:

> Failure to account for potential climate hazards can lead to poor decisions, particularly when the exposure risk to climate change is medium to high. In these circumstances, a reasonable approach is to make a decision that is robust against a range of plausible futures. These futures can be obtained from the Climate Futures web tool. Where exposure to climate change and the consequences of failure of the asset of interest are high, more detailed local studies including the use of downscaling methods are recommended. This approach ensures a balance between standardising practice and allowing for the use of informed professional judgement.
>
> For consistency with the design rainfall IFD estimates in Book 2 the chapter is intended to be applied to the design event (i.e. the design standard for the structure or infrastructure). It is applicable for rainfall intensities under the current climatic regime within the range of probability of one exceedance per year and 50% to 1% AEP. Other mechanisms that affect the magnitude of flooding, such as tailwater levels and oceanic processes (e.g. wind, waves and tides) are not considered.

From this it would seem that the ARR tools do apply climate change factors, on an average trend basis, to the databases of current rainfall exceedances; however, ARR does not appear to make use of data specific to extreme climate events to project exceedance levels over defined future periods. It has a rather mixed functionality with historical events addressed but projected events only partially considered.

Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)

The Australian Government Department of Agriculture and Water Resources operates the national web-based information system ABARES that includes an extensive range of agricultural, environmental and economic data presented in English, free to access and specific to the Australian mainland and Tasmania. The content is designed for a range of users across the agricultural sector, farmers, suppliers, irrigators and produce agents. This content includes a number of pages relating to climate change and to measuring the effect of climate variability and change on agricultural industries. In terms of the extreme events associated with precipitation, the research did not identify any specific tools or database functionality. One tool, the Rainfall reliability calculator was examined but found to be classed as an experimental prototype. The initial information suggests it is being designed to generate information of extremes such as 1-in-100-year rainfall events, etc.

CLIMDEX Datasets for Indices of Climate Extremes

The CLIMDEX web portal was established and is maintained by the Climate Change Research Centre at UNSW under funding from the Australian Research Council. The portal is presented in English and provides free access to a number of datasets at around 2.5° x 2.5° resolution (250 × 250 km) derived by the reanalysis of historical climatic observations that have global coverage. The database is designed around 27 core extreme climate indices – 10 of which relate to types of extreme rainfall events (the other 17 relate to extreme temperature events). The system has no real functionality about downloads and seems designed for research use. The portal also includes a CLIMDEX software section; however, the links take users to a list of untitled code projects so it was not possible to assess the information system using the criteria established for this report.

3.4.2 Temperature-related extremes: extreme heat, heatwave

The principal information systems described above, BoM (historical) and CCIA and NARCliM (projected), provide the best examples of tools and databases for extreme heat events. A number of additional systems were examined – such as CLIMDEX and CORDEX – as they do include datasets that characterise extreme climate events; however, neither has any demonstrable tool or database functionality beyond access to some extremely large datasets.

3.4.3 Unstable atmosphere-related extremes: dust storm, thunderstorm, hail and lightning

Although some datasets exist (see Chapter 2), the research was not able to identify any tools or databases that provided functionality for unstable atmosphere-related events in the future. There is known to be some leading-edge research using fine-scale (>1 km) resolution models to project the behaviour of mesoscale convective systems. Initial work suggests that US thunderstorm events could become three times more frequent and with increased rainfall of between 40 and 80% by late in the 21st century (Prein et al. 2017)[15].

The research identified the BoM web portal as the primary tool for analysis of historical events relating to unstable atmospheres.

3.4.4 Wind-related extremes: wind gust, storm surge and coastal flooding/tidal inundation

CoastAdapt

Under funding from the Australian Government, the National Climate Change Adaptation Research Facility (NCCARF) developed the CoastAdapt tool. The web portal is free to access, set out in English, with no apparent copyright, and specific to the Australian coast only. Overall the system was designed to support local council planners, developers and infrastructure operators with the decision-making process and to provide a consistent set of information on the selection and application of sea level benchmarks for planning. The tools and databases were developed with extensive end-user consultation and feedback. The web portal presents factual information on the impact of climate change via sea level rise and links through to climate projections in both NARCliM and CCIA. It also provides links to a number of reports and research papers on a wide range of impact topics such as inundation and erosion, waves and water levels and coastal management.

CoastAdapt provides access to inundation maps for every local government area with a coastal aspect. These maps are available for the mean sea level rise only and are based on a simple 'bucket fill approach' for 2050 and 2100 and for two emissions scenarios, RCP4.5

[15] Prein AF, Liu C, Ikeda K, Trier SB, Rasmussen RM, Holland GJ and Clark MP 2017, Increased rainfall volume from future convective storms in the US, *Nature Climate Change*, vol.7, pp.880–884, https://doi.org/10.1038/s41558-017-0007-7.

and 8.5. The information presented is heavily caveated and specifically excludes the compounding events such as storm surges and extreme events from its functionality.

The text in the section *Sea-Level Rise and You* states that the portal provides information on climate extremes (temperature and rainfall); however, these datasets seem to only be those available from the CCIA extremes tool and are not linked to the sea level rise projections.

The website does direct users towards a more dynamic inundation tool at Coastal Risk Australia. This tool allows the user to select a coastal location and choose between ‘predicted’ inundation scenarios or manually adjust them for a sea level up to of 10 m above present day; this would allow a user with knowledge of extreme sea levels to acquire information about associated inundation. It is noted that although this tool uses a very simplistic approach and does not involve the complexities of wave dynamics, it does provide a powerful illustration of potential risks. Neither CoastAdapt nor Coastal Risk Australia provides functionality relating to wind gusts.

CANUTE – The Sea Level Calculator

The CANUTE tool was developed by the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC). The web portal is free to access, set out in English, copyright of the ACE CRC and specific to the Australian coast only. The full portal requires registration and training prior to use. The sea level rises calculations are performed using three Special Report on Emissions Scenarios (SRES) emissions projections, high (A1F1), medium (A1B) and low (B1). A footnote on the main webpage states that from August 2014 CANUTE can utilise data from the Fifth Assessment report emissions scenarios. An important feature of CANUTE is that it includes a wave setup and runup calculator and a shoreline recession calculator. The web portal also provides links to case studies[16] and relevant publications. The main function of the tool with respect to extreme climate events is that it can provide values for sea level rise events expressed as exceedance probabilities. Due to the registration and training requirements it was not possible to test the full functionality of the tool.

Australian Renewable Energy Agency – Australian Wave Energy Atlas

The wave atlas is a dataset that can be layered over the Australian Renewable Energy Mapping Infrastructure (AREMI) and is a searchable, free and publicly available online web atlas of Australia’s national renewable resources including wave energy, wind, solar, etc. The information is under a Creative Commons copyright arrangement. The wave energy database consists of detailed historical records of wave characteristics (energy, direction, height, etc.) as observed at sea. This includes data on return periods. The system does not appear to provide functionality relating to storm surges and wave action on coasts.

The same web portal provides access to tools relating to wind energy. The stated aim of these is to support renewable energy development. There is a specific dataset/microscale map for average wind speed at 100 m above ground level with a horizontal spatial resolution of approximately 1 km developed for the NSW Department of Industry by the engineering consultancy DNV GL. The website provides a detailed description of the approach:

> The wind atlas provided here was generated using the DNV GL Wind Mapping System (WMS). The WMS is a dynamical downscaling system developed to generate high-resolution mesoscale wind maps for any part of the world. It represents the culmination of two decades of research and development, and combines the following two key technologies to generate ensemble downscaled time series over the area of interest:

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[16] CANUTE – The Sea Level Calculator 2012, Example Case Study – St Helens Tasmania (PDF 2.5MB)

- The Weather Research and Forecasting (WRF) model; a state-of-the-art community mesoscale model that has been thoroughly documented in the open-peer reviewed literature.
- A well-validated, published, efficient ensemble downscaling technique based upon the 'analogue ensemble method'.

The database is extensive and allows users to download data files specific to locations and/or areas. The research was not able to identify specific functionality relating to extreme wind gusts.

Project UKKO – Seasonal Wind Predictions for the Energy Sector

Project UKKO was jointly developed by the UK Met Office and the Barcelona Supercomputer Centre and funded by the European Union. The purpose of the tool is to provide more accurate seasonal forecasts of wind energy to allow the energy sector to better manage and price its business activities. The web portal does allow access to a global wind energy map but the site does not seem to be fully functional and it was not possible to test it for its capability on extreme climate events.

3.4.5 Extreme East Coast Lows (ECLs)

An East Coast Low (ECL) is an extreme climate event characterised as a system of intense low pressure that forms off the eastern coast of Australia. The research identified a small number of tools/database that deal explicitly with the ECLs.

CoastAdapt

The CoastAdapt tool is fully described in Section 3.4.4 on wind-related extremes and coastal flooding above. This section describes the findings relevant to ECLs only.

The CoastAdapt webpages present factual information on ECLs in a subsection specific to 'Cyclones and East Coast Lows' contained within the Understanding the Impacts section of the portal. It describes the impacts of ECLs in generic terms and provides a link to a global climate change resource for the end-user to further explore the effects that a rising sea level may have in magnifying the impacts of ECLs. The climate change information is basic and has been sourced from the IPCC Fifth Assessment report. The content on ECLs is linked to the broader adaptation focus of the CoastAdapt tool; however, the core content of CoastAdapt (its coastal inundation datasets) specifically excludes aspects such as storm surges generated by extreme events such as ECLs from its functionality.

MATCHES – Maps and Tables of Climatic Hazards on the Eastern Seaboard

The MATCHES tool is a free access (requires registration), read-only web portal set out in English and was designed to be an historical database of extreme cyclonic events on the Australian east coast. The tool was developed by BoM and DPIE with the objective of providing easy access to information and data on variables such as wind speed, rainfall and wave height to a range of intended users such as staff in state emergency functions, utility operators and the general public. It is known from consultation with BoM that the portal was initially used in its testing and development by a range of public sector bodies (NSW RFS, defence, SES, DPIE, ambulance, police, Emergency Management, NSW Government planning). Subsequent to the testing, 40 individual access logins were provided to individuals from NSW universities, CSIRO, engineering/hydrology consulting, insurance/reinsurance companies, and a yacht charter company.

A key weakness of the tool is that it has not been updated since 2008 and consequently it does not contain any information on the ECLs that have occurred more recently. ECLs are an area of active research for BoM and there are datasets that contain far more recent information, but these have not been integrated into MATCHES or any similar tool.

The MATCHES tool is purely historical and has no functionality to apply climate change projections to the data. It is noted that research has been conducted by Pepler et al. (2016)[17] both on how the frequency and intensity of ECLs may change under climate change scenarios and on the potential impact of ECLs when coincident with other climate events such as severe thunderstorms.

3.4.6 Bushfire and fire weather

The primary tool and databases relating to bushfire and fire weather were identified as being accessed via the BoM website for historical data and forecasts (the Maximum Fire Danger Index Maps and data catalogue). CCIA provides annual/seasonal total FFDI averages and time series and the number of days of extreme fire weather (when FFDI exceeds 50) at 39 locations. NARCliM also provides projections of the Forest Fire Danger Index. These are covered in Section 3.3.2 above.

The research identified a number of web-based information systems relating to detecting bushfires and quantifying burn areas. These include:

- Geoscience Australia – Sentinel Hotspots tool
- North Australia and Rangelands Fire Information Service – Savanna Burning Abatement Tool.

It was concluded that both of these tools deal with current and/or recent fire events and had no functionality specific to extreme climate events. The Sentinel Hotspots portal provides functionality for searching and retrieving historical records (tested in this research back to 2002). The historical data includes fire event location, temperature and fire 'power'; it may be possible to perform analysis on this data to identify extreme fire events.

3.4.7 Compound or coincident events

The research was not able to identify any tools or database specific to compound and coincident events. It was noted that extreme climate events are known to occur due to a combination of antecedence conditions such as recent heavy rain and a king tide and ECL. Many of the databases identified in this research, in particular those based on high resolution historical data and/or modelling, could be statistically analysed to identify compound or coincident events.

3.5 Conclusions

Through a combination of desk-based research and structured interviews with subject matter experts, a number of tools/databases of extreme climate events appropriate to NSW were identified. Although a number of these were well-structured and provided access tools that allowed the users to search extensive databases, none of them covered all seven types of extreme climate events of interest to NSW DPIE. Historical observations of extreme climate events were well covered by the BoM tools/databases, with the exception of compound and coincident events. Projected extreme climate events relating to temperature, rainfall and drought were well served by a number of tools/databases. The scope of this work was to look at 'rainfall-related extremes' and consequently it has not been possible to assess tools

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[17] Pepler AS, Di Luca A, Ji F, Alexander LV, Evans JP and Sherwood SC 2016, Projected changes in east Australian midlatitude cyclones during the 21st century, *Geophysical Research Letters*, vol.43, pp.334–340, DOI: 10.1002/2015GL067267.

and databases that may provide functionality on hydrological, agricultural and socioeconomic drought.

The tools and databases examined included Climate Change in Australia (CCIA; Section 3.3.1) and the NSW and ACT Regional Climate Data Portal (NARCliM; Section 3.3.2). Other types of extremes such as East Coast Lows (ECLs), coastal inundation and fire were partially served in these tools/databases. The more complex and dynamic types of extreme events as associated with unstable atmospheres (hail, lightning, storms), and compound/coincident events, are not served by any of the tools examined.

A number of key themes were observed:

- A number of the tools/databases were initially developed/deployed but then not continued/ maintained. This includes Maps and Tables of Climatic Hazards on the Eastern Seaboard (MATCHES; Section 3.4.5), CoastAdapt (Section 3.4.4), and the Australian Bureau of Agricultural and Resource Economics and Sciences, Rainfall Reliability Indicator (ABARES; Section 3.4.1).
- In terms of functionality, the tools/databases examined provide two options. Either the end-user could perform basic search and view then download relatively small parts of a larger overall dataset, or the user could request the much larger dataset (e.g. both CCIA in Section 3.3.1 and NARCliM in Section 3.3.2).
- None of the systems identified allowed users to define more sophisticated metadata and run data retrieval for that metadata on virtual machines, as may be required if, for example, a superannuation fund was seeking to identify projected levels of water stress for different types of farming systems for a number of different locations across Australia.
- Climate change is a science of probabilities where the metrics describe a range of plausible futures; however, with the exception of CCIA (Section 3.3.1) none of the tools addressed this key underlying concept, even though it is critical to the characterisation of the physical risks.
- The treatment of probability may be a particular issue for the SimCLIM tool (Section 3.3.3), where a large range of GCMs and other datasets seemed to be given equal weight.
- As climate datasets become ever larger and the types of searches become more specific, the use of virtual machines, cloud-based functions and code library resources will become more important.

A.4 Subject matter expert commentaries used in Chapter 3

Table 3.1 Subject matter experts consulted for the Chapter 3 findings

Name	Organisation	Relevant section(s)
Dr Hamish Clarke	University of Wollongong	3.4.6
Mr John Clarke	CSIRO	3.3.1, 3.4.2
Prof. Jason Evans	University of NSW	3.2, 3.3.1, 3.3.2, 3.4.1, 3.4.2, 3.4.4
Dr Felicity Gamble	Bureau of Meteorology	3.4.4
Prof. David Karoly	University of Melbourne/CSIRO	3.3.1
Dr Dewi Kirono	CSIRO	3.2, 3.3.1, 3.3.2, 3.4.1
A/Prof. Todd Lane	University of Melbourne	3.4.1, 3.4.4
Dr Chris Lucas	Bureau of Meteorology	3.2, 3.4.6
Dr Kathleen McInnes	CSIRO	3.4.4, 3.4.7
Dr Acacia Pepler	Bureau of Meteorology	3.4.4
Prof. Seth Westra	University of Adelaide	3.4.1, 3.4.7
Dr Nick Wood	Lucsan	3.3.2, 3.3.3