ELECTRICITY
SECTOR
CLIMATE
INFORMATION
PROJECT

Report on the first Weather and Climate Risk Scenario

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Australian Government
Department of the Environment and Energy

CSIRO

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Australian Government
Bureau of Meteorology

Contents

Executive Summary

The reliability and resilience of the electricity sector is affected by short-term weather and climate variability. An emerging risk is long-term climate change.

The objectives of the Electricity Sector Climate Information (ESCI) project are:

- To provide improved climate and extreme weather information for the electricity sector.
- To support improved long-term (multi-decadal) climate risk planning and decision making.

One of the key early deliverables for the project was a risk scenario workshop for industry participants from across the National Electricity Market (NEM) which will gather information on vulnerabilities to weather and climate events. Planning for the workshop drew upon operational interaction between BoM and AEMO (for example, the Bureau has a forecaster embedded in AEMO's operations) resulting in a rich amount of information being available to the project. This prior interaction exploring vulnerability and the electricity system has greatly informed the design of the extreme weather and climate scenario, and the design of the workshop itself.

The NEM is vulnerable to weather and climate risks at *all* timescales, ranging from the influence of antecedent conditions, through the instantaneous consequences of high-impact weather, and through planning lead times of minutes (weather forecasts), multi-week and multi-month (seasonal forecasts of climate variability), multi-year (2-10 year experimental forecasts) to decadal (climate change projections) timescales. The spatial coverage, wide range of interconnected assets, and coordinated operability of the NEM encompasses vulnerability to a similarly wide range of hazards. Most notable amongst these are rising temperature and extreme temperatures, heatwaves, drought, bushfires, dust, wind and extreme wind, storms, hail and lightning. Some of the vulnerabilities identified, including those exposed by High Impact Low Probability (HILP) weather and climate events, will present challenges to the way current data can be best employed, and challenges for how new projection data is best modelled.

Some of these hazards are important in complex ways. For example, demand, generation and transmission of electricity within the NEM is sensitive to average temperatures, single days of extreme heat, sequences of extreme heat and the highest value temperature over a given period. The sensitivity to each of these aspects of temperature covers point locations across the NEM, as well as the synoptic-scale (weather pattern) progression of events over the entire spatial domain of the NEM—and over periods of days, weeks and months. Similarly, generation and transmission within the NEM is sensitive to different wind characteristics, and in addition, the NEM is sensitive to coincident and compound extreme events, where multiple hazards interact simultaneously.

To suit many of these needs, regional-scale projections should ideally include techniques that resolve high-impact weather (on sub-daily time-scales and less than 10 km spatial-scales). It was noted that the *Climate Data Inventory* for the project identified a wide range of regional climate projections currently available, with different spatial and temporal resolutions, covering different parts of the Australian region. However, none of these have sufficiently high spatial resolution for extreme weather events over the entire domain of the NEM (the eastern half of Australia and South Australia). Instead, there are national-scale projections at coarser resolutions, and various high-resolution projections covering individual States.

The first climate scenario workshop focused on the near-term future (2021-2023) and on two themes, *Reliability* and *Resilience* Planning. Identifying these broad planning functions, with their inbuilt processes for modelling risks to the NEM, presents a relatively quickly-achievable means of including climate change information to support current decision making. This approach was strongly supported by industry participants, and contrasts to an approach that targets an exhaustive list of assets and classes of assets, or operational systems—which would take more time to achieve impact.

At this stage, the most practical and tractable path forward, and most immediate results, are likely to be gained by focusing on temperature—as used in current demand modelling and syntheses—informing the AEMO Integrated System Plan (ISP), and Electricity Statement of Opportunity (ESOO). These processes currently use limited observational (historical) weather data.

Some potential ‘quick wins’ were identified, including:

- The resolution to focus the project initially on a set of existing risk management models used by the industry is an important outcome for the project and provides a strong focus to the extension of support to the sector.
- A more detailed knowledge and understanding of the strengths and weaknesses of NEM modelling and planning processes, and weather and climate modelling, has facilitated a better understanding of the problem space, and has allowed for revised interpretation or scrutiny of data used in existing planning inputs.
- An effort already underway to incorporate existing temperature projections from eight climate models, using statistical downscaling to produce 30-minute weather data that is analogous to the historical weather data currently used to estimate electricity demand.
- The possibility of using existing temperature, rainfall, wind and solar radiation projections from eight climate models in a similar way to above.
- While the above approaches will attempt to fit climate data into existing demand model data requirement—gains may be achieved by reconfiguring risk models to incorporate *more* information from high-resolution observational reanalysis data and, by extension, climate model projection data, and this has been identified as an achievable early goal, that will be pursued in parallel, to the work above.

The scenario workshop also identified a range of non-climate factors that will confound efforts to mitigate climate risk. Chief among these are limitations placed on NEM asset managers related to the cost of mitigation provisions to the consumer by the regulator (AER). It is likely that the ESCI project can assist in informing future policy settings around building resilience, but that is beyond the current scope of the project.

1 The ESCI Project

The Electricity Sector Climate Information (ESCI) Project was designed to deliver information and data based on projections of the future climate to the electricity sector to help better manage weather and climate risks to electricity supply. ESCI project partners were the Department of Energy and Environment[1], the Australian Energy Market Operator (AEMO), the Bureau of Meteorology (BoM) and CSIRO.

This report covers the design, activities and outcomes of the first weather and climate scenario exercise and workshop for industry participants, which was held on 17 May 2019. The climate data and NEM vulnerabilities identified through prior stakeholder engagement have informed the scenario exercise, while outputs from the scenario exercise will continue to guide the development of new climate information by the project.

2 Workshop overview

Climate change is not modelled thoroughly throughout the sector in support of long-term planning, so while the workshop aimed to collect information from participants, it was also designed to raise the profile of climate change modelling in the sector.

2.1 The objectives of the scenario exercise:

To run a scenario exercise and workshop with broad NEM industry participation based on an initial assessment by the project of areas the NEM is vulnerable to climate change.

Prior to the workshop the team developed:

i. An initial inventory of existing NEM vulnerabilities to weather and climate and how they are susceptible to the physical impacts of climate change.
ii. An initial inventory of existing industry models and decision-making processes for mitigating risks to the NEM which could be better informed by tailored climate information.
iii. A detailed risk scenario that tests the key vulnerabilities specific to the identified climate change physical risks.

Participants at the workshops were asked to evaluate, validate and extend (i) the initial vulnerability inventories, (ii) the identified industry decision making processes for mitigating those risks and vulnerabilities, and to consider (iii) the likely data requirements needed to inform those decision-making processes. Industry workshop participants included representatives from the Department of the Environment and Energy (DoEE), The Australian Energy Market Operator (AEMO), The Bureau of Meteorology (BoM), CSIRO, Energy Networks Australia (ENA), ElectraNet, Powerlink, TasNetworks, Ausnet Services, NSW Office of Environment and Heritage (NSW OEH), The Climate Change Authority (CCA).

The Workshop timetable and list of participants are attached in Annex A.

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[1] Since replaced as project partner by the Department of Industry, Science, Energy and Resources (DISER).

Participants were allocated a table relevant to their expertise. Each table included representatives from the electricity sector and climate science data experts.

The morning content and exercises were developed to identify system vulnerabilities and to elucidate all the possible interactions between weather (driven by climate change) and electrical systems. The afternoon content and exercises aimed to identify improvements required to capture climate change risks appropriately, including:

1. Industry process changes required.
2. Climate science data and insights required.
3. Any emerging quick wins, medium-term solutions and long-term development pathways.

The exchange between electricity sector representatives and climate experts resulted in rich information that will help direct the development of future solutions.

3 Weather and climate risk scenario design

The scenario reported in this document is designed to test key risks to the NEM, and thereby to inform existing industry risk assessment, planning and associated decision-making processes, and will frame the work of the team going forwards.

As noted in the project contract, the science and decision support output from the project should inform an appropriate risk mitigation framework. Therefore, the first industry risk scenario workshop was structured around an existing high-level risk framework for disaster risk reduction and mitigation, and a preliminary set of NEM risk modelling processes described in section 3.5.

3.1 Planning and risk context

Planning for the extreme weather scenario used a framework common to critical infrastructure, national security, transport, public safety and emergency services all of which plan on three time-scales:

(i) **Strategic Planning:** Long lead time (years to decades) planning of assets and operational systems toward management of risks, through improving future resilience, redundancy and efficiency. This planning includes transmission line route selection as well as anticipating changes in future integrated risks due to changes in technology (including new generation technology), population and climate, and putting in place long-lived measures to mitigate those risks.

(ii) **Tactical Planning:** Medium lead time (months to years) decisions made for the management of risks to the NEM, within the existing envelope of assets, operational systems and market rules and regulation. This includes planning for equipment redundancies, scheduling of planned outages and developing operational procedures. These processes provision against probable near-term (minutes to months) weather and climate risks associated with supply and demand.

(iii) **Operational Planning:** Short lead time (minutes to days) decisions made to address risks to supply. This includes operational decisions such as enacting protected events for out-of-merit generation dispatch (dispatch of supply that is triaged according to system state), islanding (parts of the NEM becoming isolated), or load shedding (rationing of supply) to protect the system should a customer outage be unavoidable. Existing mechanisms for operational management of these risks include Ancillary Services (FCAS), Reliability and Emergency Reserve Trader function (RERT).

The focus of the ESCI project is on *Strategic Planning*—as future climate change is expected to change risks to the sector in significant and critical ways over decades to come. Strategic planning of assets, and operational systems with matching lifetimes, must consider the best estimates of those changing risks. Effective *Strategic Planning* necessarily includes a goal of making *Operational* and *Tactical* decision-making mechanisms more robust and easier to deploy, which requires a sensitivity to high-impact weather and climate on the timescale of minutes to months. This presents a difficult challenge for this project since climate models do not represent physics at the appropriate spatio-temporal resolution for resolving some high-impact weather phenomena such as thunderstorms.

3.2 The role of weather and climate in AEMO Strategic Planning

AEMO has existing risk modelling tools that underpin planning for the NEM. This means that climate data must be matched to existing processes for modelling vulnerability, rather than the vulnerability itself. The principal metric for AEMO's planning for the NEM is the calculation of unserved energy which captures the potential mis-match of supply and demand at different points in the NEM. This supports modelling for AEMO's **Integrated System Plan** (ISP) which looks 20-30 years ahead and the **Electricity Statement of Opportunities** (ESOO) which considers a 10 year horizon. Construction of the ISP and ESOO includes scenario risk planning tools and modelling that are highly relevant to the ESCI project, especially the industry risk scenario workshop. Future asset and infrastructure changes to the NEM will have a large contribution associated with climate change, including the transition to more renewable generation sources, and vulnerability to climate change is expected to increase.[2]

Strategic Planning to calculate unserved energy has established four main components for modelling where climate and extreme weather risk have direct interactions:

A. Customer electricity demand given changes in the electricity market, economy, population, industrial activity, electricity price, technology, embedded generation and response to weather.
B. Thermal ratings of lines and output of generation plant (Physical Risk).
C. Outage rates given asset condition, standards and extreme weather (Integrated Risk).
D. Economic and societal cost of outages (Integrated Risk).

While economic and societal costs of outages (D above) are outside the scope of the ESCI project, the ESCI project is most aligned to producing data and information for the assessment of physical risks associated with A, B and C above. Climate change is also introducing new and significant risks to assets and the NEM beyond those currently identified, with very high consequences for supply and demand. While all organisations in the NEM apply Risk Management Standard ISO 31000-2018, risk analysis and risk mitigation also involve interactions between knowledge (our focus), values and rules (including cost).

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[2] Finkel Review (2017): "The National Electricity Market is particularly exposed to climate change impacts. An increase in the frequency and intensity of extreme weather events can increase stress on the power system in several ways."

Decisions supporting risk management are complex. Climate and weather are primarily a consideration in physical risk assessment but can also influence transitional risk (e.g. the speed of the transition to renewable energy sources) and institutional risk (e.g. risk from policy change or assessed liability as society changes). Only physical risk is within scope for the ESCI project.

3.3 NEM physical vulnerability to climate and weather

3.3.1 Relevant climate hazards

The NEM is vulnerable to weather and climate risks at *all* timescales, ranging from the influence of antecedent conditions, through the instantaneous consequences of severe or high-impact weather—and through planning lead times of minutes (weather forecasts), weeks and months (seasonal forecasts of climate variability), years (2–10 year experimental forecasts) and decades (climate change projections). Not all assets or sectors have such vulnerabilities across all timescales. For example, water supply risks are mostly driven by long-term trends (decadal changes) in rainfall and streamflow, rather than by sub-daily high-impact weather.

The spatial coverage, wide range of interconnected assets, and coordinated operability of the NEM encompasses vulnerability to a similarly wide range of hazards. These include:

- Heatwaves
- Drought
- Bushfires
- Dust
- Wind and extreme wind
- Storms
- Hail
- Lightning
- Destructive events (sometimes known as compound events, comprising extremes in multiple variables simultaneously).

Some of these hazards are important in complex ways. For example, demand, generation and transmission of electricity within the NEM is sensitive to average temperatures, single days of extreme heat, sequences of extreme heat and the highest value temperature over a given period. The sensitivity to each of these aspects of temperature covers point locations across the NEM (e.g. single assets), as well as the synoptic-scale (weather pattern) progression of events over the entire spatial domain of the NEM—and over periods of days, weeks and months. For example, the NEM is sensitive to the manner in which a heatwave develops as a time-dependent footprint across load centres (how the heatwave moves across Australia's population centres, how many population centres have simultaneously extreme conditions, and what the most extreme values are at any location at any given time). Similarly, generation and transmission within the NEM is sensitive to average wind speed, maximum extreme winds and wind 'ramping' events (rapid changes in wind) across the same spatial and temporal domains as temperature.

3.3.2 NEM vulnerabilities and exposure

Climate change needs to be integrated in current planning of the NEM for the following reasons:

1. Customer demand has long been highly responsive to weather.

2. Changes in climate will occur over the lifetime of assets (~50 years).
3. Generation is transitioning away from thermal synchronous generators:
    a. Supply is also now highly responsive to weather.
    b. Loss of synchronous generation increases demands on forecasting and modelling.
4. Models that do not represent or preserve spatial and temporal correlations between weather variables will likely mismatch supply and demand, potentially leading to inappropriate system planning.
5. While electricity systems have always been built to withstand extreme weather, risk management processes may not be keeping up with the *changes* in weather extremes and interactions.
6. New investments must consider location diversity, equipment design and ratings that are consistent with long term expectations.

The vulnerability of transmission lines and generation plants provides an asset level (or classes of assets) lens for future climate risk. Namely, are current assets appropriately designed and rated for future climate change? Generation and transmission assets are both vulnerable to extreme temperatures, effecting both efficiency and failure. Power generation that includes a mix of renewable energy sources is also vulnerable to extremes or spatio-temporal changes in humidity, wind and solar radiation. All are at risk from coincident or compound weather events (Zscheischler, 2018, Cainey, 2019). These are exacerbated by climate change in ways that have not been deeply explored either in Australia or internationally.

Matching weather and climate data to AEMO *planning tools* (risk models) is the clearest path to early achievable outcomes to improve decision making. This contrasts to matching climate data to vulnerability at the *asset level*, which will still be explored in the medium term for the ESCI project.

3.4 NEM climate modelling requirements

AEMO planning tools for assessing risks effectively model systemic vulnerabilities and hence provide a very useful basis for understanding needs and gaps in the science, that need to be addressed in order to improve decision making[3]. At the same time, the risk modelling processes currently used by AEMO may, as a result of this project, need to be revised so that they account for more currently available (and potentially under-used) weather and climate information; or better account for future changes in risk.

The ESCI project is therefore considering that:

- Risk models make use of probability density functions of maximum and minimum demand by season.
- Risk models use half-hour data for customer demand and generation supply, across an entire year to capture multiple periods of system strain due to extremes (summer maximum, winter maximum, shoulder minimum).
- The system has critical dependency on major load centres; i.e, what happens in the large cities is critically important.

Ideally, simulations should capture the synoptic development (the growth, movement and decay) of future high-impact extreme weather systems across Australia (at least across the spatial domain of

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[3] For a more complete discussion of AEMO planning tools refer to section 2.3.

the NEM). This high spatial and temporal resolution requires climate modelling, which is significantly more computationally intensive than, for example, future changes in low-resolution seasonal-average temperature (typically the output from global general circulation models).

It should be noted that changes in demand due to a warming climate are complex, since there are likely to be a range of transitional changes to demand (e.g. changes in building energy efficiency, or the introduction of electric vehicles). While modelling of future temperatures are relevant to future demand scenarios, attempting to account for transitional changes is not within scope for the ESCI project.

3.5 Industry decision making processes

The operational and critical infrastructure components of risk planning for the NEM (as opposed to, say, the economic component) are aimed at ensuring that supply, including the quality and locational characteristics of supply, matches demand across the NEM at all times. AEMO has identified the five most-relevant industry decision making processes with respect to climate risk, that incorporate stakeholders across the NEM. These form the basis for the industry scenario exercise reported here and are expected to form the basis for the project decision support elements going forward.

The five processes are:

(i) *System Capacity & Reliability Planning:*
The probabilistic calculation of customer outage risk arising from:
- Credible events
- Protected events
- Some other non-credible events
- Proposed solutions to mitigate outage risk may include process or market changes and/or infrastructure investments

(ii) *System Resilience Planning*
The calculation of customer outage risk arising from:
- High Impact, Low Probability (HILP) events
- Insufficient system strength, stability or inertia
- Cascading failures
- Proposed solutions to mitigate outage risk may include process or market changes and/or infrastructure investments

(iii) *Tactical Planning*
Planning for transmission and generation source/route selection. Solutions should minimise weather interaction between transmission and generation sources.

(iv) *New Generation Connections*
Studies of new generator connections, including ramping studies for intermittent generation and generator specifications. Solutions may include process changes and/or additional infrastructure investments.

(v) *Network Risk and Asset Management*
Asset management decision making involves understanding and managing the performance and degradation of assets that make up the electricity system; weather is a driver of degradation and therefore performance.
Appropriate risk management involves reducing safety risks as low as reasonably practicable (ALARP).

Of the five most-relevant industry risk modelling processes, this first ESCI industry risk scenario workshop focused on (i) *Reliability* and (ii) *Resilience Planning,* which falls mostly under the higher-level *Strategic Planning* decision making tier described in section 3.1 above.

4 First weather and climate risk scenario exercise

During the scenario workshop on 17 May 2019, NEM industry participants were taken through a two-stage tactical-to-strategic planning exercise, which drew upon the learnings from numerous risk scenario workshops conducted by government for various sectors over the past three years. Scenarios were designed to match the weather and climate risks with the relevant NEM vulnerability inventory.

The first half of the workshop introduced the operational weather and climate risk scenario exercise. Participants considered a multi-month extreme weather and climate scenario that is both plausible and aimed at highlighting risk exposure and vulnerabilities in the NEM.

The second half of the workshop was a planning exercise. This exercise was structured around the five, high-level decision-making processes from AEMO's industry scoping and cognizant of some of AEMO's established methods for assessing risks (see section 0 above).

A copy of the workshop agenda is attached in Annex A.

4.1 The Physical Risk Scenario

What it is

The scenario was intended to be used as a narrative to highlight for the ESCI project current challenges in managing and planning for the NEM.

The scenario described a sequence of extreme weather and climate that could be used in stress-testing for risk planning. The weather sequence was based on history and could plausibly occur in Australia in the near future, it included a projected climate trend with a nominal setting in the early 2020s. It is worthwhile highlighting that vulnerability to changes in extremes is focused on acute impacts, while vulnerability to changes in average climate is focused on chronic impacts.

The scenario provided a plausible but otherwise hypothetical 'perfect storm' of future weather and climate events aimed at a set of vulnerabilities within the NEM identified by AEMO. The scenario was portrayed for the years 2021-2023 in a combination and sequence that is consistent with the patterns of historical weather and climate in Australia (*synoptic* pattern).

While the scenario is not dependent on further warming of the climate system (these conditions could happen today), such warming is expected to occur – in part because of additional greenhouse gases already released into the atmosphere. Many of the conditions in the scenario will likely occur much more frequently in future decades, along with novel extreme events.

What it is not

The scenario is *not* a forecast or a prediction and is not based on climate model projections per se — such as the use of specific simulations of future weather extremes as provided by regional climate models driven by scenarios of increasing greenhouse gases.

It should be noted, however, that the intention for the project is that future scenario workshops (focused on the mid-21st century) will be more informed by regional climate model data, where such projections provide the required representation of novel synoptic weather and weather extremes and, to the extent possible, will include likelihood and probabilistic information from a range of appropriate projections.

4.1 The Vulnerability Space

The first workshop scenario exercise was built around key vulnerabilities which were validated and extended by workshop participants. The vulnerabilities identified in the workshop were:

1. Direct (destructive) physical threats to critical infrastructure affecting supply (both generation and transmission/distribution assets):
    - Reduction of generation availability due to deferral of maintenance due to extreme heat occurring during shoulder seasons, ultimately leading to increased unplanned plant failure. While this affects generation from coal, gas, diesel, hydro and large-scale wind and solar, it is more problematic for some generation types compared with others.
    - Loss of transmission, storage and generation infrastructure due to direct or indirect impact of destructive winds, lightning, heavy rainfall and flooding and bushfire. While most significant for large-scale assets, this also affects distributed assets such as battery storage and rooftop PV).

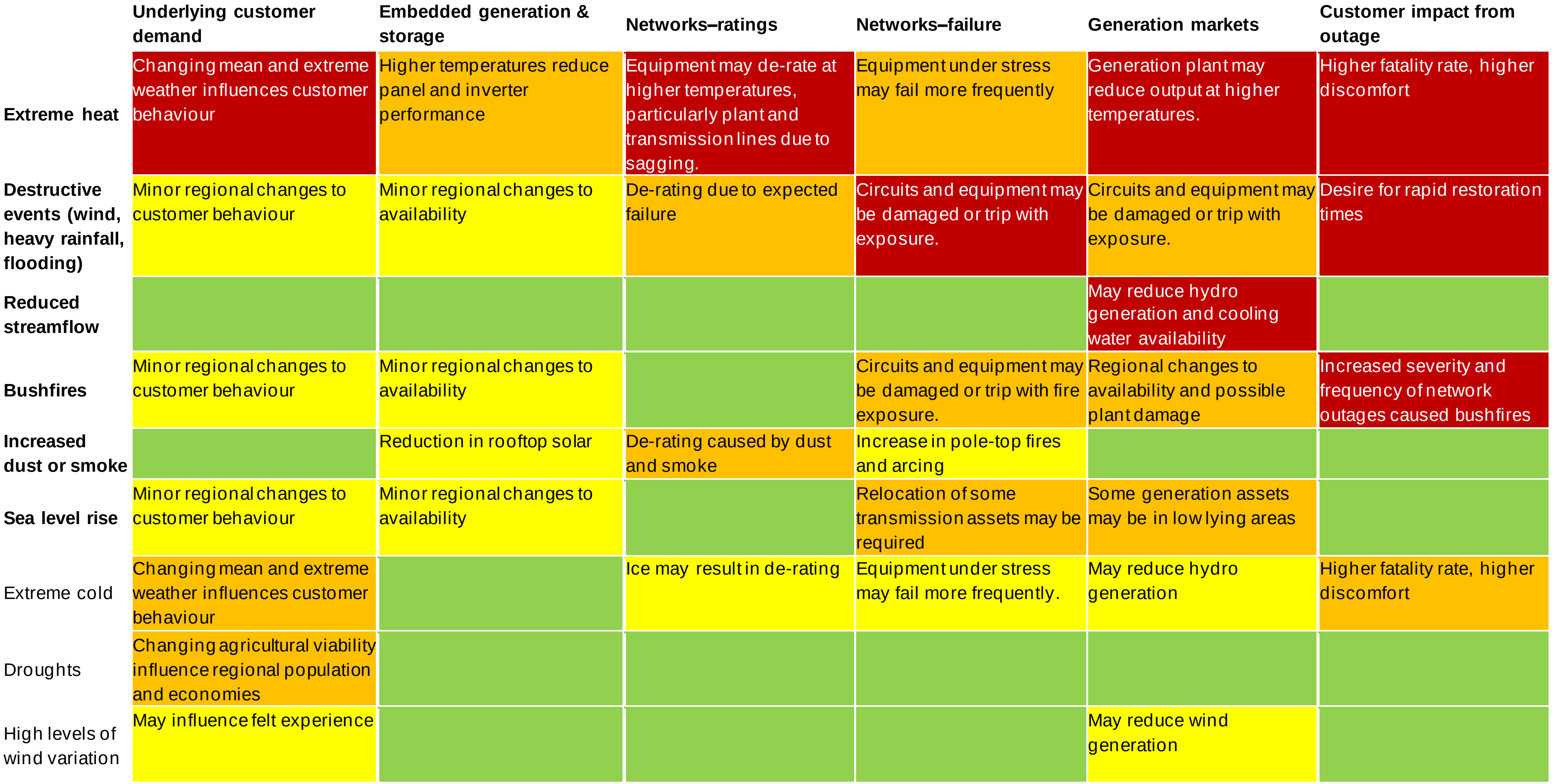
2. Loss of generation due to impact of weather on both renewable generation and other generation sources:
    - Reduction in hydro generation due to reduced streamflow and/or snowmelt as a result of drought.
    - Reduction in wind generation due to calm conditions associated with a large high pressure weather system.
    - Reduction in wind generation due to extreme temperatures.
    - Reduction in wind generation due to high winds.
    - Reduction in rooftop solar due to dust storm or smoke or dark storm clouds.
    - Reduction in coal generation due to increased cooling water temperatures or restricted access to cooling water.
    - Reduction in coal generation due to de-rating and/or unplanned outages associated with extreme temperatures.
    - Reductions in output from gas and diesel generation due to prolonged high ambient temperatures.

3. Reduction in electricity supply due to impact of weather on power distribution and transmission assets:
    - Reduction in transmission efficiency due to high temperatures.
    - Reduced transfer capability through fire-affected and high fire danger regions.

4. Increase in customer demand due to extreme heatwave conditions:
    - High demand due to prolonged heatwave associated with air-conditioning loads and heat build-up that may exceed grid capacity.

- Increased risk of extended periods of load shedding, leading to significant economic costs (for example, the South Australian black-out in Dec 2016 cost the business sector $367 million) and public health costs, including loss of life.

An initial matrix of interactions between weather and electricity system components is shown below in Figure 1. This matrix was tested and updated as part of the scenario workshop. The matrix indicates that many elements of the system are vulnerable to weather interactions, in particular to extreme heat, bushfires and destructive events. The transition away from synchronous generation further exacerbates these interactions and results in new system risks.



	Underlying customer demand	**Embedded generation & storage**	**Networks–ratings**	**Networks–failure**	**Generation markets**	**Customer impact from outage**
Extreme heat	🟥 Changing mean and extreme weather influences customer behaviour	🟧 Higher temperatures reduce panel and inverter performance	🟥 Equipment may de-rate at higher temperatures, particularly plant and transmission lines due to sagging.	🟧 Equipment under stress may fail more frequently	🟥 Generation plant may reduce output at higher temperatures.	🟥 Higher fatality rate, higher discomfort
Destructive events (wind, heavy rainfall, flooding)	🟨 Minor regional changes to customer behaviour	🟨 Minor regional changes to availability	🟧 De-rating due to expected failure	🟥 Circuits and equipment may be damaged or trip with exposure.	🟧 Circuits and equipment may be damaged or trip with exposure.	🟥 Desire for rapid restoration times
Reduced streamflow	🟩	🟩	🟩	🟩	🟥 May reduce hydro generation and cooling water availability	🟩
Bushfires	🟨 Minor regional changes to customer behaviour	🟨 Minor regional changes to availability	🟩	🟧 Circuits and equipment may be damaged or trip with fire exposure.	🟧 Regional changes to availability and possible plant damage	🟥 Increased severity and frequency of network outages caused bushfires
Increased dust or smoke	🟩	🟨 Reduction in rooftop solar	🟧 De-rating caused by dust and smoke	🟨 Increase in pole-top fires and arcing	🟩	🟩
Sea level rise	🟨 Minor regional changes to customer behaviour	🟨 Minor regional changes to availability	🟩	🟧 Relocation of some transmission assets may be required	🟧 Some generation assets may be in low lying areas	🟩
Extreme cold	🟧 Changing mean and extreme weather influences customer behaviour	🟩	🟨 Ice may result in de-rating	🟨 Equipment under stress may fail more frequently.	🟨 May reduce hydro generation	🟧 Higher fatality rate, higher discomfort
Droughts	🟧 Changing agricultural viability influence regional population and economies	🟩	🟩	🟩	🟩	🟩
High levels of wind variation	🟨 May influence felt experience	🟩	🟩	🟩	🟨 May reduce wind generation	🟩

Figure 1: Weather and climate—NEM interaction inventory

Green = no interaction, yellow = low interaction, orange = moderate interaction, red = significant risk from the interaction.

4.2 The Weather Scenario

This scenario for 2021-2023 has been conceived as a sequence of antecedent (precursor) climate events, ahead of a record-breaking heatwave at the summer peak. However, it can be seen as one extended climate event. The events are designed to be slightly beyond those captured in the recent historical record. However, this amplification may result in significantly different impacts, since we are dealing with the tails of the distribution. The climatological background and historical context for the climate and synoptic conditions are given in Annexes B and C respectively.

4.2.1 Requirements based on vulnerability space

- A meteorologically and climatologically plausible time series of extreme weather events affecting east and southeast Australia, including South Australia, Victoria, Tasmania, New South Wales and southeast Queensland for 2021-2023.
- The weather events will be record-breaking (beyond our historical experience) and based upon past climate analogues superimposed on future global warming.
- The scenario has been designed with specific NEM vulnerabilities in mind, in order to highlight current challenges.
- The scenario will provide initial guidance for services, systems and asset planning to further increase the resilience of the NEM to physical climate risk.

4.2.2 Detailed description of the physical scenario

The sequence of weather and climate events, natural hazards, and NEM vulnerabilities and impacts tested at each stage of the developed scenario are as follows:

Antecedent conditions

- A prolonged (multi-year) drought, with similar characteristics to the Millennium Drought, is affecting the whole of southeast Australia.
- The 2021-2022 summer saw near-El Niño conditions in the Pacific, with very dry conditions across southeast Australia.
- Winter 2022 saw very warm and dry conditions across southeast Australia, affecting SA, VIC, TAS and southern NSW, driven by Indian Ocean temperatures (positive phase of the Indian Ocean Dipole).
- The conditions also reduce soil moisture and lead to the further curing of vegetation, elevating the bushfire risk.
- Streamflows are substantially reduced across eastern Australia. Low flows in particularly are observed in southern Murray-Darling basin, Victoria and Tasmania.

Spring 2022

- An early start to spring, with record-breaking heat in August.
- Summer-like conditions occur from September onward, with a heatwave in November peaking at over 40 ^{o}C in Adelaide, Melbourne and western Sydney, followed by Brisbane as the heat moved north.
- A very active spring bushfire season in northern NSW and southeast QLD including northern rivers and inland border regions. Widespread dust storms across Vic and NSW.

Late 2022

- A hot start to summer, with a succession of slow-moving high pressure systems over large parts of central and southeast Australia. Cool changes are weak and brief, as frontal systems fail to push significantly into the subtropical-ridge, and slip south of the continent as heat continues to build over inland Australia.
- The persistent and large high pressure systems lead to generally calm conditions.
- Overnight temperature reductions are generally limited over southeast Australia.
- Severe rainfall deficiencies persist. Water restrictions are in place.
- A 3-day heatwave affects South Australia and Victoria prior to Christmas, peaking at 43 ºC in Adelaide and 41 ºC in Melbourne.

January 2023

- An extended, two-week January heatwave affects the eastern states, after starting in southern Western Australia in early January, with intense heat in the first week, and little relief in the second.
- A stationary high over the Tasman Sea directs hot, dry air across the country and into the southeast, aided by a severe Tropical Cyclone off the northwest coast of Australia (which strengthens the upper ridge through anticyclonic potential vorticity advection).
- Victoria recorded four consecutive days over 41 ºC, with three over 43 ºC and elevated heat conditions overnight. Heat wave conditions persist over some part of eastern Australia for over two weeks. Several regional towns break their all-time temperature records, with temperatures around 48 ºC. Many locations exceed forecast maximum temperatures. Winds are lower than expected overnight.
- The intense heat reaches northern Tasmania. Temperatures reach 41 ºC at Launceston on days 5 and 6 of the event, and approach 35 ºC along the Tasmanian north coast.

February 2023 heat wave and bushfires

- An unprecedented February heatwave event, and bushfires fanned by gale force winds and record-breaking temperatures, provides an extreme climax to the sequence of heatwaves since November 2022.
- The duration and intensity of the heatwave are unprecedented for South Australia and Victoria for February, lasting for 6 days, (with a slow moving high or extended ridge south of the continent; similar to the week before Black Saturday 2009) —with critical extreme weather days in the middle of the week.
- Calm conditions over February 3-6.
- Friday 3 February 2023 sees the first of five days of at least 41 ºC in Adelaide. The extreme heat reaches Melbourne on Saturday, the first of four days above 40 ºC. Temperatures in the high 30s or low 40s persist in Canberra, Sydney and Brisbane over most of the 3-9 February 2023 period.
- On Tuesday 7 February 2023, increased winds drive temperatures in Adelaide to record-breaking 49.2 ºC, exceeding advance and real-time forecasts for maximum temperature.
- The approaching front also drives temperatures in Melbourne to 45 ºC late on Tuesday 7 February 2023.
- Fire danger reaches Catastrophic or Code Red (the Fire Danger Index is increased due to the prolonged drought and lack of soil moisture). The approaching front on Tuesday 7 February 2023 sees a number of bushfires ignite, then fanned by the high winds. Out of control fires burn across the state, including large fire-grounds near Benalla in north-east Victoria and near Dartmoor in western Victoria.

- Emergency services are stretched, the Victorian and Tasmanian Fire Services allow some fires to burn due to lack of resources.
- The heat-wave persists into Wednesday 8 February and Thursday 9 February 2023 in NSW and Sydney.
- Wednesday 8 and 9 February Southeast QLD and Brisbane affected by severe thunderstorms.

5 Impacts on the NEM—as identified by workshop participants

Immediate and long-term system impacts on the NEM at each stage of the scenario were identified by workshop participants.

Participants were also asked to prioritise key interactions between extreme weather and the NEM – This prioritisation will help inform future workshops.

5.1 Immediate system impacts

Antecedent conditions 2021-2022

- Lower hydroelectric generation from Tasmania & Snowy.
- Winter maintenance program truncated due to early hot conditions, resulting in increased risk of failures.
- Underground cables heating up during the day and unable to dissipate heat overnight results in assets derating.
- Increased rooftop solar due to sunny conditions.
- Calm conditions result in low wind generation.
- Reduced flexibility of supply / and or ability to match demand.
- Increase in spot price of energy.

Spring 2022

- Low inflows for Snowy & Tasmanian hydroelectric dams.
- High spot-price volatility and possible market ‘gaming’.
- Dust on insulators results in transmission line failures, requiring pre-emptive de-energising to avoid fire initiation that would compromise supply.
- Reduced PV generation from smoke haze.
- Higher local demand reduces inter- and intra-regional power flows.
- Key assets fail because of reduced maintenance, creating greater demand for hydro power.
- Increase in air conditioner use.
- Calm conditions result in low wind generation.
- Greater use of utility-scale power reserve (e.g. SA battery).
- Importing energy from QLD, bushfires limit NSW/QLD interconnector capacity.
- Increased gas generation increases fire risk from active pipes.

Late 2022

- High daytime temperatures and lack of overnight cooling risks transmission asset failure – not rated for extreme temperatures.

- Reduced household solar panel efficiency with heat and following dust storms
- Overnight electricity demand remains high.
- Public holidays make predicting demand more difficult.
- Challenging prioritisation decisions need to be made – which loads are serviced?
- General de-rating of the system: transmission line cooling is less efficient in light wind conditions, increasing the risk of failure of these assets if not managed carefully.
- Insufficient supply across the NEM leading to load shedding.
- Blanket ban on system maintenance, increasing risk of asset failure.

January 2023

- Coal and gas generators de-rated due to insufficient cooling.
- Plant failure – transformers, generators tripping.
- Reduced capacity of multiple assets – thermal units, transmission lines, solar.
- Basslink outage due to high temperatures in George Town. Tasmanian energy security issues due to limited water resource and insufficient alternate generation to meet high demand.
- Rolling black-outs impact transport.
- Emergency reserve purchased from large consumers e.g. aluminium smelters.
- Regional islanding.
- Physical damage to assets from bushfires.
- Fuel shortages e.g. Gas for thermal generators.
- Customer infrastructure failing (e.g. inverters, air con, fridges etc).

February 2023

(Students return to school and businesses return to normal operations following the holiday period)

- System failures result in rolling blackouts.
- Wind generation high at times, but high temperatures result in de-rated transmission lines and generator output.
- Extreme wind may damage assets including rooftop PV and distribution assets.
- Lightning damages some circuits resulting in local blackouts.
- Psychological stress – fatigued AEMO & BoM workforce.
- Heat fatigued public results in rising complaints, political pressure and increased hospital admissions.
- Smoke from fires leads to lines de-rating.
- Regional islanding, results in up to 5 electrically separate islands. AEMO unlikely equipped to manage such a network.
- North West Victoria susceptible to system failure due to bushfires.
- Combination of fire, smoke and light rain leads to an increase in the number of faults in the distribution network.
- Widespread load shedding for active system management may result in economic impact if major industry consumers are affected.
- Cascading failure of computer infrastructure because of heat and cooling issues – risk to high performance computers.
- QLD not affected by heat but entering their own storm season – potential drawing on already stretched resources.
- Possible state-wide blackout.

5.2 Longer term system impacts

Generation

- Less water for cooling thermal generators, and available water is warmer, resulting in reduced generation.
- Long term maintenance deferred.
- Increased use of gas-powered generation may put pressure on fuel supplies (may be partially mitigated by above average reserves following a warmer winter).
- Reduced maintenance leads to shortage of spare parts, especially a problem for long-lead time parts.
- Reduced asset life because of stressed system.
- Towards the end of the year, the gas network traditionally undertakes maintenance of critical infrastructure – could result in lower output, or decision to reduce maintenance and increasing risk of system failures into future.
- Net depletion of fuel reserves.
- Ongoing low hydroelectricity capacity requiring significant rain to replenish water storage.

Transmission and distribution

- Fire hazard-reduction burning window shrinking, creating a cascade effect with increasing fire fuel load.
- Long term maintenance deferred.

Demand side and customer impact

- Desalination plants operating as a result of the drought add to the load.
- May need to renegotiate contracts with large consumers to reduce energy usage over summer.

Grid management and political impacts

- Shorter maintenance period over winter increases general risk of failure.
- Strategic planning potentially required to conserve water for future events.
- Political trade-off between water for agriculture, environment and cities versus hydro for power generation and water for cooling thermal plants.
- Increased political stress to provide solutions.
- Long-term economic and political pressure.
- Loss of trust and reputation of energy providers – losing public support, making price rises even more unpopular and difficult to sell, may drive customers off the grid.
- Trade-off between drinking water and electricity.
- Institutional risk.
- Potential liability through loss of life.

6 Improving risk management capabilities

The goal of the ESCI project is to help support electricity sector decision-makers access and use tailored climate information to improve long-term climate risk planning. In doing so, the project is expected to contribute towards realising a longer-term vision for the next generation of climate projections and seamless climate and weather information.

There are two factors that make the process of matching system vulnerabilities and weather and climate complex:

i. A chief limitation is the ability to model certain aspects of future climate. Some weather and climate variables (especially extremes) are more robustly modelled than others. For example, future surface temperatures are based on physics that is much easier to numerically model than future rainfall. Further, even when contained to a single weather or climate variable, future *average* temperature is easier to model than future temperature *extremes*, and the future average extreme temperature over a given *season* is easier to model than an individual *heatwave*.

ii. A second factor is that vulnerabilities may themselves be modelled and hence carry uncertainty. This is particularly true for complex systems such as the NEM. This presents an opportunity to fit climate data into existing risk models which can lead to early achievable results. However, as with physical climate models, risk models are different to physical risk in the real world, so such modelling processes will also vary in how faithfully they capture each risk.

This introduces some additional nuance to the matching of data needs that can be separated into:

- short term goals of fitting with existing system risk models, and
- longer term goals of attempting to optimise both system risk and physical model information.

6.1 Summary of data and decision support capability gaps

The weather and climate risk scenario stresses the management and resilience of the NEM, in its current state, in the following ways:

- The extreme conditions were beyond historical experience. Recent climate data used for the assessment of risk does not sufficiently capture future record-breaking extremes.
- The extreme conditions were under-forecast (the magnitude or severity of record-breaking conditions were forecast, but conditions on the day exceeding those in all available forecast products).
- Extreme stress on generation and transmission assets in the network, extending beyond its typical operational envelope, which is based upon historical climate and experience (Based on current temperature ratings for operational assets).
- Lack of coordinated response across emergency services and interconnected/cross-dependent critical infrastructure and systems — due to a lack of coordinated scenario planning across relevant interdependent agencies.
- Large losses from businesses similarly unprepared for the extreme conditions due to inappropriate scenario planning and stress testing.
- Loss of life from outages related to heatwaves and bushfires.

There are gaps in our ability to mitigate the problems described above. The elements of missing data for physical risk and scenario planning in Australia (in comparison with other jurisdictions, such as the EU) are summarised here:

- A relative lack of high-resolution historical and national reanalyses data (hourly data at spatial and temporal scales that render extreme weather).
- A relative lack of real-time geospatial weather and climate monitoring data.

- Despite the availability of a wide range of dynamically and/or statistically downscaled climate projections for different parts of Australia, none use nationally consistent methods, including a suitably large suite or multi-model ensemble which captures low probability and high consequence weather sequences.
- Disparate holdings of asset, vulnerability and exposure data, with disparate data formats.
- A lack of standardised methodologies for undertaking risk assessments
- A lack of standardised methodologies for scenario-based risk planning (war gaming).
- A lack of knowledge brokers on weather and climate hazards, exposure, vulnerability and risk.

6.2 Potential solution space

It is very likely that existing data can provide more information than is currently being utilized, so integration of this data into risk planning and decision-making will continue to be explored as the project evolves. A large multi-model ensemble of high-resolution national projections is very likely required to adequately sample rare events of high impact and consequence, and to generate robust future *likelihood* and *risk* information (such as required for stress testing). Such an ensemble does not exist at present and is beyond the current scope of ESCI.

The ESCI project will focus on providing climate information for the vulnerabilities and processes identified through the workshop that are of highest value and can realistically be informed by climate science and projections and will also develop a standardised risk framework within which the climate information can be used.

7 References:

Cainey, J.M., 2019, *Resilience and Reliability for Electricity Networks*. The Royal Society of Victoria, 131, 44-52, 10.1071/RS19005.

Dr Alan Finkel AO, Ms Karen Moses FAICD, Ms Chloe Munro, Mr Terry Effeney, Professor Mary O'Kane AC., (2017) Independent Review into the Future Security of the National Electricity Market - Blueprint for the Future **https://www.energy.gov.au/publications/independent-review-future-security-national-electricity-market-blueprint-future**

Zscheischler et al (2018). Future climate risk from compound events. *Nature Climate Change* **8**, 469–477. **https://www.nature.com/articles/s41558-018-0156-3**

8 Annex A: Workshop participant list and agenda

Generalised Attendee list

AEMO Forecasting	6
AEMO National Planning	2
AEMO New Connections	1
AEMO Ops Forecasting	1
AEMO Ops Planning	1
AEMO Vic Planning	1
Ausnet Services	3
BoM	5
Climate Change Authority	1
CSIRO O&A	4
DoEE	2
ElectraNet	1
Energy Networks Australia	1
NSW Environment	1
Powerlink	2
TasNetworks	1

Workshop Activities and Timetable

Time (Melbourne)	**Activity**	**Led By**
9:15am	**Arrive for 9:30 Start**	
9:30 – 9:45 am	**Welcome**	**Nicola Falcon, GM Forecasting AEMO**
9:45 – 10:15am	**Setting the Scene Presentation: Project and Climate Risk background** A quick history of climate research for adaptation in Australia – identifying strengths and weaknesses in the current state of the science (which essentially reflect stakeholder needs to date). The ESCI project is breaking new ground as a 'next level' for connecting projections with applications and decision support. There are several aspects of the ESCI project worth noting: • It requires projections of specific high impact weather and compound events, and there have been relatively few such projects • Such projects have been very regional in scale, ESCI is the first to apply consistent future high impact weather modelling nationally. Since the modelling is being done for the NEM, and not a single asset or region, it is also the first project to consider future projections of synoptic weather. • It is the first project of this nature to deliver results directly to a highly-aligned sector. The Australian electricity sector has a range of entities that are highly coordinated through existing regulators and requirements. There is a significant advantage in reaching the sector through the national operational agency (AEMO) for use in a well-developed national operational planning framework (AEMO ISP), and with a considerable effort toward standardizing methodologies. • To the best of our knowledge there is no prominent example of such a project globally, and expectations should be cognizant of the considerable ambition of the project.	**Karl Braganza, Head of Climate Monitoring BoM**
10:15 – 11:00am	**Presentation: Sector Needs and Opportunities; International experience; Australian relevance** • Reliability and Resilience internationally • Why is this important to your business?	**Ben Jones, Forecasting Specialist, AEMO**
11:00 – 11:30am	**Morning Tea**	

Time (Melbourne)	**Activity**	**Led By**
11:30 – 1:00pm	**War Gaming Workshop** The first workshop is focused on the impacts of a weather and climate risk scenario for the NEM. To a lesser extent, particip ants may consider tactical and operational responses to inform the afternoon planning session. Participants for the workshop have been drawn from across the industry, to represent the five high-level risk planning processes. A profession scribe will be taking notes. **Climate Scenario:** (10-minutes) Presentation of a high impact weather and climate sequence that plays out over a period of from 2021 to 2023 (1 year of antecedent conditions, 2 years of high impact events). **Workshop (30 minutes):** Participants break into groups to discuss and document the likely impacts and system interactions for the climate scenario. • **Aim to identify the system impacts from the scenario.** An A3 form of scenario events will be provided for this purpose. *The ESCI project has come up with their own NEM impacts for comparison during the group reporting session.* • Groups to be *predetermined* to contain a mix of decision makers from the five high-level risk planning processes. • Each table to have a facilitator from one of the project partners, who is free to also participate in the activity. **Reporting and capture (50 minutes):** Reporting will take up more of the workshop session than is typically provided for these exercises. The reporting will also be organized *by scenario event* rather than by table (we will go through one event at a time, with each table providing their impacts and system interactions for each event). Coordination through lead room facilitator (giving direction) and the other room facilitator will consolidate responses on th e whiteboard. Groups must nominate a single spokesperson for each event to report verbally.	**Scenario Presenter: Karl Braganza** **Room Facilitators:** **Ben Jones** (leads table reporting discussion), **Karl Braganza** (to assist all tables with questions relating to the scenario) **Table Facilitators** (proposed): **Mitchell Black** (BoM), **David McQueen** (BoM), **Kevin Hennessy** (CSIRO), **Marcus Thatcher** (CSIRO**), Miriam McMillan** (DoEE), **Daniel Guppy** (AEMO)
1:00 – 1:45pm	**Lunch**	

Time (Melbourne)	Activity	Led By
1:45 – 2:15pm	**Workshop to assign interaction priorities:** • **Populate the matrix of all possible risk interactions**. Using an A3 matrix of the ESCI Preliminary Climate Change Interaction Inventory. *The ESCI project has a short list of NEM climate and weather related vulnerabilities it will provide toward the end of the session to assist in stretching the thinking of the groups.* An open session to assign the priorities stemming from the previous session and the Preliminary Climate Change Interaction matrix. Participants will be guided by the whiteboard from the previous session. The scribe will record the session.	**Judith Landsberg**, (BoM)
2:15 – 2:45pm	Review the 5 high-level industry process descriptions and discuss current gaps • System Capacity & Reliability Planning • System Resilience Planning • Tactical Planning • New Generation Connections • Network Risk and Asset Management	**Karl Braganza** (BoM), **Marcus Thatcher** (CSIRO), **Ben Jones** (AEMO)
2:45 – 3:15pm	**Afternoon Tea**	
3:15 – 4:15pm	**Workshop what you need do you need to mitigate risks identified this morning.** Each group is allocated to a specific high-level industry process from: • *what do you need to mitigate the risks identified in the morning?* • *what improvements are needed to process?* • *what data do you need?* • Participants will be guided by the whiteboard from the previous session. • Present back on findings Participants may wish to consider potential solutions according to work package themes for the ESCI project:	**Ben Jones** (AEMO), **Katrina Proppe** (Select Right)
4:15 – 4:30pm	**Summary and Close**	**Ben Jones** (AEMO)

9 Annex B: Climatological Background

9.1 Single days of extreme heat

Large-scale heatwaves are those that cover a broad area of the Australian continent. Large-scale heatwaves are a feature of the climate of Australia. Typically, they occur when the movement of high pressure systems across the continent is slowed. Slow moving or stationary high pressure systems allow clear skies to persist over the interior of Australia, which is associated with a build-up of heat during the warmer months of the year.

The geographical position of high and low pressure systems governs which parts of the country experience this heat on any given day. Typically, northwesterly winds bring concurrent heatwave conditions to southeast South Australia, Victoria, Tasmania, southern New South Wales and the Australian Capital Territory as they direct hot air masses from the continental interior over those regions. Eastern New South Wales and southeast Queensland tend to experience summer heatwaves under the influence of westerly winds. South-west WA has summer heatwaves under the influence of northeasterly winds.

Due to the nature of the weather patterns involved in these heatwaves, it is difficult to have extreme conditions on individual days concurrently affecting Brisbane, Sydney and Melbourne. This is because weather patterns that are associated with northwesterly winds over southeast Australia tend to preclude westerly winds along the New South Wales and southeast Queensland coasts on the same day.

Hence, it is very rare for the heat to extend from north-to-south (Brisbane to Melbourne) and east-to-west (Sydney to Adelaide) at the same time. Much larger counts of hot days or nights are found when grouping the cities into smaller, regional areas such as north (Brisbane and Sydney), south (Melbourne, Hobart and Adelaide) or east (Brisbane, Sydney and Canberra).

Since 1960, there have been no instances of days over 35 °C concurrently in Brisbane, Sydney and Melbourne. However, there are numerous instances of concurrent days over 30 °C in those cities. For extreme and large-scale heat days, it is more typical to see an extreme event affecting south-west WA first, then southeast SA, Victoria, Tasmania, southern NSW and ACT the next day, most of New South Wales in the next 24-hours, and southeast Queensland the following 24 hours.

The presence of favourable winds is not a necessary condition for extreme heat in Adelaide and Melbourne during summer, which can experience temperatures in the high 30s under stable conditions. For the greater Sydney and Brisbane areas, westerly winds are generally required for extreme heat across in both coastal and inland locations, since the influence of a cooling sea breeze in more coastal locations is typical without this influence. Using inland locations for Sydney (Richmond) and Brisbane (Amberley) — since 1960 there have been eight instances of concurrent daytime temperatures above 35 °C at Melbourne, Canberra, Richmond and Amberley, and four instances of temperatures above 35 °C at Adelaide, Melbourne, Canberra, Richmond and Amberley.

There are relatively frequent occurrences of concurrent extreme heat at Adelaide, Melbourne and Richmond.

9.2 Multi-day heatwaves

Using the 3-day window of combined daytime and overnight extreme temperatures, there are many more instances of concurrent heatwave conditions across all eastern capital cities.

The combination of Brisbane, Sydney, Canberra, and Adelaide has had 12 concurrent heatwave days in the past 57 years (or 15 days when using Amberley and Richmond instead of Brisbane and Sydney respectively) and three instances of heatwaves affecting Adelaide, Hobart, Melbourne, Canberra, Sydney and Brisbane at the same time — on 14 February 1981; 2 February 1993; and 1 January 2015.

9.3 Trends

Australia is warming. A brief summary of temperature trends, including trends in heatwaves and fire weather, is contained in the **State of the Climate 2018 report**, and references for temperature trends accompanying the report.

It should be noted that while there is a clear trend in the number of days with widespread extreme heat (days in the 99th percentile for temperatures, figure B1) — there are no clear trends in the geographical extent of those days. This is likely due to the limitation imposed by the necessary weather patterns for such events described previously. In this way, there is a trend toward more frequent individual hot days at most locations, and there is a trend in many (not all) locations toward more frequent, longer lasting and hotter heatwaves — but no clear trend in the number of concurrent extreme days across Melbourne, Sydney and Brisbane. Very high monthly maximum or minimum temperatures that occurred around 2 per cent of the time in the past (1951–1980) now occur around 12 per cent of the time (2003–2017). Multi-day heat wave events have increased in frequency and duration across many regions.

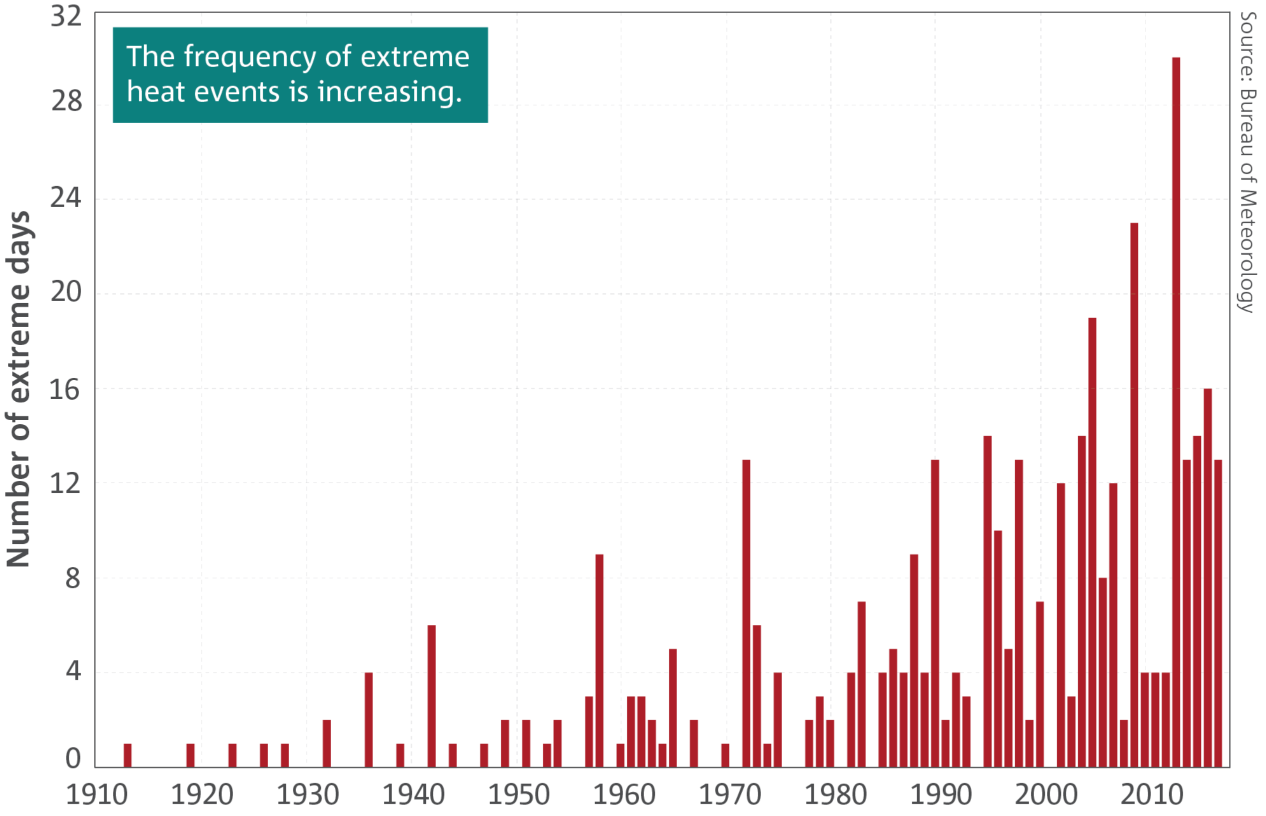
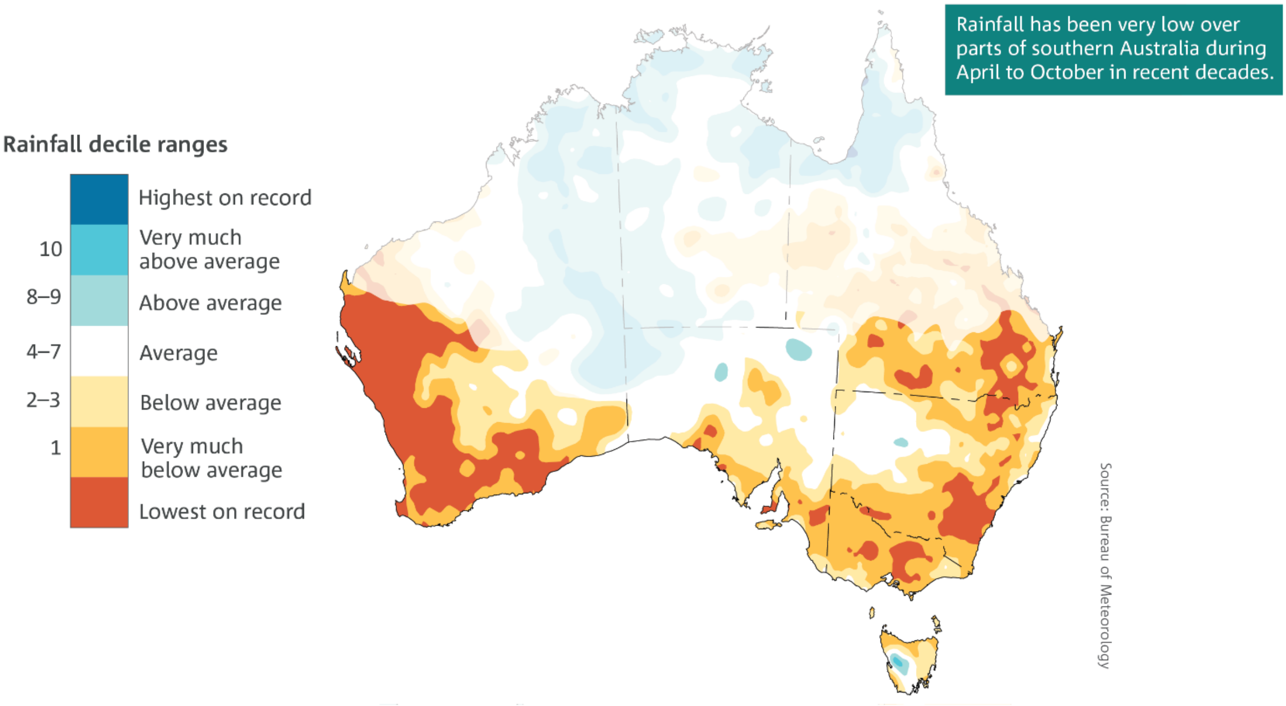


Figure B2: Number of days each year where the Australian area-averaged daily mean temperature is extreme. Extreme days are those above the 99th percentile of each month from the years 1910-2017. These extreme events typically occur *over a large area, with generally more than 40 per cent of Australia experiencing temperatures in the warmest 10 per cent for that month.*

Australian rainfall varies greatly from one year to the next and from one decade to the next and is strongly influenced by phenomena such as El Niño and La Niña. Despite this large natural variability, underlying longer-term trends are evident in some regions.

There has been significant drying across southern Australia, especially across April to October (figure B2). For the southeast of the continent, rainfall for the period 1999 to 2018 has decreased by around 11 per cent compared with the 1900 to 1998 period. The recent period encompasses the Millennium Drought, which saw low annual rainfall totals across the region from 1997 to 2010. The drying trend is particularly strong between May and July over southwest Western Australia, with rainfall since 1970 around 20 per cent less than the average over 1900 to 1969. Since 1999, this reduction has increased to around 26 per cent.



Rainfall has been very low over parts of southern Australia during April to October in recent decades.

Source: Bureau of Meteorology

Figure B3: April to October rainfall deciles for the last 20 years (1999–2018). Areas across northern and central Australia that receive less than 40 per cent of their annual rainfall during April to October have been faded.

10 Annex C: Scenario climate and historical context

This scenario for 2021-2023 has been conceived as a sequence of antecedent (precursor) climate events, ahead of a record-breaking heatwave at the summer peak. It includes the influence of global warming trends interacting with naturally-occurring climate variability over that three-year period — in a combination and sequence that is consistent with the patterns of historical weather and climate in Australia. This Annex shows how the scenario events were developed to be slightly beyond those captured in the recent historical record. Examples are given of maps used to generate the scenario and their historical context. An important consideration in the scenario is the impact on the hydrological cycle of drought conditions in a historically warm climate. This includes evaporation, soil moisture content and runoff, which impact streamflow and water storage levels.

10.1.1 Antecedent conditions

- A prolonged (multi-year) drought, with similar characteristics to the Millennium Drought, is affecting the whole of southeast Australia. Figure C1 shows rainfall deciles for 2006, at the peak of the Millennium Drought. This was Victoria's third driest year on record.
- The 2021-2022 summer saw near-El Niño conditions in the Pacific, with very dry conditions across southeast Australia. Figure C2 shows an historical example from 1982, which is Victoria's second driest year on record, and the fifth-driest year on record for New South Wales.

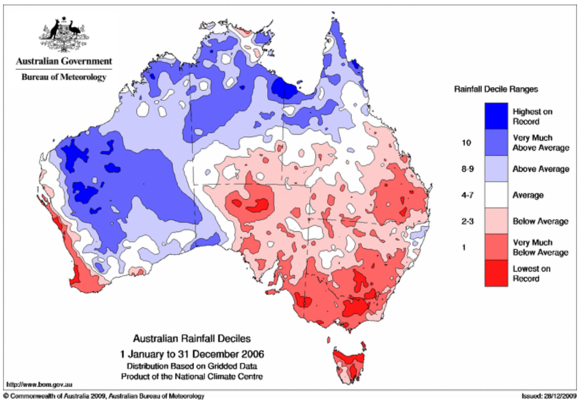


Figure C4: Rainfall deciles for 2006 (based on all years of data since 1900).

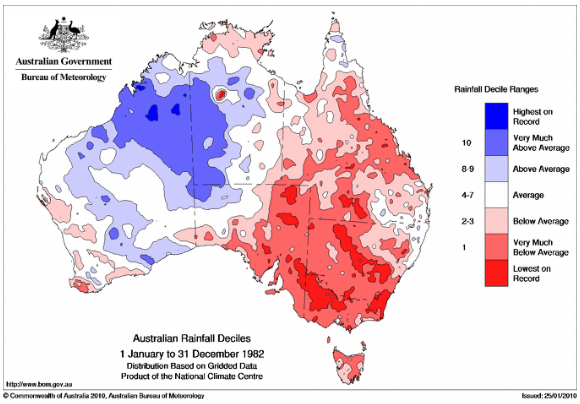


Figure C5: Rainfall deciles for 1982 (based on all years of data since 1900).

- Winter 2022 saw very warm and dry conditions across southeast Australia, affecting SA, VIC, TAS and southern NSW, driven by Indian Ocean temperatures. Figure C3 shows the scenario rainfall for winter 2022. This is the combined lowest rainfall from 1982 and 1997. These years saw strong El Niño conditions contributing to a positive phase of the Indian Ocean Dipole (IOD), both of which typically result in below average winter rainfall (figures C4 and C7).
- The conditions also reduce soil moisture and lead to the further curing of vegetation, elevating the bushfire risk.
- Streamflows are substantially reduced across eastern Australia. Low flows in particular are observed in southern Murray-Darling basin, Victoria and Tasmania.

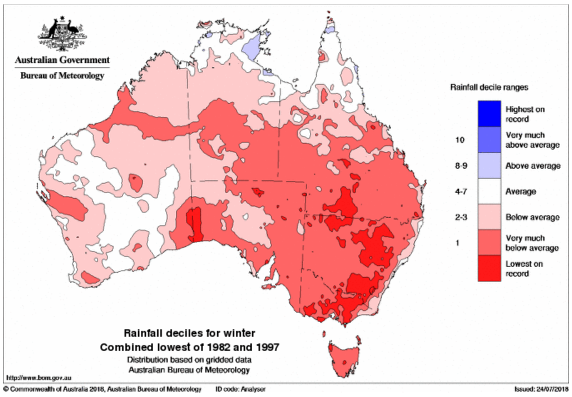


Figure C6: Scenario rainfall deciles (relative to 1900-2018) for winter 2022. This is computed using the lowest rainfall in winter 1982 and 1997.

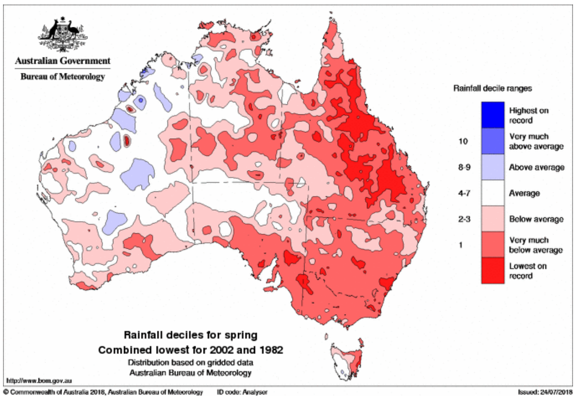


Figure C8: Scenario rainfall deciles (relative to 1900-2018) for spring 2022. This is computed using the lowest rainfall in spring 2002 and 1982.

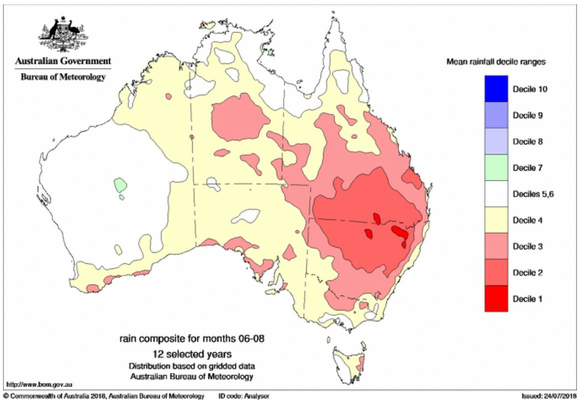


Figure C7: Composite average rainfall deciles (based on all years since 1900) for winter during 12 years with El Niño events.

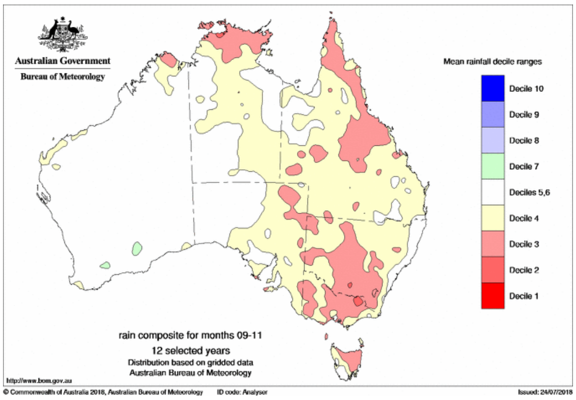


Figure C9: Composite average rainfall deciles (based on all years since 1900) for spring during 12 years with El Niño events.

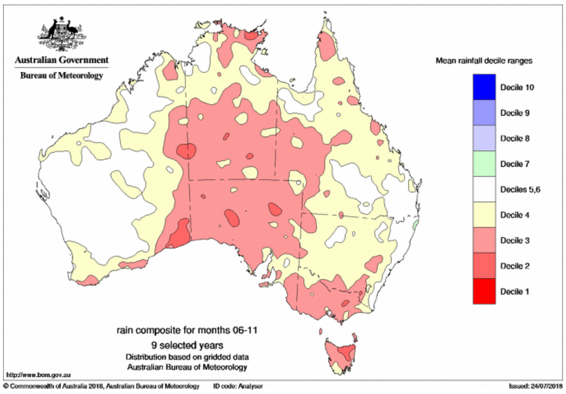
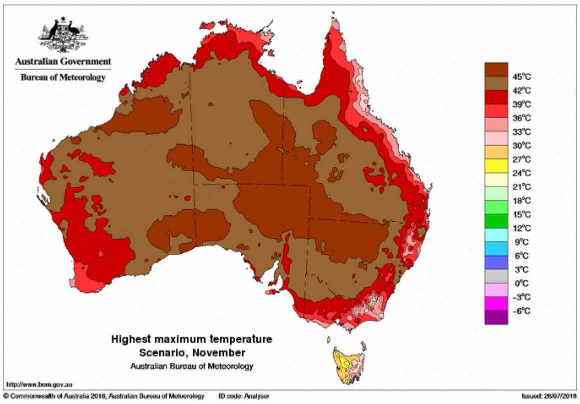


Figure C10: Composite average rainfall deciles (based on all years since 1900) for winter and spring during 9 years with positive IOD events.

10.1.2 Spring 2022

- An early start to spring, with record-breaking heat in August.
- The dry conditions continue across much of eastern Australia (figure C5), as the El Niño-like conditions continue to drive a positive phase of the IOD. Historically, both events are more likely to result in below average spring rainfall (figures C6 and C7).
- Summer-like conditions occur from September onward, with a heatwave in November peaking at over 40 ^{o}C in Adelaide, Melbourne and western Sydney, followed by Brisbane as the heat moves

north. The scenario peak maximum temperature for November 2022 is shown in figure C8, based on maximum temperatures for November 2014 (shown in figure C9 as deciles) and November 1982.



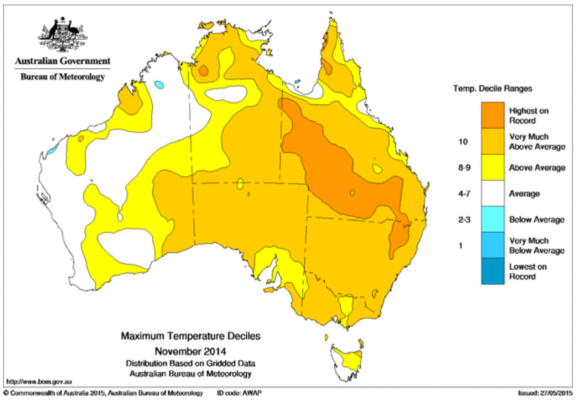


Figure C12: Mean maximum temperature deciles for November 2014.

Figure C11: Scenario highest daily maximum temperature reached during November 2022. This is computed using the highest daily maximum temperature for November 2014 (increased by 0.5 °C) and November 1982 (increased by 1.0 °C).

- As a result of the hot and dry conditions, there is a very active spring bushfire season in northern NSW and southeast QLD including northern rivers and inland border regions. This is reflected in peak daily FFDI in in the Severe to Extreme categories in November 2022 (figure C10).
- Widespread dust storms across Victoria and NSW.

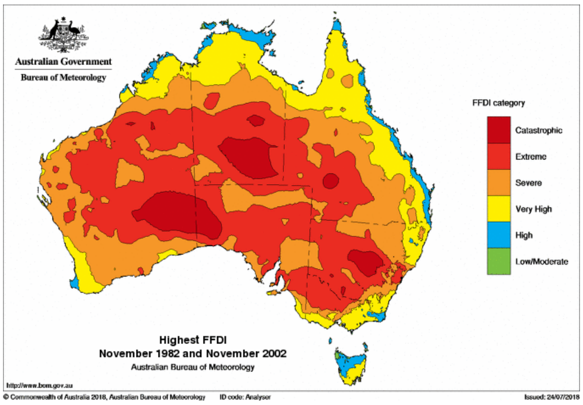


Figure C13: Scenario highest daily FFDI reached during November 2022. This is computed combining the highest daily FFDI for November 1982 and November 2002.

10.1.3 Late 2022

- A hot start to summer, with a succession of slow-moving high pressure systems over large parts of central and southeast Australia. Cool changes are weak and brief, as frontal systems fail to push significantly into the subtropical-ridge and slip south of the continent as heat continues to build over inland Australia.
- The persistent and large high pressure lead to generally calm conditions, high overnight minimum temperatures and a continuation of the severe rainfall deficiencies.
- A 3-day heatwave affected South Australia and Victoria prior to Christmas, peaking at 43 ^{o}C in Adelaide and 41 ^{o}C in Melbourne. Examples of recent December heatwaves are shown in figures C11 and C12 for 15-18 December 2002 and 16-19 December 2015 respectively.

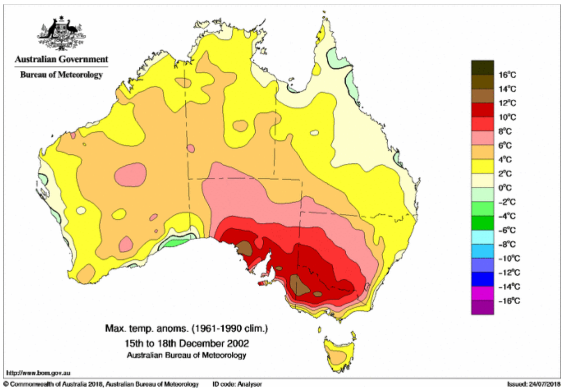


Figure C14: Mean maximum temperature anomalies (1961-1990 climatology) for 15-18 December 2002.

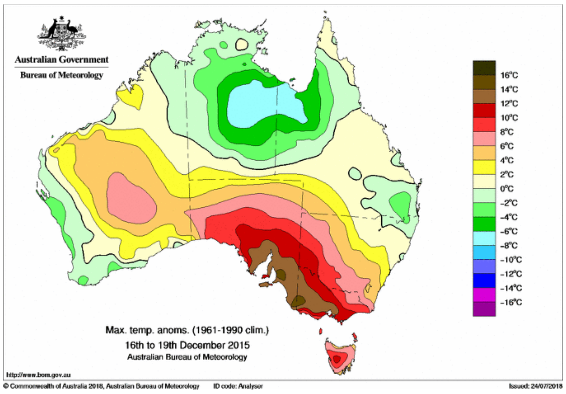


Figure C15: Mean maximum temperature anomalies (1961-1990 climatology) for 16-19 December 2015.

10.1.4 January 2023

- An extended, two-week January heatwave affects the eastern states, after starting in southern Western Australia in early January, with intense heat in the first week, and little relief in the second. The scenario daily maximum temperatures are shown in figure C13. They are based on 25 January-7 February 2009, with notional dates of 4-18 January 2023.
- A stationary high over the Tasman Sea directed hot, dry air across the country and into the southeast, aided by a severe Tropical Cyclone off the northwest coast of Australia (which strengthens the upper ridge through anticyclonic potential vorticity advection).
- Victoria records four consecutive days over 41 ^{o}C, with three over 43 ^{o}C and elevated heat conditions overnight. Heat wave conditions persist over some part of eastern Australia for over two weeks. Several regional towns break their all-time temperature records, with temperatures around 48 ^{o}C. Many locations exceed forecast maximum temperatures. Winds are lower than expected overnight.
- The intense heat reaches northern Tasmania. Temperatures reach 41 ^{o}C at Launceston on days 5 and 6 of the event and approach 35 ^{o}C along the Tasmanian north coast.
- Historically, January 2009 saw highest daily maximum temperatures of over 42 ^{o}C over much of Victoria, South Australia and inland New South Wales (figure C14). At the peak of January heatwaves in 2009 and 2014, mean daily maximum temperatures over a 4 day period were over 12 ^{o}C above the 1961-1990 climatological average (figures C15 and C17). The January 2014 heatwave was rated as "L4 Severe" at its maximum severity (figure C16).

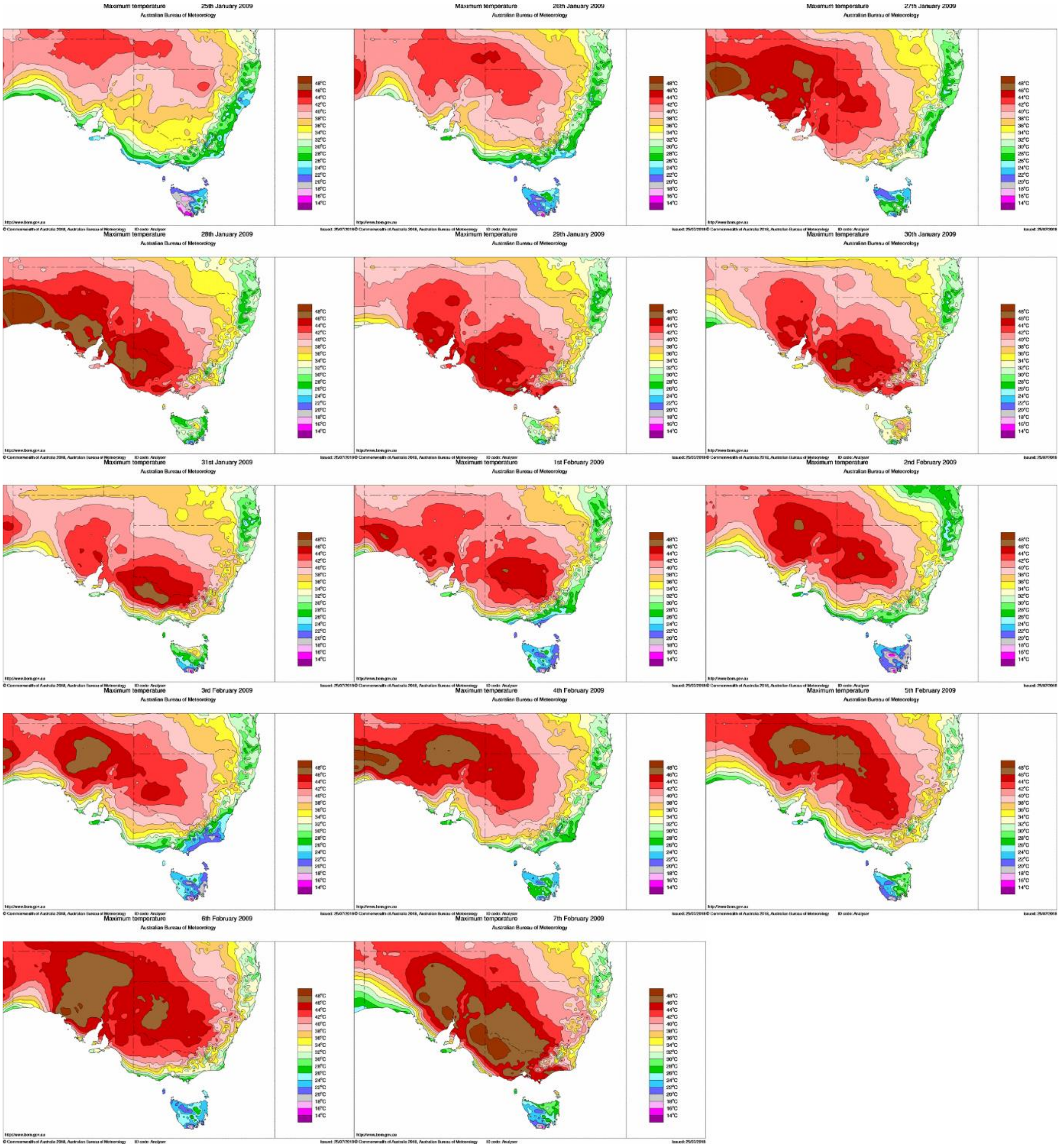


Figure C16: Scenario daily maximum temperatures for 4-18 January 2023. This uses daily maximum temperatures from 25 January 2009 to 7 February 2009, increased by 1 °C.

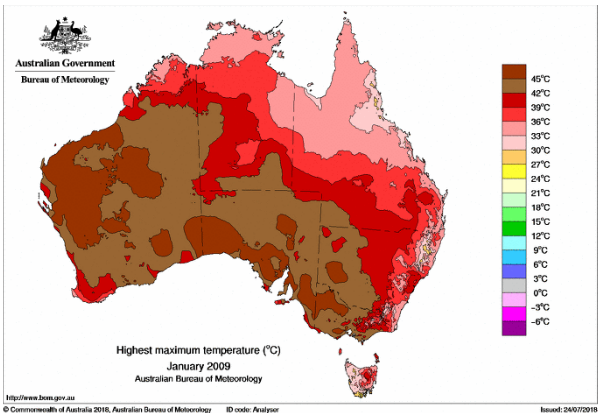


Figure C17: Highest maximum temperature during January 2009

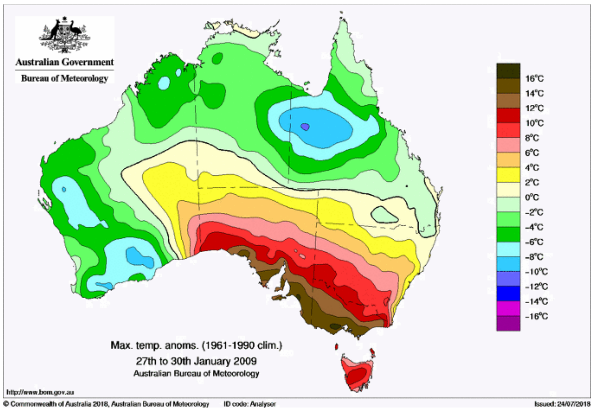


Figure C18: Mean maximum temperature anomalies (1961-1990 climatology) for 27-30 January 2009.

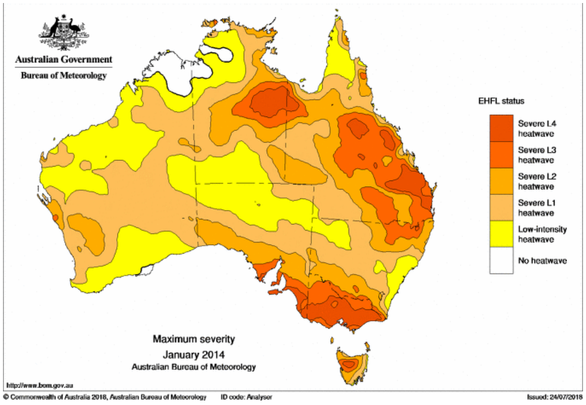


Figure C19: Highest heatwave severity during January 2014.

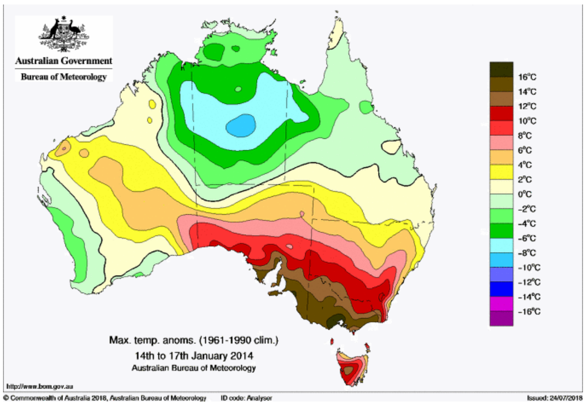


Figure C20: Mean Maximum temperature anomalies for (1961-1990 climatology) for 14-17 January 2014.

10.1.5 February 2023 heat wave and bushfires

- An unprecedented February heatwave event, and bushfires fanned by gale force winds and record-breaking temperatures, provides an extreme climax to the sequence of heatwaves since November 2022.
- The duration and intensity of the heatwave are unprecedented for South Australia and Victoria for February, lasting for 6 days, (with a slow moving high or extended ridge south of the continent; similar to the week before Black Saturday, 7 February 2009) — with critical extreme weather days in the middle of the week.
- Friday 3 February 2023 saw the first of five days of at least 41 ^{o}C in Adelaide. The extreme heat reaches Melbourne on Saturday, the first of four days above 40 ^{o}C. Temperatures in the high 30s or low 40s persisted in Canberra, Sydney and Brisbane over most of the 3-9 February 2023 period. There are calm conditions over the southeast over 3-6 February 2023.
- On Tuesday 7 February 2023, increased winds drive temperatures in Adelaide to a record-breaking 49.2 ^{o}C.
- The approaching front also drives temperatures in Melbourne to 45 ^{o}C late on Tuesday 7 February 2023. The scenario daily maximum temperatures for 7 and 8 February 2023 are shown in figures C18 and C19. They are based primarily on Black Saturday, increased by at least 2 ^{o}C. This equates to anomalies over 16 ^{o}C above the 1961-1990 climatological average.

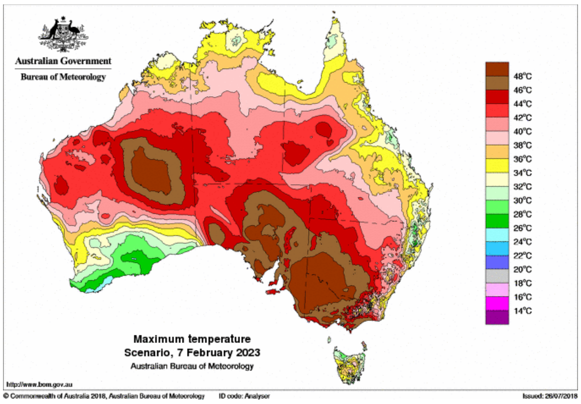


Figure C21: Scenario maximum temperature on day five of the February 2023 heatwave. This combines the daily maximum temperatures of 7 February 2009 and 2 February 2014, increased by two or more degrees.

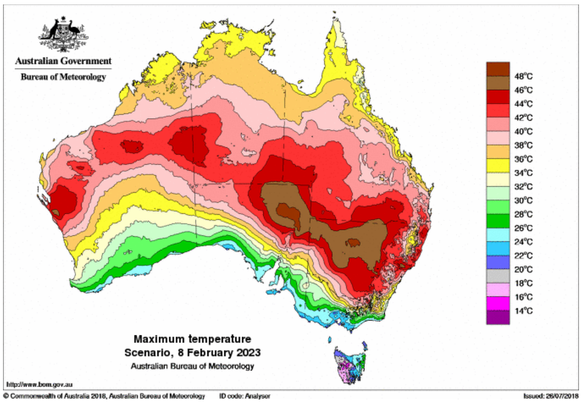


Figure C22: Scenario maximum temperature on day six of the February 2023 heatwave. This combines the maximum temperatures of 8 February 2009 and 21 February 2004, increased by two degrees.

- Fire danger reaches Catastrophic or Code Red (the Fire Danger Index is increased due to the prolonged drought and lack of soil moisture). The approaching front on Tuesday 7 February 2023 sees a number of bushfires ignite, then fanned by the high winds. Scenario FFDI for 7 February 2023 is shown in figure C20. The region of Extreme to Catastrophic FFDI is comparable to the combined regions for Black Saturday and Ash Wednesday (16 February 1983) (figure C21).

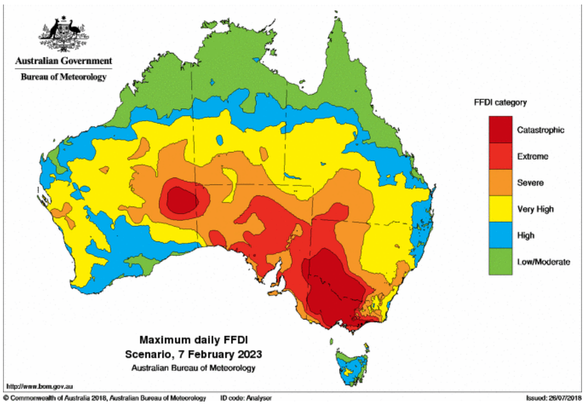


Figure C23: Scenario daily FFDI on day five of the February 2023 heatwave. This combines the maximum daily values of 7 February 2009 and 2 February 2014, increased by at least 10%.

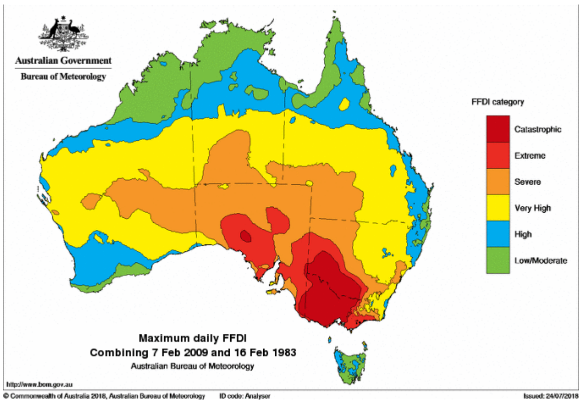


Figure C24: Combined highest daily FFDI on 7 February 2009 and 16 February 1983.

- The heatwave persists into Wednesday 8 February and Thursday 9 February 2023 in NSW and Sydney.
- Wednesday 8 and Thursday 9 February 2023 see Southeast QLD and Brisbane affected by severe thunderstorms.

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