DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

NSW Climate Extremes Baseline Assessment

Summary report

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Cover photo: Western sunset, observing the wildlife on the grass plains of Sturt National Park. John Turbill/DPIE.

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Executive summary

The climate of New South Wales (NSW) is highly variable and changing. Climate change will increasingly affect the environment and society in every part of the state. Changes in extreme climate events are already being observed; for example, heatwaves, heavy precipitation and severe bushfire conditions have become more frequent and more intense.

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 (DPIE 2020). 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.

This document is a summary of the full DPIE report (DPIE 2020), which includes three major chapters:

- 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 chapters were informed by conversations and correspondence with a set of subject matter experts (SMEs) in the science of extreme climate events (see Appendix A). The full report included outcomes from a workshop in Sydney on 19 February 2018 attended by 22 SMEs. Table E.1 below summarises the findings from the report and the workshop, including high (bold font) and medium/low priority research themes.

DPIE Climate Research priorities identified by the climate research community listed in Table E.1 are being investigated as part of the projects on regional climate modelling, natural hazards and climate change impacts on critical infrastructure.

Data and information needs for climate extremes cannot be solved by scientific research advancements alone. Two other priorities identified in this extremes baseline assessment for the climate science community, including DPIE, are:

1. further development of application-ready datasets
2. better user support to understand the research, access the data, and apply tools and databases in risk assessments.

Further development of application-ready datasets

When delivered in a format that is fit-for-purpose (e.g. GIS layers, site-specific values, maps), climate data can be used directly in impact assessments that inform adaptation planning. While a significant range of application-ready data are available, they are not always fit for purpose and the databases and tools that provide access to the data generally have limited functionality (see full report, Chapter 3). None of the databases and tools reviewed allow users to define more sophisticated metadata and run associated data retrieval on virtual machines.

NSW needs to expand the range of available extreme climate data (e.g. hail and compound events), improve accessibility and guidance material, and provide data tailored for specific needs (e.g. an extreme heat index that combines temperature and humidity). 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 (see full report, Chapter 3).

DPIE are aiming to improve climate information related to climate extremes and hazards under multiple future climate projections using a diverse range of climate indices. This project incorporates climate measurements, enhanced climate projections (NSW/ACT Regional Climate Modelling version 1.5 (NARCliM1.5)), and other climate datasets. The newly developed data and accompanying analyses will be formatted according to user needs, acquired through extensive and long-term stakeholder consultations. Expanding the existing NSW Government Climate Data Portal to include additional application-ready data, guidance material and ways of accessing data is under consideration.

Better user support to understand the research, access the data, and apply tools and databases in risk assessments

Research and development of user-support services requires a clear understanding of a broad spectrum of user needs. This involves a dialogue between researchers and stakeholders to establish the context (e.g. climate-sensitive management decisions) before identifying and analysing risks, evaluating and applying management options, and monitoring and evaluating the outcomes. Support mechanisms for accessing climate extremes data and information must be flexible to suit a variety of user expertise types.

Better user support could contribute to more efficient and effective use of the data and tools on extreme climate events in impact assessments across a wider range of end-users, and greater potential for science to influence decisions that build resilience to climate extremes. Such support services could include guidelines on how to use projections in impact assessments, case studies, fact sheets, face-to-face training, online training, webinars and videos, and help desk services.

DPIE already has significant knowledge brokerage capabilities, but recognises the need to provide ongoing support on extreme climate events for climate risk assessments aimed at building the resilience of NSW to natural hazards. DPIE offers support for bespoke and tailored data requests for NARCliM regional projections and other climate data or information. DPIE is investigating a formal support service in conjunction with an evaluation of current data service delivery practices.

Table E.1 Summary of research challenges, priorities and associated benefits to NSW

Research themes in bold are regarded as high research priorities based on engagement with SMEs and the February 2018 workshop outcomes. Research being undertaken by DPIE that addresses the recommended research topics is highlighted with *italicised font*. Acronyms are expanded in Appendix B.

Research theme	Gaps and challenges	Recommended priority research topics	Benefits of research to NSW
Extreme rainfall and flooding	Extreme (sub-daily/ sub-hourly) rainfall is poorly represented in projections.	• *Develop finer resolution (less than 4 km) convection-permitting models to improve representation of sub-daily rainfall and regional phenomena (e.g. East Coast Lows)* • *Make use of more Global Climate Model (GCM) ensemble members when downscaling for improved extreme events analysis* • Develop statistical regression relationships based on the large-scale climate to identify precipitation extreme hotspots	Extreme rainfall and associated flooding events in NSW can cause extensive damage to the built and natural environments, and loss of life and productivity. Better characterisation of extreme rainfall and flooding would enable improved resilience of NSW infrastructure that is water sensitive, better emergency management, and more efficient risk pricing.
Drought	Current generation of GCMs are not able to accurately hindcast the duration and intensity of Australian droughts.	• Better understanding of causes and terminations of droughts • *Time/space evolution of drought events* • Integrated databases for droughts (e.g. satellite, land observations, paleoclimate data) • *Integrate more variables for drought analysis (e.g. runoff and soil moisture)*	Mitigating the impacts of future droughts on communities and agriculture would be of benefit to NSW. Documentation or data about drought impacts or sensitivity could help towards the development of socioeconomic-environmental drought assessments, which would be more relevant to the wellbeing of NSW communities than assessments based on a lack of rainfall alone.
Hail and thunder-storms	There are no reliable thunderstorm and hail projections.	• Improved quality assurance of radar data for improved evaluation of modelled hail • *Investment in microphysics evaluation and model development to better capture thunderstorms, convective cells and hail processes at finer resolution (e.g. 1 km).*	Thunderstorms and associated hazards (e.g. hail storms) can result in severe impacts in NSW and are of importance to many sectors, including insurance, health and emergency services. Evaluating and improving thunderstorm microphysics within climate models may ultimately reduce uncertainties in projections of associated hazards.

Research theme	Gaps and challenges	Recommended priority research topics	Benefits of research to NSW
Greater accuracy & reliability of projections	Projections struggle with poor representation of some extreme weather and climate, especially rain, drought, hail, wind gusts, storms, lightning and waves.	• Reduce underlying biases of GCMs for large-scale phenomena that influence local climate (e.g. ENSO) • *Use finer resolution model simulations to reduce the number of required parameterisations at coarser resolutions* • *More robust methodology for model design for reduced computation resource usage, model independence and fit-for-purpose* • *Participate in international modelling efforts for consistent model design and outputs* • *Leverage/coordinate other regional downscaling projects within Australia*	A more complete characterisation of the projected intensity, frequency and duration of extreme climate events is a fundamental requirement to the design of a range of physical, social and financial responses.
Compound and coincident events	Very little is known about the future compounding and/or coincidence of extreme weather/climate events and other non-climatic risk factors.	• *Review ecosystem of frameworks, methods, tools, datasets and expertise for compound and coincident events* • *Approaches for developing scenarios for system stress testing concepts* • *Review and assessment of historical and potential future combinations of drivers/ hazards, and the extent to which current modelling systems/ products can represent these combinations*	Improved understating of how weather and climate drivers and/or hazards translate to societal and/or environmental risk.
Developing 5–20-year predictions	There are limited climate predictions (i.e. observationally constrained assimilated models) over the next 5–20 years, initialised by observed data, especially for various types of extreme climate events.	Further investment into predictions for 1–10-year business plans	Seasonal to annual forecasts would benefit short-term planning strategies for health, and hazard preparedness, such as bushfires. Predictions are also valuable for evaluation of climate risks in short-term investment decisions for both the public and private sectors.

Research theme	Gaps and challenges	Recommended priority research topics	Benefits of research to NSW
Extreme wind gusts	Projections for seasonal and daily average wind-speed have an insufficient temporal resolution for capturing wind gust patterns.	*Model projections including maximum daily wind gusts and sub-daily wind speed*	Better characterisation of the future incidence of extreme wind gusts informs resilience planning, especially for emergency management, transport and energy supply.
Waves – linked to East Coast Lows	Recent events in the Sydney northern beaches indicate that future changes in wave direction associated with ECLs requires further study.	Improved understanding of how tides, storm surge and regional sea level variations combined result in extreme sea level events and coastal floods	Improved information would assist across a range of activities such as coastal defences, planning, infrastructure costing and the availability of insurance.
Synoptic systems	Extreme weather events are often driven by changes in synoptic-scale systems, but these systems are poorly simulated by climate models.	*More research is required to improve 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 and larger-scale models of variability)*	Improved representation of these synoptic systems in models will allow better projection of extreme events and better planning for resilience.
Heat and humidity in a comfort index	Heatwaves are a significant human and animal health issue, and impact domestic budgets via energy costs.	*Projected changes in a comfort index associated with heat stress*	Better information about heat stress will guide city planning, health systems, energy systems, building design, and adaptation to major climate events associated with temperature extremes.

1. Introduction

The climate of New South Wales (NSW) is highly variable and changing. Climate change will increasingly affect the environment and society in every part of the state. Often, this will be through extreme climate events. Changes in extremes natural hazards are already being observed; for example, heatwaves, heavy precipitation and severe bushfire conditions have become more frequent and more intense (see DPIE (2020), Chapter 1).

The NSW Government has been investing in new scientific research to understand and respond to the local impacts of climate change in NSW. This knowledge has helped local government, business and the community build resilience towards future extreme climate events.

The NSW Department of Planning, Industry and Environment (DPIE) has led much of this effort and is currently working to catalyse research on climate extremes that will ultimately support NSW Government policy directions outlined in the NSW Climate Change Policy Framework (OEH 2016): (i) reduce risks and damage to public and private assets in NSW arising from climate change, (ii) reduce climate change impacts on health and wellbeing, and (iii) manage impacts on natural resources, ecosystems and communities.

DPIE Climate Research has designed, delivered and supported major projects on regional climate modelling through the NSW and Australian Capital Territory Regional Climate Modelling (NARCliM) project, East Coast Lows, finer resolution modelling over Sydney and the Australian Capital Territory (ACT), and several cross-disciplinary projects associated with climate dynamics, health, transport, energy, infrastructure and vegetation across NSW. DPIE is a major partner in the Australian Research Council's Centre of Excellence for Climate Extremes (CLEX), and has partnered extensively with corporate, industry, government and research organisations to investigate drivers behind major climate impacts in NSW and develop climate data and information for the wider public.

Over 2018–2022, DPIE Climate Research will focus on updating and enhancing regional climate projections, develop spatial maps and tools that depict how natural hazards will evolve under various climate futures, and identify climate risks to critical infrastructure.

In 2017, DPIE commissioned a project on defining a baseline for climate research on extreme events, and associated datasets, tools and databases. This summary report draws on the findings of the DPIE (2020) report, and the associated subject matter expert (SME) workshop, summarising findings related to research on the following seven extremes types:

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.

Section 2 of this document summarises the current scientific research on climate extremes, Section 3 summarises the available datasets, and Section 4 the available tools and databases, for climate extremes data and information. In conclusion, Section 5 summarises priorities for research on climate extremes that are being investigated by DPIE. Nomenclature is provided in Appendix B.

2. Review of extreme climate events research

Summary

Chapter 1 of the DPIE (2020) report is a concise review of findings from climate extremes research. The focus of the literature reviewed 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, and projected changes from Global Climate Model (GCM) and downscaling simulations of the future climate, rather than shorter time scales (seasonal-to-decadal variability) or much longer time scales of palaeontology. Literature is summarised with a focus on the overarching conclusions of recent studies for NSW and Australia, as well as globally in some cases.

Knowledge and research gaps for extreme types

We have some understanding of past changes in extreme events, while also noting that observations have some limitations such as containing few events of the scale that cause major disasters. Similarly, modelling the extreme events that cause major disasters also has significant limitations, given the complexities and spatio-temporal scales of the processes that can cause these events to develop. Consequently, there are some significant knowledge and research gaps, including uncertainties about future changes in drought and flood risk; tornadoes, hail and lightning; dust storms; extreme wind gusts, and compound or coincident events. Table 2.1 summarises the literature for the seven extreme types listed in Section 1.

Table 2.1 General summary of the literature reviewed on the influence of climate change on weather and climate hazards

Further details can be found in the (DPIE (2020) report, Chapter 1) and references therein.

Extreme weather and climate events	Summary of climate change influences
Rainfall: extreme rainfall, flood, snow and drought	High confidence of an increase in wettest day in a year and wettest day in 20 years. High confidence in less snow cover (decrease in fall and increase in melt). High confidence that the time spent in rainfall-related drought will increase in southern Australia. Larger uncertainties for other types of drought and 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. Large uncertainties exist in changes and trends of tornadoes, wind extremes, hail and lightning, and 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 (particularly during winter) but potentially more intense ECLs and associated severe weather impacts, including potential increases in the intensity of associated extreme rainfall.

Extreme weather and climate events	Summary of climate change influences
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.

Priority research directions

Outcomes from SME consultations and the literature review presented in Chapter 3 of DPIE (2020) were used to identify priority directions for climate research associated with the seven focus extreme types listed in Section 1 above. The following is a list of 12 identified priorities for future research on extreme climate events (those in **bold** were considered to have the highest priority). A summary of the priorities is provided in Table E.1 in the executive summary.

An expanded summary of research directions and benefits for NSW for the five high priority themes is included below. Research tasks in the expansion of the five high priorities items below that align with DPIE's research direction over the 2018–2022 period are denoted by a double asterisk (**).

1. **Extreme rainfall and flooding**
2. **Drought**
3. **Hail and thunderstorms**
4. **Greater accuracy and reliability of projections**
5. **Compound and coincident events**
6. Developing 5–20-year predictions
7. Unstable atmosphere: storms and lightning
8. Extreme wind gusts
9. Better functionality of existing tools and databases
10. Waves
11. Synoptic systems driving weather extremes (e.g. ECLs)
12. Heat and humidity in a comfort index.

Marine heatwaves and aerosols were also identified as priorities, but these were not within the extremes baseline assessment for NSW project scope.

1. Extreme rainfall and flooding

Extreme rainfall and associated flooding events can cause extensive damage to the built and natural environments, as well as loss of life and productivity. Better characterisation of extreme rainfall and flooding would enable improved resilience of NSW infrastructure, better emergency management, and more efficient risk pricing. Research priorities are to:

- ****improve understanding, and model representation, of regional-scale phenomena that cause daily precipitation extremes** (including ECLs, thunderstorms and fronts) for better projections of extreme rainfall over daily durations. This includes gaining better insight into physical processes and dynamical drivers, evaluating modelling and computing capacity, and using quality measurements where possible.
- ****develop convection permitting model resolutions (less than 4 km) for projection of extreme rainfall over sub-daily durations** (minutes to hours) which are often

associated with small-scale features of thunderstorms or convective cells embedded within other regional-scale phenomena like ECLs. Li et al. (2017) demonstrated how 2 km climate model simulations of Greater Sydney could be used to provide information on future sub-daily rainfall events; however, such simulations have not yet been used to generate climate projections for NSW and it is unclear precisely what improvements to the existing projections an ensemble of simulations might bring and how one should be designed to maximise benefits.

- ****develop projected changes in rainfall Intensity–Frequency–Duration (IFD) curves**, which are used in event-based flood estimation and are a vital input to the design of water sensitive infrastructure and flood risk assessments. The Australian Rainfall and Runoff Handbook (Ball et al. 2016) provides IFD curves but uses a simple 'rule of thumb' to estimate projected changes. Further research is needed for a better understanding of antecedent soil moisture conditions, changes in the sequencing of rainfall events, and coincidence of river flooding and coastal inundation.

2. Drought

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 loses from agriculture. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BoM) indicated a projected increased risk of drought in eastern Australia, including an increased amount of time spent in drought and a greater frequency of severe droughts (CSIRO & BoM 2015).

Drought projections often give information on meteorological drought. Meteorological drought is characterised by a lack of rainfall; it takes no account of other factors, such as soil moisture, which may determine how impactful this is to agriculture and other water-sensitive activities. It is therefore a 'partial' definition of drought in terms of climate impact (e.g. Kiem et al. 2016). Drought is an area of concern in climate modelling. Models do not reproduce long severe droughts such as the Millennium Drought and have limitations in their ability to represent rainfall teleconnections and El Niño Southern Oscillation (ENSO) in some regions including NSW (Watanabe et al. 2012).

Drought focused research directions are as follows:

- **better identify causes of drought** by understanding the roles played by large scale climate modes, land–atmosphere feedbacks, climate change and human interference (e.g. land-use change, water extraction)
- ****better understand the evolution of drought in space and time, and the processes involved in the termination of drought**
- **integrate traditional databases (e.g. land observation) with other emerging datasets (e.g. satellite, paleoclimate data) for drought analysis**
- ****integrate multiple variables for defining and analysing drought** (e.g. soil moisture and runoff).

3. Hail and thunderstorms

Understanding hail and thunderstorm patterns is of importance to many sectors, including insurance, health and emergency services. Thunderstorms hazards can result in severe impacts in NSW, including loss of life, damage to property and disruption to power networks. Severe thunderstorm events such as the Sydney hail storm of 1999 rank among the most expensive weather events ever recorded in Australia in terms of insurance losses (Coleman 2002). Evaluating and improving thunderstorm microphysics within climate models could reduce uncertainties in projections of associated hazards.

The recommended research required to improve the projections of extreme hail events includes both model development and improvement in quality assurance of measurements:

- investing in BoM radar data to **properly calibrate and quality control the NSW radar archive** to provide the high-quality data necessary to evaluate model simulations of hail and long-term investigation of these datasets
- ****investing in microphysics evaluation and development (and diagnostic parameterisations) for use by high-resolution downscaling models and convection-permitting models**. This would use the radar data for evaluation purposes. Such development and evaluation should be completed before investing in another downscaling effort like NARCliM. This approach would prevent the risk of running downscaling experiments with parameterisations and parameterisation settings that would not be ideally suited to analysis of hail risks.

4. Greater accuracy and reliability of projections

Reliability stems from the degree to which models include processes based on established laws of physics, simulate regional-average climatic patterns, and simulate past changes in climate. Climate models include most of the key large-scale processes and are designed to represent climate averages and trends and correctly simulate sequences of events such as the progression of maximum temperatures in a particular month. They should be able to simulate 30-year average climate statistics with reasonable accuracy (e.g. summer average temperature, winter average rainfall). They are not expected to correctly simulate the sequence of maximum temperatures in a particular month and year (e.g. during April 2047).

Climate models will always have a range of uncertainty; this is made up of a number of contributing factors such as the effect of future forcing and systematic and numeric biases in the models themselves. Greater accuracy and reliability requires improvements in some specific aspects of climate modelling. Identified research priorities are to:

- **reduce underlying biases in GCMs**, such as the western Pacific cold tongue bias that affects the simulation of ENSO, which has implications for NSW climate extremes (e.g. greater flood/storm risk in La Niña years). This requires better understanding and simulation of physical processes at temporal and spatial scales relevant for extreme events
- ****reduce errors associated with parameterisations** by using spatial resolutions that do not require such parameterisations (e.g. convective-permitting models with less than 4 km resolution, which also allow better representation of surface and orographic features). Using higher resolution will require more computing power and storage
- ****reduce errors/biases inherited by regional climate models from the boundary conditions provided by GCMs**. These biases can be reduced in some cases by applying bias correction techniques to the boundary conditions before running the regional model, while noting that some underlying limitations of GCMs may still remain after bias-correction (e.g. limitations around simulating aspects of ENSO variability in some cases)
- ****develop more robust methods for designing model ensembles**. Methods would consider model independence (i.e. the degree to which different models have plausible but independent representations of key processes) to improve the information diversity in model ensembles. This is challenging because limitations in computer power and storage restrict the length and number of high-resolution model simulations needed for analysing extreme events. We also need methods to use these ensembles to provide probabilistic projections
- ****participate in an international modelling effort**, such as the Coordinated Regional Climate Downscaling Experiment (CORDEX), to provide coordinated multi-model experiments at convection-permitting resolutions over a series of common domains to estimate modelling uncertainty. This would allow a comprehensive evaluation of the

potential for improving extreme event simulations, and other aspects of climate such as land–atmosphere interactions, convective systems, and mountain or urban effects that are impacted by the improved representation of surface heterogeneities

- ****leverage/coordinate other downscaling projects within Australia**, such as the Climate Change in Australia (CCIA) downscaled projections using the Cubic Conformal Atmospheric Model (CCAM), the Victorian Department of the Environment, Land, Water and Planning (DELWP) downscaled projections using CCAM, the South Australian Goyder Institute statistically downscaled projections, the WA statistically downscaled projections using SIMCLIM, the Queensland downscaled projections using CCAM and the Tasmania downscaled projections using CCAM. There would be enhanced efficiency and effectiveness if a consistent approach was used for all downscaling across Australia, perhaps funded through a consortium of federal and state/territory government departments.

5. Compound and coincident events

Compound weather/climate events refers to multiple drivers and/or hazards that combine to contribute to societal or environmental risk.

Very little is known about the future compounding and/or coincidence of extreme weather/climate events and other non-climatic risk factors; however, the benefits for NSW of further understanding the likely impacts of compound and coincident events is significant. Compound and coincident extreme events research would contribute to planning for rare but potentially catastrophic climate-related events and could therefore contribute to mitigating the risk that future coincident events will have unforeseen negative impacts on critical societal and environmental systems in NSW.

Dependencies between drivers and/or hazards can make estimation of probabilities difficult. The risk of catastrophic impacts is often greater than a simple additive combination of the individual components.

It is unlikely we know about all combinations of drivers and/or hazards related to extreme climate events that could lead to risks to the NSW community in the future. Further, the extent to which available datasets provide reliable data on known damaging combinations of extreme event type is unclear. Observational datasets contain limited samples of rare coincident events and the processes governing the interaction between different types of event are not necessarily well-represented by models.

Addressing the challenge of compound/coincident events should recognise that:

- ****the identification of societal and/or environmental risks should act as a precursor to identifying which drivers and/or hazards could lead to extreme impacts**, placing greater emphasis on ‘bottom-up’ and ‘stress-testing’ approaches to risk assessments
- ****a review is needed to assess the ecosystem of frameworks, methods, tools, datasets and expertise** required to enable bottom-up and stress testing concepts to be applied in the context of understanding how weather and climate drivers and/or hazards translate to societal and/or environmental risk
- ****approaches for developing scenarios for system stress testing require observations, modelling outputs, and both weather/climate and system expertise**
- ****a review is needed to assess historical and potential future combinations of drivers and/or hazards that could lead to societal and/or environmental risk**, and an assessment of the extent to which current modelling systems and data products can represent these combinations.

3. Review of extreme climate events datasets

Summary

Chapter 2 of the DPIE (2020) report summarises the datasets available for research into extreme climate events in New South Wales (NSW) and identifies gaps where extreme event data requires expansion and development. The reviewed datasets include (i) observational data, (ii) reanalyses, and (iii) data derived from GCMs or Regional Climate Models (RCMs). Observational data sources include station and gridded products, satellites, tide gauges and wave buoys. Reviewed datasets suitable for different types of extremes are summarised in Table 3.1.

Updates and improvements are ongoing for key datasets including: GCMs being developed under Coupled Model Intercomparison Project Phase 6 (CMIP6), RCM datasets being enhanced in NARCliM1.5 in 2020, and reanalyses through the European Centre for Medium-Range Weather Forecasts Reanalysis and the BoM Atmospheric high-resolution Regional Reanalysis for Australia (BARRA). Interviews with SMEs indicated there is a strong willingness for collaboration that facilitates the use and sharing of datasets.

Datasets that provide information on extreme events directly without further processing (e.g. incidence of ECLs; count of days over a temperature threshold) are summarised in Table 3.2. An example of a dataset requiring further processing would be an extraction and analysis of relevant variables from a reanalysis dataset to provide information on extreme events such as drought, or synoptic conditions conducive to ECLs. With some exceptions (e.g. NARCliM and CCIA), many of these datasets contain data that characterises the intensity, duration and frequency for only one or two extreme event types and few provide direct information on coincident or compound events. 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. For example, longer timescales would be required to adequately characterise many types of extreme events and coincident/compound events.

Knowledge and research gaps

Despite the wealth of existing datasets and ongoing activities to update and improve these, there remain several challenges for extreme event datasets, namely:

- the underlying utility of existing projections to provide robust and reliable information
- accessibility of datasets to end-users, especially those unfamiliar with the data formats used by climate scientists
- lack of climate services to support the uptake of datasets in research and decision-making
- translation of technical/scientific information about the datasets to end-users
- limited data on hail and compound/coincident events
- long records and time series data that is often required for statistical analysis of extreme events
- regular updating and long-term management of datasets accompanied by protocols documentation.

Table 3.1 Summary of datasets that provide information on extreme climate events directly without further processing

Historic datasets cover the past few decades; projected datasets cover most of the 21st century.

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). Australian Rainfall and Runoff (ARR) provides detailed information on flood analysis but few datasets readily available on flood events. Snowy Hydro has snow monitoring datasets for three NSW sites.
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 datasets.
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 Storms Archive) and Manly Hydraulics Laboratory (MHL).
Extreme East Coast Lows (ECLs)	Maps and Tables of Climate Hazards on the Eastern Seaboard (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.
Fire: bushfire and fire weather	Historic and projected data on Forest Fire Danger Index (FFDI) available through multiple sources (e.g. NARCliM; CCIA; BoM); the cHaines index is also available for NARCliM. 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).

Table 3.2 Overview of reviewed datasets and the type of extreme event covered by each*

Dataset	Section in full report	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 in full report	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.

4. Review of extreme climate events tools and databases

Summary

Chapter 3 of the DPIE (2020) report reviews currently available climate extremes databases and tools and identifies challenges in data accessibility. Data on extreme climate events can be found on a number of different types of information systems; these range from simple web portals to a soft copy of a specific report through to virtual computers running on national mainframes. Although some databases and tools reviewed were well-structured and provided tools that allowed the users to search extensive databases, none of them covered all seven types of extreme climate events of interest to DPIE. Historical observations of extreme climate events were covered to a varying degree by the BoM databases and tools. The main exception was the lack of coverage of compound and coincident events.

Chapter 3 of the DPIE (2020) report defines a 'database' as a large collection of data organised especially 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 excludes the wide array of analysis code, software, algorithms and tools used in academic research.

Projected extreme climate events relating to temperature, rainfall and drought were well served by a number of tools/databases such as Climate Change in Australia (CCIA) and the NSW/ACT Regional Climate Modelling (NARCliM) project. Other types of extremes such as ECLs, coastal inundation and fire were partially covered in these databases and tools.

In terms of functionality, the databases and tools provide two options. Either the end-user could perform a basic search and view, then download relatively small parts of a larger overall dataset, or they could request the much larger dataset (e.g. both CCIA and NARCliM).

Knowledge and research gaps

There were a number of challenges for databases and tools:

- Hail, lightning, storms and compound/coincident events are not served by any of the tools examined.
- ECLs, coastal inundation and fire were partially covered by databases and tools.
- None of the databases and tools allowed users to define more sophisticated metadata and run data retrieval for that metadata on virtual machines.
- The NARCliM tool provides downscaled data from superseded CMIP3 GCMs and only one emissions scenario (SRES A2).
- 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 number of the databases and tools were initially developed/deployed but then not continued/ maintained.
- Climate change is a science of probabilities where the metrics describe a range of plausible futures; however, with the exception of basic level and limited functionality in CCIA, none of the tools addressed this key underlying concept, even though it is critical to the characterisation of the physical risks.

5. Conclusions

The DPIE (2020) report reviews the currently available research and datasets/tools associated with climate extremes, provides a comprehensive analysis of results from engagement with subject matter experts, and suggests priorities for further work on extreme climate events in NSW, some of which are priority research areas for DPIE to 2022. DPIE research priorities aligned with recommendations from the DPIE (2020) report can be summarised as follows:

- Develop finer spatial resolution climate model projections that better capture sub-daily microphysics, such as hail, cloud convection and storms.
- Increase the number of GCMs for future NARCliM projections projects to better encompass the range of plausible climate impacts.
- Investigate the climate processes associated with droughts and integrate multiple climate variables (e.g. runoff and soil moisture) for drought analysis.
- Continue to design regional climate projections in accordance with international modelling efforts (e.g. NARCliM and NARCliM1.5 align with the CORDEX framework).
- Actively participate in the coordination of climate modelling computation and organisational resources within Australia.
- Investigate impacts of single and multiple natural hazards in the present day and future.

In addition, DPIE regards improved access, support and uptake of information in planning and decision-making a high priority objective. This includes knowledge-brokering services, communication products, datasets, databases, tools, co-production of risk/adaptation assessments between researchers and stakeholders, and monitoring and evaluation of impacts/benefits.

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Appendix A Subject matter experts

Table A.1 List of subject matter experts
Workshop attendees are listed on the left.

Name	Organisation
Kathleen Beyer	NSW DPIE
Kevin Cheung	Macquarie University
Alejandro di Luca	University of NSW
Andrew Dowdy	Bureau of Meteorology
Stephanie Downes	NSW DPIE
Jason Evans	University of NSW
David Hanslow	NSW DPIE
Kevin Hennessy	Climate Comms
Vanessa Hernaman	CSIRO
Jamie Hodgkinson	Lucsan
Mandy Hopkins	CSIRO
Agata Imielska	Bureau of Meteorology
Fei Ji	NSW DPIE
Todd Lane	University of Melbourne
John Leys	NSW DPIE
Ian Macadam	NSW DPIE
Acacia Pepler	Bureau of Meteorology
Sarah Perkins-Kirkpatrick	University of NSW
Mahesh Prakash	CSIRO
Owen Price	University of Wollongong
Seth Westra	University of Adelaide
Nick Wood	Lucsan

Name	Organisation
Lisa Alexander	University of NSW
Ross Bradstock	University of Wollongong
Karl Braganza	Bureau of Meteorology
Hamish Clarke	University of Wollongong
John Clarke	CSIRO
Ian Goodwin	Macquarie University
David Karoly	CSIRO
Anthony Kiem	University of Newcastle Australia
Dewi Kirono	CSIRO
Sophie Lewis	UNSW Canberra
Chris Lucas	Bureau of Meteorology
Kathleen McInnes	CSIRO
Andy Pitman	University of NSW
Tony Rafter	CSIRO
Michael Roderick	Australian National University
Nigel Tapper	Monash University
Chi Hsiang Wang	CSIRO

Appendix B Acronyms

ACT	Australian Capital Territory
BARRA	Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia
BoM	Bureau of Meteorology
CAWCR	Collaboration for Australian Weather and Climate Research
CCAM	Cubic Conformal Atmospheric Model
CCF	Climate Change Fund
CCIA	Climate Change in Australia
CLEX	Australian Research Council Centre of Excellence for Climate Extremes
CLIMDEX	Climate Indices
CMIP	Coupled Model Intercomparison Project Phases 3, 5, and 6
CORDEX	Coordinated Regional Downscaling Experiment
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPIE	Department of Planning, Industry and Environment
ECL	East Coast Low
ECMWF-ERA5	European Centre for Medium-Range Weather Forecasts Reanalysis
ENSO	El Niño Southern Oscillation
ETCCDI	Expert Team on Climate Change Detection and Indices
ET-SCI	Expert Team on Sector-specific Climate Indices
FFDI	Forest Fire Danger Index
GCM	Global Climate Model
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
MATCHES	Maps and Tables of Climate Hazards on the Eastern Seaboard
MHL	Manly Hydraulics Laboratory
NARCliM	NSW/ACT Regional Climate Modelling project
NESP ESCC	National Environmental Science Programme Earth System and Climate Change Hub
NSW	New South Wales
RCM	Regional Climate Model
SILO	Scientific Information for Land Owners
SME	subject matter expert
SRES A2	Special Report on Emissions Scenarios; A2 is the business-as-usual scenario