Climate Systems

National Environmental Science Program

Deluge and drought: Insights into swings between dry, wet, and hot-and-dry conditions

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For further information about this report contact Christine Chung, Bureau of Meteorology, christine.chung@bom.gov.au

The Climate Systems Hub acknowledges the Tradition Custodians of the land across Australia where this work occurred. We pay our respects to Elders past and present and recognise the important role traditional knowledge plays in understanding Australia's climate.

CONTENTS

Executive summary

This report provides a comprehensive summary of the research delivered by the *Extreme climate: dry, wet, hot-and-dry* project, conducted under the National Environmental Science Program's Climate Systems Hub. The research enhances our understanding of extreme climate conditions experienced in Australia, focusing on the transitions between dry, wet, and hot-and-dry periods. This provides new insights into the characteristics of drought, a quantified influence of large-scale climate drivers on recent climate extremes, and an evaluation of the ability of current-generation climate models to simulate these relationships. Projections of future climate are also discussed, with a focus on drought risk and changes to large-scale climate drivers.

KEY TOPICS

Characterising drought: The report summarises new methodologies for understanding meteorological drought patterns, including the identification of eight key rainfall archetypes. Factors influencing the onset of 'flash droughts,' which can develop rapidly and have significant impacts, are also discussed. Tailored regional drought information has been developed with and provided to several stakeholders, including the Australian Wildlife Conservancy, through this project.

Large-scale climate drivers: The project examined the roles of three major climate drivers in influencing Australia's rainfall variability: the El Niño–Southern Oscillation (ENSO), the Southern Annular Mode (SAM), and the Indian Ocean Dipole (IOD). Essential studies were conducted on how much extreme rainfall can be attributed to ENSO, and how consecutive La Niña events impact Australian rainfall. The ability of climate models to simulate the relationships between climate drivers and rainfall is also evaluated, finding a significant improvement in the representation of relationships with winter and springtime rainfall.

Co-design resulting in decision-ready science: Detailed case studies provide practical insights into the real-world implications and applications of these climatic phenomena, including on what caused the extreme wet conditions in eastern Australia from 2020 to 2022, and regional drought projections to the Australian Wildlife Conservancy.

We also include a case study that highlights how our early-career practitioners saw firsthand the impacts of climate-related events on communities and learnt how stakeholders in northeast NSW could use information from this project.

Introduction

"Australia is a land of stark beauty and extraordinary extremes. Our climate is one of the harshest and most unpredictable in the world, with periods of drought followed by devastating floods." - Tim Flannery

Australia is a land of extremes. In recent decades, understanding the behaviour of Australian climate and its place in the global climate system has advanced tremendously. However, we are still faced with numerous challenges when it comes to being a land of ‘drought and flooding rains’.

This is made clear in recent years. The severe drought conditions in 2018 and 2019 which culminated in some of the worst bushfires in recorded history in southeast Australia (Abram et al. 2021), are immediately followed by three very wet years that resulted in several catastrophic floods. Both these drought and extreme wet periods are associated with swings in Pacific and Indian Ocean sea surface temperatures along with shifts in Southern Hemispheric winds. However, there are many aspects yet to explore on how droughts start, intensify and end, and how these flip into periods of extreme wet that can remain for years, as in the most recent period. The NESP Climate Systems Hub’s *Extreme climate: dry, wet, hot-and-dry* project explores key questions concerning drought, prolonged wet conditions, and the processes influencing year-to-year swings in unusually dry or wet conditions, like those experienced from 2018 to 2022.

Specifically, the project provides new ways of characterising important aspects of extreme rainfall patterns and drought. It performs an Australia-wide analysis demonstrating how rapidly soil moisture can change to drought conditions. The project also examines the impacts of climate change on the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Southern Annular Mode (SAM), as well as their interrelationships. It quantifies their role in Australia’s highly variable rainfall. This includes stakeholder-focused research on the extremely wet conditions and triple La Niña of 2020–2022, which affected much of eastern Australia, jointly conducted with the hub’s *Extreme events explained* project.

The *Extreme climate: dry, wet, hot-and-dry* project aims to better understand drought impacts and provide tailored drought projections information to decision makers, including the Australian Wildlife Conservancy, for their species-based and property-based vulnerability assessments. This report summarises the main activities and outputs of the project and provides links to detailed articles and journal papers for further information. While much of this research is relevant Australia-wide, some results were targeted to specific regions.

Multiple approaches are used by the project team to understand the characteristics and dynamics of extremely wet conditions, droughts, and hot-and-dry events. They investigate the science and seek input from decision makers. Throughout the course of the project, the team produced a range of co-designed outputs, led targeted engagement sessions, and published peer-reviewed journal articles.

Knowing more about what is important on the ground means the research provides new insights and can be used to prepare for future events.

Acknowledgements

We thank all the project team and stakeholders, including state government and local decision makers significantly affected by wet conditions over recent years, non-government organisations such as the Australian Wildlife Conservancy, Australian government agencies such as the Australian Climate Service, CSIRO Drought Mission, and others.

Research	Knowledge Brokering and Communication	Stakeholders
Ghyslaine Boschat (Bureau of Meteorology)	Helen Bloustein (DEECA, Victoria)	Australian Climate Service
Christine Chung (co-lead; Bureau of Meteorology)	Tahnee Burgess (Monash)	CSIRO Drought Mission
Ailie Gallant (co-lead; Monash)	Eliza Keck (CSIRO)	Australian Wildlife Conservancy
Zoe Gillett (ECP; co-contributor; Bureau of Meteorology, UNSW)	Elise Lesuma-Mitchell (ANU)	DCCEEW
Pallavi Goswami (ECP; Monash)	Tanya Wilkins (CSIRO)	State Government departments and agencies, local community groups and councils
Dewi Kirono (co-lead; CSIRO)		Ramsar wetland management (via DCCEEW)
Huazhen Li (ECP; UNSW)		Climate Services for Agriculture
Shayne McGregor (Monash)		NESP Resilient Landscapes Hub
Didier Monselesan (CSIRO)		Agricultural sector, specifically southern and southeastern Australian cropping sector
Yann Planton (ECP; Monash)		NSW Reconstruction Authority
James Risbey (CSIRO)		Hydrological Services, Bureau of Meteorology
Vanessa Round (CSIRO)		
Andrea Taschetto (UNSW)		

Table 1 Project members and primary stakeholders involved in the project. The project benefited from the productivity, energy and fresh perspectives of our four early career professionals (ECPs). Project members (above) are listed alphabetically.

Characterising drought

Drought is a significant feature of Australia's climate, due to the large natural variability in rainfall. There are many definitions for drought, but a common feature is the occurrence of reduced rainfall over a prolonged period. Meteorological drought refers to a shortfall in rainfall compared to the average, whereas hydrological drought reflects its impact on water sources, such as streamflow and groundwater. Agricultural drought is determined by the impact of water availability on agriculture, such as crop losses resulting from low soil moisture.

Droughts can also be defined over different time periods depending on what is relevant to a particular purpose. For example, ongoing low average rainfall may be more relevant to water resource management. In contrast, an acute period of low rainfall over several months may be more important to agriculture or emergency services. In this project, we consider different types of droughts and tackle the challenge of characterising and quantifying these various aspects of drought in a highly variable climate, through three lenses:

1) identifying the characteristics of extreme monthly rainfall patterns. This results in new insights on how Australia emerges from drought.
2) analysing properties of rapid-onset droughts (commonly known as 'flash droughts'). This leads to a new understanding on how Australia transitions to drought.
3) using insights from the Standardised Precipitation Index (SPI) and other climate data and information to provide tailored regional drought information to a range of stakeholders.

New insights into how Australia emerges from drought

Australia is a large continent with varying rainfall and drought patterns. No two years evolve in the same way. However, finding common patterns in our rainfall can help us understand and predict the future. Understanding how the country emerges from drought can provide essential insights into periods of extreme rainfall deficit. Using a technique known as 'archetypal analysis', researchers from this project were able to identify eight key patterns, or 'archetypes', in extreme rainfall across the country. This method enables us to recognise when these patterns become apparent, their duration, and the transition from one to the other. Figures 1 and 2 on the next page summarise these eight patterns.

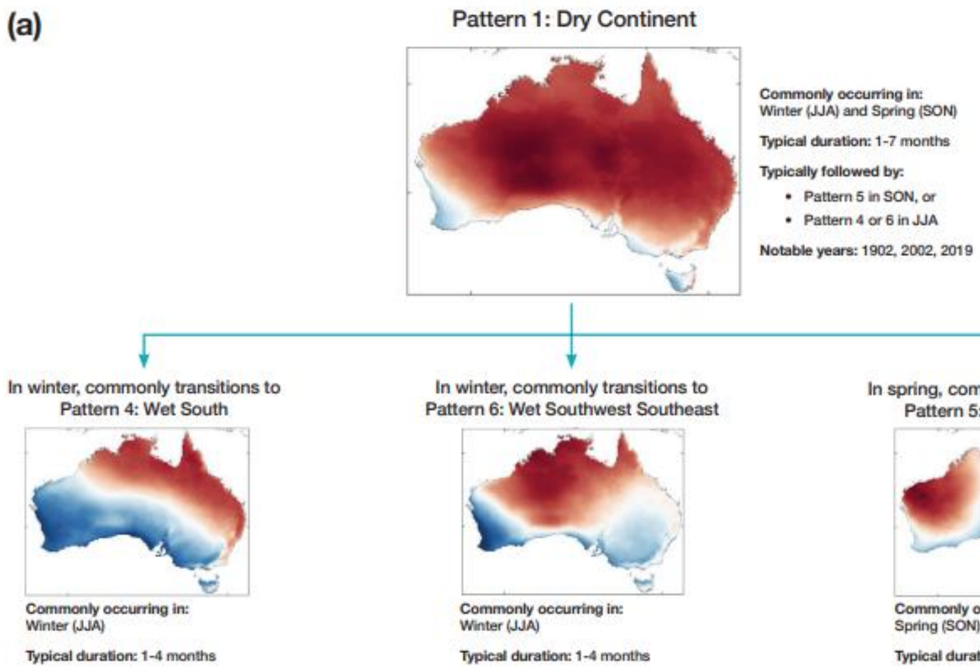

Figure 1: The most commonly occurring rainfall pattern, the Dry Continent, its key characteristics and its typical transitions.

The research found that the most commonly occurring rainfall pattern corresponded to a Dry Continent (Pattern 1; Figure 1 – above).

Dry Continent occurs mostly in winter and spring and can last for up to seven months. How we move out of a Dry Continent pattern, and the patterns that replace it, depends on the time of year. During winter, the Dry Continent pattern conditions are often replaced by patterns 4 and 6, which are emphatically wetter in southwest Australia, and a bit wetter in southeastern Australia. However, if the continent-wide dry pattern does not break until spring, then it is commonly replaced by Pattern 5, which favours wet conditions in southeast but not southwest Australia. This pattern was strongly expressed in years like 1902, 2002, and 2019, which were particularly dry years in Australia.

The second most common pattern is the Wet Continent (Pattern 2; Figure 2 – next page). This pattern is most common in the summer months when the monsoon is active in the northern part of the continent. It was particularly evident in 1974 and 2010–2011, which were particularly wet years for Australia. These wet conditions are usually shorter-lived than the Dry Continent pattern, transitioning to Patterns 3, 7 or 8 within the same summer season.

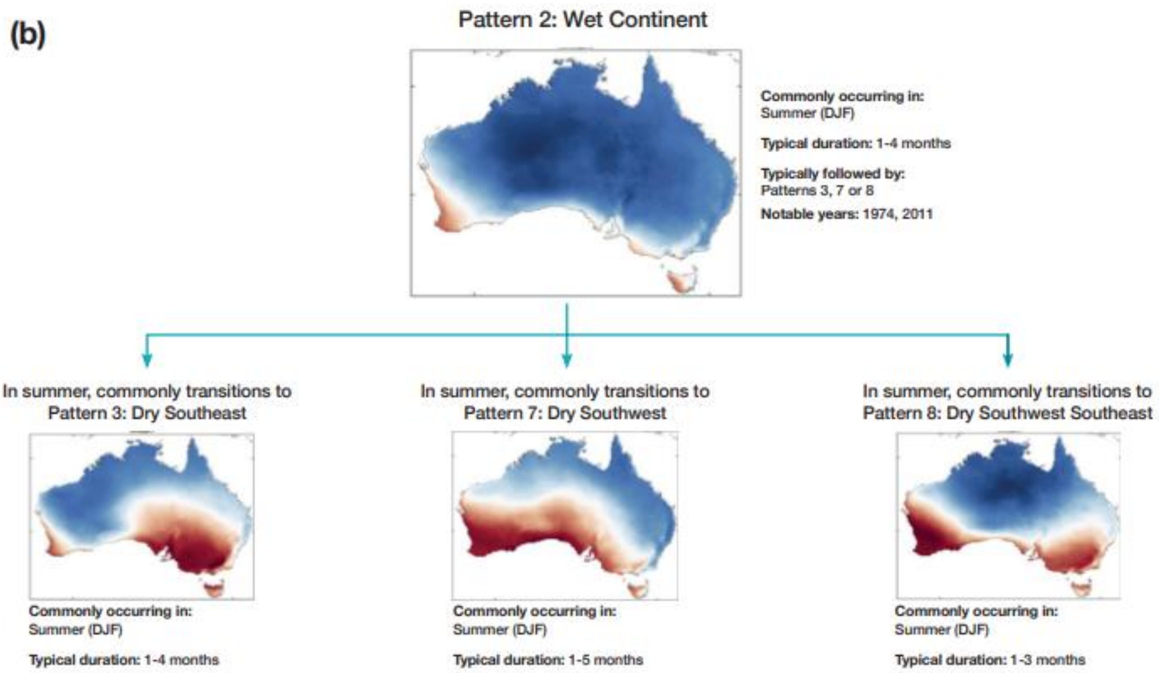

Figure 2: The second most commonly occurring rainfall pattern, the Wet Continent, its key characteristics, and its typical transitions

This new approach to understanding the typical way that rainfall shifts over time has been used to better prepare for drought in marginal grain zones for CSIRO's drought mission. In that work, analysis of the rainfall archetypes was extended to link them with grain yields from crop models. When combined, the analyses were used to identify periods of repeated dry years that were challenging for grain farms. The rainfall archetypes are also being used in work for the Australian Climate Service to identify drought periods and regions, characterising drought risk for regional sectors. More information on this work can be found in the New insights into how Australia emerges from drought explainer.

Rapidly emerging 'flash droughts'

Much of the existing research on droughts focuses on slow-developing phenomena that take months or longer to onset. However, recent studies identify that some droughts intensify more rapidly. These rapidly emerging droughts have been referred to as 'flash droughts' in the scientific literature, and they can have significant impacts on agriculture ecosystems, water resources and the natural environment. Researchers conducted studies to examine rapid transitions from near-normal to drought conditions (later defined) for soil moisture and streamflow to identify conditions that have the potential to cause high-impact and rapid effects in agricultural, ecological and hydrological systems.

Our results show that such transitions between near-normal and drought conditions can occur in as little as two weeks, and that these conditions can be sustained for months in some instances.

Our first study compared how soil moisture transitions into drought conditions across Australia. This challenged typical characterisations that drought takes months to onset and quantified the time scale of drought emergence across Australia. We also investigated how quickly the fastest droughts, or 'flash droughts', can emerge and what causes them to onset so rapidly.

Transitions to soil moisture drought are typically defined as events where 5-day averaged root zone (top 1m) soil moisture transitions from near normal conditions (or wet conditions) to dry conditions relative to the climatology, and these dry conditions are maintained for at least 20 days.

Our findings show that the rate of drought onset varies across the country, but is much quicker than our traditional perception. Most locations transition from near-normal (above the 40th percentile) to sustained drought conditions (at or below the 20th percentile) in just three to four weeks, with some regions in as little as two weeks (Figure 3a). In parts of southwest, south, southeast, and northern Australia, soil moisture drought conditions typically develop within 15–20 days, while central Australia and the east coast have slightly longer onset times of around 20–30 days. In some instances, those drought conditions are sustained for several months. Some of the fastest onset droughts take as little as two to three weeks at most locations (Figure 3b). Again, the most rapid drought onset times were in parts of the southwest, south, southeast, and northern Australia, at approximately 10–15 days (as illustrated by the brown and dark orange shades on the map); while the rate of rapid onset in central Australia and parts of the east coast were around 20 days. These results demonstrate that Australia's soil moisture typically dries quickly, faster than those rates of flash droughts that are reported from studies carried out in other parts of the world.

The preliminary results from this work were also presented at the hub webinar Drying out: Looking at the summer ahead and beyond in October 2023.

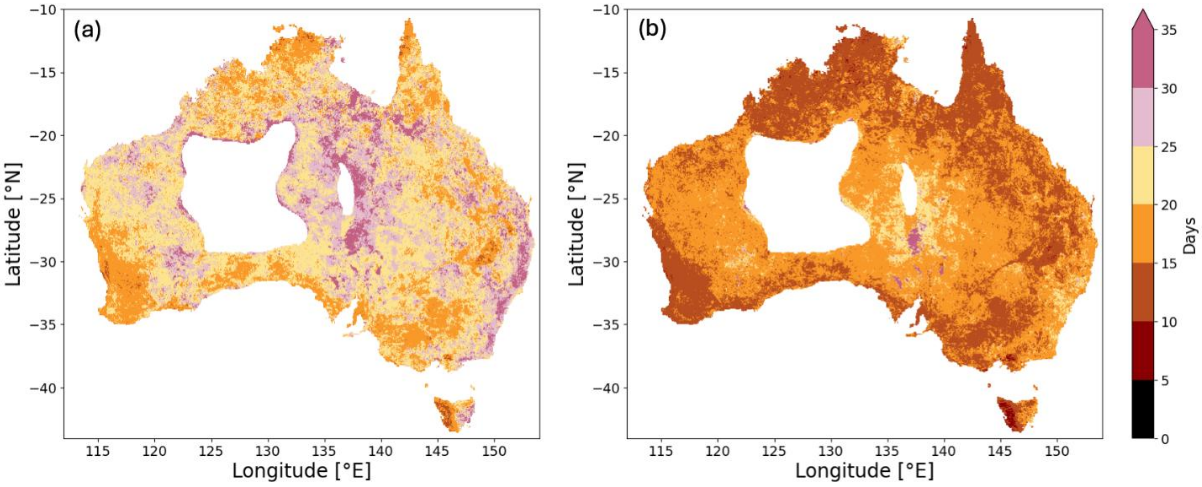

Figure 3: Spatial patterns of the (a) median and (b) the top 10% (i.e. most rapid) of the time to drought onset over Australia using root zone soil moisture data from the Australian Water Resource Assessment Landscape model (AWRA-L), Bureau of Meteorology (Frost et al, 2018). Drought onset is defined as the period in which root zone soil moisture changes from being near-normal (i.e. above the 40th percentile) to well below normal (i.e. at or below the 20th percentile). Areas in white represent regions with insufficient observations and were excluded from the analysis.

Researchers found that both rapid and typical transitions into soil moisture drought have similar underlying meteorological causes. These include abnormally low rainfall, a 'thirsty' atmosphere (e.g. low humidity), and less cloudy conditions (i.e. higher solar radiation). However, the faster transitions to soil moisture drought are distinguished by significantly higher magnitudes of these atmospheric anomalies during onset. For example, very low rainfall, very low humidity, and near-cloudless conditions, such as those that led to flash droughts in parts of southwest Western Australia in 2000 and 2006.

Through this research, engagement with the Bureau of Meteorology's Hydrological Services experts also raised questions about droughts in hydrological systems. Ongoing, aligned engagement has led to research into the existence of rapid declines in streamflow levels, resulting in hydrological droughts. This new research investigates streamflow records from undisturbed perennial catchments across Australia to establish how rapidly streamflow can change. Our preliminary work shows that rapid transitions from near-normal to low flow can occur in as little as two weeks, with typical reductions (as measured by the median reduction) of nearly 70% when such rapid transitions occur. Our research indicates that instances of streamflow flash droughts have occurred in numerous catchments in Victoria and New South Wales during the Millennium Drought (2001–2009) and the Tinderbox Drought (2017–2019).

We highlight that transitions to abnormally dry soil moisture and streamflow conditions can occur rapidly and have a significant impact on both the agricultural sector and the natural environment. The outcomes of this research aim to advance our understanding of sudden and unexpected reductions in water availability. Engagement with the Bureau of Meteorology, CSIRO Drought Mission, and the NSW Reconstruction Authority has focused ongoing research on developing information about these rapid transitions to low moisture availability and their compounding effects throughout the hydrological cycle.

The information from our research on flash droughts aims to enhance the monitoring and forecasting of flash drought drivers, thereby supporting effective drought management and early warning systems. Researchers found that more emphasis could be placed on improving short-range forecasts, as our study shows that flash droughts, as well as conventional droughts, can set in more quickly than the traditional perceptions of their onset duration (e.g., three or more consecutive dry months).

Local authorities responsible for drought mitigation and management strategies may also consider revising their decision-making frameworks and processes to ensure that timely action is taken to minimise agricultural losses from these events. This will contribute to making communities and natural resource managers better equipped in the future. Further details can be found in the explainer [What makes flash droughts different: understanding how Australian droughts develop.]

Bespoke drought information for conservation vulnerability assessments and applications

In 2020, the NESP Earth Systems and Climate Change Hub published updated drought projections for Australia, using the Standardised Precipitation Index (SPI) and the Standardised Soil Moisture Index (SSMI). Since its publication, an increasing number of decision-makers have been seeking assistance to understand and apply the drought projections information. We met this need through this *Extreme climate: dry, wet, hot-and-dry* project, providing tailored drought projections guidance and datasets to various decision makers. These engagements not only met stakeholder needs but also helped develop a simplified set of regional drought information and data for use by a broader range of decision-makers.

As part of the project, we sought to understand better the implications of the potential changes to projected drought for drought-related impacts. A key part of this was understanding how drought has been linked to past impacts. We conducted a detailed case study at two Australian Wildlife Conservancy properties, examining the impacts of drought on endangered mammal populations (see case study below). We also reviewed drought impacts in the literature and assessed the association between drought and its impacts on wetlands, particularly Ramsar wetlands.

The key outcome of this research was that impacts are most often associated with droughts falling into the ‘extreme category’. This led us to shift focus from the commonly used category of ‘drought’ to ‘extreme drought’ in the drought projections information. The ‘extreme drought’ categorisation refers to drought events where the 12-month accumulated rainfall is 2 standard deviations drier than the average (occurring 5–10% of the time), whereas the ‘drought’ categorisation includes events 1 standard deviation drier (occurring around 30% of the time). Common practice in climate projections is to assess change based on 20-year periods; however, this approach has been found to be insufficient for capturing rare extreme droughts. Our solution was to compare the entire 20th century with the entire 21st century to obtain the most robust signal of change possible. The extreme drought projections based on these more extended comparison periods are used in the updated drought projections. Further information can be found in our Regional drought projections for Australia explainer.

Case study: Australian Wildlife Conservancy

The Australian Wildlife Conservancy (AWC) is Australia's largest non-profit wildlife conservation organisation, with over 30 sanctuaries and partnership sites across the country. AWC is developing a Climate Change Adaptation Strategy to maximise conservation outcomes in the face of the challenges presented by climate change. Still, the necessary interpretation of climate data can be challenging. This Extreme Climate: Dry, Wet, Hot-and-Dry project helped AWC select and interpret climate projections data, with a particular focus on drought metrics. This data fed into both species- and location-based vulnerability assessments, assessing how suitable climate zones may shift geographically and identifying which climate hazards will be of most concern at each property. For example, projections of future changes to extreme drought for each property could highlight locations where drought is most likely to increase in the future (Figure 4).

In addition, the project collaborated with the AWC to undertake a detailed assessment of the relationship between climate variables and endangered mammal species at two conservation properties in southern Australia, with a particular focus on drought metrics and the 2019–2020 drought which saw dramatic declines in mammal populations. Population decline was linked to specific climate variables, with high temperatures suspected to be a strong compounding factor. Encouragingly, at least partial recovery of the populations started when long-term rainfall returned to normal. Future projections indicate that several AWC properties may spend twice as much time in extreme drought conditions.

Future projections of such conditions will be essential to guide properties' management and adaptation options to help these vulnerable species make it through periods of increasingly dry and hot droughts. A key outcome of this Project collaboration is that Golden Bandicoot populations in parts of northern Australia were relocated to a property where the climate is projected to remain within their historical tolerance range. Further details are provided in our report and webinar.

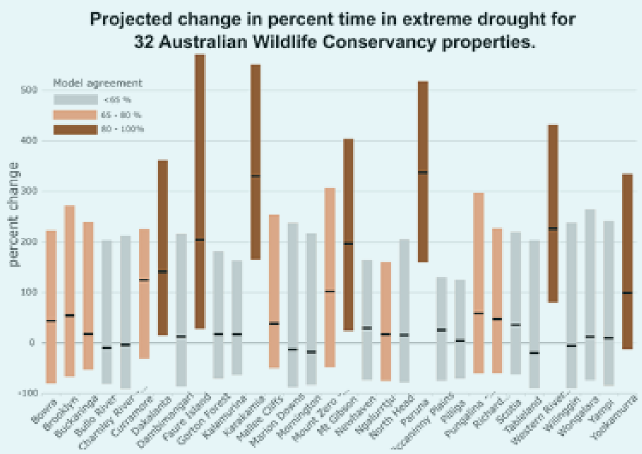

Figure 4: The projected change in percent time spent in extreme drought for 32 AWC properties. Dark brown bars indicate properties where climate models were in high agreement (>80% agreement) that time spent under drought conditions will increase into the future. This information helps identify which properties are most likely to be prone to increasing drought conditions in the future.

Figure 5: As an outcome of collaboration with the Australian Wildlife Conservancy, Golden Bandicoot populations in parts of northern Australia were relocated to a property where the climate is projected to remain within their historical tolerance range. Image credit: Tom Sayers, AWC

From dry to wet: the climate drivers influencing our seasonal rainfall

Another large component of the *Extreme climate: dry, wet, hot-and-dry* project focused on researching the climate drivers that influence Australian rainfall on seasonal to annual timescales. Being uniquely placed near the Pacific, Indian, and Southern Oceans, Australian climate variability is heavily modulated by the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Southern Annular Mode (SAM).

The shifts from one state to another can be dramatic and have a significant impact on our lives and the environment. For instance, eastern Australia experienced some marked swings from dry and hot conditions from 2018–2020, to heavy rainfall and flooding from 2020–2022. These events caused major environmental, social, financial and economic damage to many places, including 17 local government areas and 2,250 primary producers (Climate Council of Australia, 2022). Understanding how these climate drivers have interacted during this time, and quantifying their role in setting these conditions, is very important.

To address these gaps, climate scientists analyse a range of data, including observational datasets and climate model outputs. It is crucial to evaluate climate models to establish confidence in their simulated past climates and future projections. The latest, sixth phase of the Coupled Model Intercomparison Project (CMIP6) comprises over 50 models from international modelling centres, including two versions of the Australian Community Climate and Earth Systems Simulator (ACCESS).

In this project, researchers conducted studies to: (i) improve our understanding about the ENSO, IOD and SAM based on observational datasets; and (ii) perform a comprehensive evaluation of CMIP6 models with an Australian focus. Results are summarised in the next section.

El Niño–Southern Oscillation

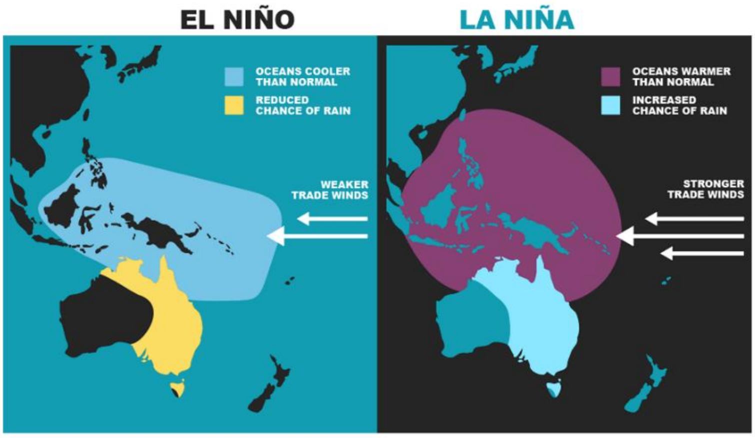

Figure 6: Schematic showing the typical impacts of the phases of El Niño–Southern Oscillation on Australian rainfall. Impacts are typically strongest in the winter-spring seasons.

Existing studies have shown that the typical circulation in the tropical Pacific Ocean features east-to-west trade winds along the equator that accumulate warm water in the west and allow for cool water from the subsurface to upwell in the east, creating a feature known as the Pacific cold tongue. As a result, usually more rain occurs over the warm water to the north of Australia and Indonesia compared to in the east Pacific. Every 3 to 7 years this normal atmospheric and oceanic circulation in the tropical Pacific is disrupted by a natural phenomenon known as the El Niño–Southern Oscillation or ENSO. ENSO's positive phase, called El Niño, is characterised by a warming of the equatorial Pacific Ocean, while its negative phase sees a cooling in the central Pacific named La Niña. Figure 6 (on previous page) shows a schematic of ENSO and its typical impacts on Australian winter-spring rainfall.

During El Niño, the east-west trade winds weaken, less warm water is pushed to the west, less subsurface water is upwelled to the east, and the eastern Pacific gets warmer than usual while the western Pacific becomes cooler than usual. With this change, clouds and rainfall increase over the central and eastern Pacific and rainfall typically reduces over Australia. In a La Niña, the tropical Pacific circulation intensifies, including the east-west trade winds, the ocean upwelling in the east, and the warmer water to the north of Australia. The warmer ocean temperatures close to Australia increase moisture availability and the chances of rain for Indonesia and north and east Australia.

However, results from our project showed that the strength of an El Niño (typically measured by the magnitude of sea-surface temperatures in the eastern tropical Pacific Ocean) is not directly related to how impactful El Niño will be for Australia. A collaborative study between a researcher from this project and the cotton industry, showed that cotton yields in northern New South Wales and southern Queensland are more impacted by El Niño events which exhibit stronger sea-surface warming along the central Pacific El Niño rather than over the east Pacific (Welsh et al. 2022). While ENSO is not the only driver of climate in cotton growing areas, El Niño and neutral ENSO years often result in lower dryland proportions, generally from reduced rainfall negatively affecting yield. These findings provide a valuable step in accounting for climate variability and yield-related inputs such as fertiliser and water resources, and help in managing expectations and better planning for cotton production.

Even though El Niño can reduce the chances of rain in eastern Australia, not all dry spells or droughts are associated with El Niño. An example is the Tinderbox drought that occurred in 2017–19 in the Murray–Darling Basin (Devanand et al. 2024) and preconditioned the landscape for the 2019–20 Black Summer bushfires (Abram et al. 2021). Researchers from the project showed that El Niño did not heavily influence the onset of these dry conditions. Instead, it was the reduction of the Tasman Sea moisture source that contributed to the cool season rainfall deficit in 2017 and 2018 (Taschetto et al. 2024).

The ENSO-Australian rainfall relationship is known to be asymmetric, meaning that the impact of La Niña is usually more consistent than for El Niño. In a study from the project, researchers quantified this asymmetry and the risk of ENSO for east Australian rainfall using a sophisticated attribution technique known as the Fraction of Attributable Risk, a framework commonly used in anthropogenic climate change attribution studies (McGregor et al. 2024).

Climate attribution techniques allow scientists to isolate the amount of influence that a particular factor has on the frequency, magnitude, and intensity of extreme events. They showed that La Niña increases the risk for wet conditions in east Australia and decreases the chances for dry conditions. On the other hand, dry conditions become more likely during El Niño, while neutral and wet conditions become less likely. In addition, they showed that ENSO-Australian rainfall risk is asymmetric in certain regions of Australia; for example, the risk is larger for positive rainfall anomalies in the Murray–Darling Basin than the risk for negative rainfall anomalies. Their study also showed that La Niña played a role in driving large rainfall anomalies in spring 2022, which coincided with widespread flooding across eastern Australia.

Our researchers looked into how the 2020–22 triple La Niña event affected the rainfall in eastern Australia (Huang et al. 2024; see case study box). According to a study from collaborators in our project, a specific weather pattern that brings rain to eastern Australia is more likely to occur during La Niña rather than El Niño (Gillett et al. 2023). This pattern involves a cyclone, or deep low-pressure system, in eastern Australia along with a high-pressure system in the Tasman Sea. Although similar weather patterns can occur during El Niño, they are more pronounced during La Niña and result in increased moisture transport from the tropical Pacific Ocean and heavier rainfall in eastern Australia. In another study from the project, researchers found that La Niña events are associated with temporary global sea level decline, while El Niño events are associated with a temporary global sea level increase, most pronounced during the developing phase of ENSO (Li et al. 2025).

Research from this project also showed that global climate models have shown an overall substantial improvement in the representation of ENSO-Australian rainfall relationship from version 6 of the Coupled Model Intercomparison Project (CMIP6) relative to the earlier version, CMIP5. Collectively, the climate models improved their performance in simulating Australian spring rainfall during ENSO, including the more consistent relationship with La Niña (Chung et al. 2023).

A common stakeholder question is: how are climate drivers projected to change in the future? This has historically been difficult to answer, as it is complex to distinguish between model biases and climate change signals and model internal variability.

We addressed this gap by analysing large ensembles of model simulations, we identified the optimal number of ensemble members required to achieve this, providing a simple equation that relates ensemble size to projection uncertainty, specifically for ENSO metrics (Planton et al., 2024). This is a significant step toward constraining projections of how ENSO might respond to climate change. Our analysis of all available climate models and ensemble members also showed that, despite the large amount of internal variability in models, there is a significant trend for both El Niño and La Niña events to become more frequent by the late 21st century (Chung et al. 2024).

More importantly, our study found that, using all available models, there is no significant change projected in the occurrence of consecutive El Niño or La Niña events.

Southern Annular Mode

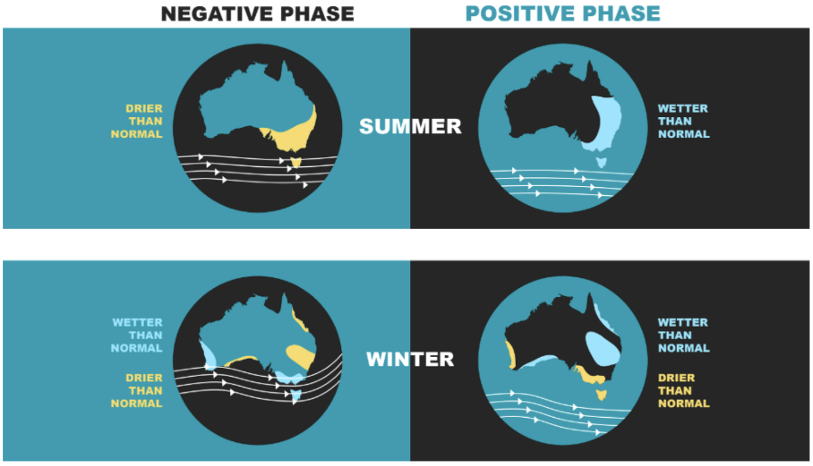

Figure 7: Schematic showing the impacts of the phases of the Southern Annular Mode on Australian rainfall for summer and winter.

The SAM describes variations in the strength and position of the westerly wind belt around Antarctica near 50 °S. A positive phase of the SAM corresponds to stronger and more poleward westerly winds, and a negative phase to a more equatorward and/or weaker westerly winds. Variations in these winds are generally believed to be zonally symmetric across the southern mid-latitudes, although our research shows that some asymmetries can arise, particularly outside of summer. These changes related to SAM can then impact Australia's surface climate.

In winter and spring, positive SAM is associated with warmer and drier conditions across southern Australia. In contrast, during late spring and summer, it is associated with increased rainfall in the east. A negative SAM in summer tends to shift the wind regime across eastern Australia to warm and dry westerlies, which can drive hot and dry air from the interior of Australia to the southeast coastal regions and increase the risk of fire weather hazard. Figure 7 (above) shows a schematic of the phases of SAM and their typical impacts on winter and summer rainfall. In late spring 2019, a record-negative SAM significantly contributed to unusually persistent hot and dry conditions, which led to the extreme 2019–20 bushfires that occurred across eastern Australia.

Although the SAM is generally an internally driven mode of variability in the atmosphere lasting days or weeks, it can also persist for longer as it is forced by processes/winds higher up in the atmosphere (the stratospheric polar vortex) as well as variability in the tropical Pacific (such as ENSO). These processes can act in concert or have opposing influences, so it is important to better understand how these drivers interact to better predict the impact they will have on our climate, today and in the future.

The SAM can also interact with an asymmetric pattern of high-latitude winds and pressure called Zonal Wave 3. The interaction of these two phenomena leads to regional sea ice concentration change in Antarctica as seen in the severe 2015–16 sea ice decline (Eabry et al. 2024). This interaction can also amplify the impacts of SAM on southeastern Australia during springtime, in particular intensifying warmer temperatures and drying during the negative phase of SAM (Boschat et al. 2023).

Evaluation studies under this project have also shown that the latest CMIP6 climate models can reasonably simulate the mean position of the westerly wind belt and variations in the SAM (as illustrated in Figure 7), as well as the positive trend observed during summer. A majority of these models project a continued strengthening of the SAM (i.e. a strengthening and poleward shift of the westerly wind belt) for all seasons by the end of the century (Chung et al. 2024). However, uncertainties remain in terms of their ability to capture existing zonal asymmetries in the structure of SAM, its connection with ENSO and the stratospheric polar vortex, its impact on Australian climate and how it will respond to the opposing influences of ozone recovery and increasing greenhouse gases in the future.

Indian Ocean Dipole

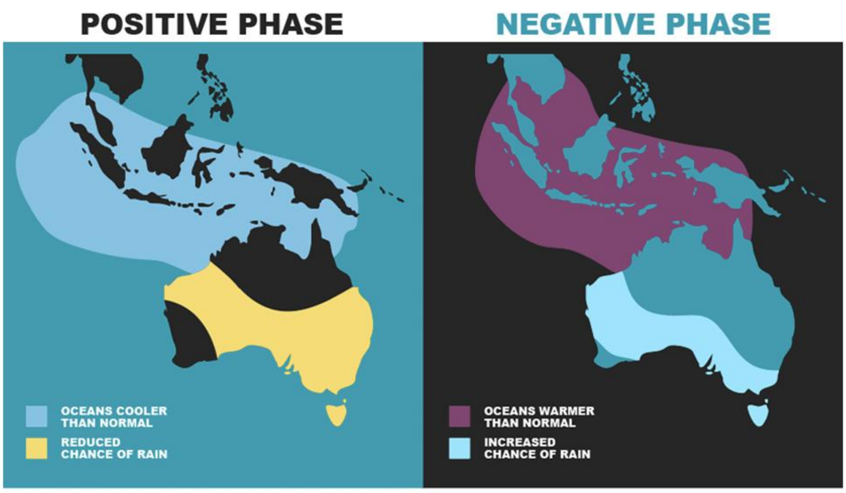

Figure 8: Schematic showing impacts of the phases of the Indian Ocean Dipole on Australian rainfall. The impacts are typically strongest in winter-spring.

The IOD is characterised by swings in sea surface temperature along the tropical Indian Ocean. During positive IOD events, the western Indian Ocean anomalies are warmer than in the east, reducing the likelihood of winter and spring rainfall across southern and eastern Australia. During negative IOD events, the western Indian Ocean is cooler than the east, increasing the likelihood of winter and spring rainfall in these regions. Figure 8 shows a schematic of these phases and their impacts on winter-spring rainfall. The IOD is closely linked to ENSO, with positive IOD events typically co-occurring with an El Niño event, and negative IOD events with a La Niña event. Significant examples of this include the 2018–2019 El Niño and positive IOD events which exacerbated the hot and dry conditions leading up to the 2019–20 Black Summer bushfires.

This was followed by three consecutive years of La Niña, negative IOD, and positive springtime SAM events, resulting in extremely wet conditions across eastern Australia (see below).

Model evaluation studies conducted under the project showed that overall, CMIP6 models demonstrate a significant improvement in their simulation of the IOD's relationship to winter and spring rainfall in Australia. However, there are still aspects of the IOD, such as its strength and skewness, that many models fail to capture accurately. Due, in part, to these model biases, there is also considerable uncertainty around projections of future IOD change. However, our study indicates a possible weakening of IOD variability under by the end of the 21st century. Our study, using all available models, also shows a projected decrease in consecutive positive IOD events (Chung et al. 2024).

As the various phases of ENSO, IOD, and SAM often co-occur, researchers also developed new metrics for quantifying how much these three climate modes influence Australian rainfall, independently and collectively. They found that collectively, ENSO, IOD and SAM variability can explain up to 45% of eastern Australian springtime rainfall variability, with ENSO being the dominant influence (Boschat et al. 2025). Although there is some uncertainty on how these climate modes might change in the future, climate models project that certain regions such as southwestern Western Australia and southern Victoria will experience a robust drying trend in springtime regardless of how the climate modes may change (Chung et al. 2025).

Case study: What made it so wet across eastern Australia in 2020–2022?

During the spring seasons of 2020 to 2022, three consecutive La Niña, negative IOD, and positive SAM events occurred. This led to heavy rainfall and widespread flooding across eastern Australia. In spring 2022, southeastern Australia received a record-breaking amount of rainfall. As part of our co-design approach, we teamed up with the Hub's *Extreme Events Explained* project and hub knowledge brokers to survey state-based decision makers on what was important to them, find out how they were impacted and what questions they had, and what new science information we could provide.

The responses we received were mainly focused on i) the role of climate drivers in extreme rainfall, and how this is projected to change, and ii) the role of climate change in extreme rainfall events. These questions helped to frame our research throughout the course of the project.

In investigating how Australian rainfall behaves during triple La Niña events, we found that rainfall in northern and eastern parts of the country tends to increase progressively (year after year) during the spring and summer months of a triple La Niña. This is not because the La Niña sea surface temperature patterns get stronger, but is likely due to a gradual increase in soil moisture. Triple La Niña events are also more common than Triple El Niño events (Figure 9).

The likelihood of above or below average rainfall due to La Niña and El Niño was also quantified for the first time, as mentioned above. An analysis of all CMIP6 models also showed that La Niña events are projected to strengthen in the future. A subset of models project an increase in consecutive La Niña events, though there is less consensus when considering all models.

The *Extreme Events Explained* project conducted experiments showing that the positive SAM of spring 2022 pushed the already high rainfall over southeast Australia into record-breaking amounts. Experiments also showed that in a world without human-induced global warming, southeastern Australia would have received around 16% less rainfall during spring 2022 – suggesting that human-induced climate change did play a role.

These results were presented in our what made eastern Australia so wet from 2020 to 2022? explainer and an interactive webinar. Decision makers who originally contributed their perspectives and informed the research design, alongside many others participated, learning more about this new science to help them prepare for future events.

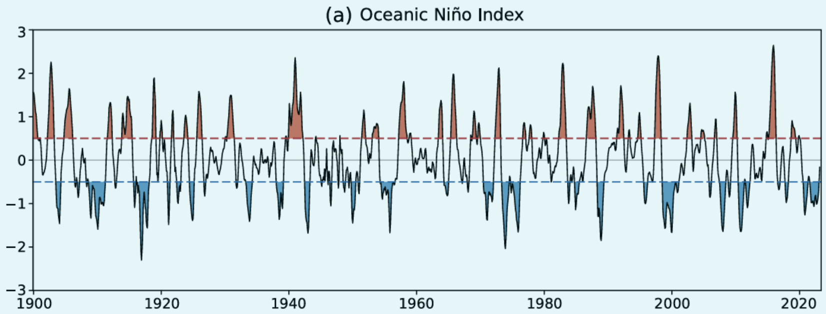

Figure 8: Time series of the Oceanic Niño Index from 1900–2022; showing periods of El Niño (red) and La Niña (blue). There have been 5 triple La Niña events since 1900, and one triple El Niño. From Huang et al. (2024)

Case study: On the road engagement for our early-career professionals

In August 2024, several project members participated in the NESP Climate Systems Hub Early Career Professionals (ECP) field program. ECPs spent the week travelling around far northeast NSW in an area that was keenly affected by both bushfires in the Black Summer of 2019–20 and by floods in 2022. This included the town of Lismore, which is still rebuilding from severe flooding in February and April 2022.

The tour was eye-opening and sometimes confronting, as ECPs spoke to stakeholders, including local community groups, local councils, and state governments, learning and listening to the information they need for adaptation to climate disasters and climate change. Interactions between some of these stakeholders and members will continue.

The tour highlighted several areas where the information from this project is both directly and indirectly useful for stakeholders in northeast NSW, which are now described:

Local and regional information on extremes is key

All stakeholders were only interested in local and regional information on high-impact climatic events (eg wet extremes). The presence of uncertainty in this information was an acceptable byproduct of having local information, which they viewed as imperative. This confirms the need to understand the nuanced characteristics of wet and dry extremes at the regional and local levels, and to demonstrate how large-scale climate processes influence local climate extremes.

Cascading and compounding climate extremes

Of particular interest to local and state government stakeholders was the concept of cascading and compounding climate extremes. The interest from stakeholders stemmed from the risk related to repeated hazards, which could be multiple flooding events, or drought/fire to flood, or vice versa.

A synthesised knowledge base for climate risk preparation

State government stakeholders provided feedback that a synthesis on localised, current climate knowledge was a useful exercise as this information did not exist at the local and regional levels for their needs, and so not all climate risks could be adequately identified.

Science often contributes via indirect, low-visibility but high-impact pathways

When speaking to stakeholders, it was not always clear where, how, or if they directly used or needed scientific information. However, it was clear that climate science knowledge was indirectly utilised. For example, stakeholders casually mentioned using knowledge of the connections between ENSO and rainfall in their region. They also relied on information about future climate change and seasonal and weather prediction information to plan and prepare for climate risks. This demonstrates that scientific research is routinely utilised, but in indirect ways that are not entirely transparent to users.

Impact and future considerations

This project has made significant contributions to a broad range of topics related to climate variability and extremes. From fundamental research to the provision of targeted datasets in response to end users' specific requests, we have delivered a broad range of outputs.

The collaboration with the Australian Wildlife Conservancy has led to an enhanced understanding and integration of climate and drought information into their Climate Change Adaptation Strategy, providing researchers with the opportunity to investigate the connections between drought and the impacts on species conservation.

Meanwhile, the three different webinars on drought and the wet conditions of 2020–2022 reached over 1000 decision-makers from a range of sectors. The flash drought study highlights the potential of the Australian landscape to dry much more quickly than is traditionally believed. This implies that more efforts are needed to improve the forecasting and management of these events, as there is often not enough time to prepare due to the sudden onset of their occurrence. The physical drivers of rapid drying events are very similar to those responsible for causing conventional slow drying. Still, they are characterised by much higher anomalies of these drivers for the former than the latter. Future research quantifying the differences in impacts caused by flash droughts compared to conventional droughts may further help stakeholders understand how losses can amplify when droughts occur more rapidly.

Our evaluation of climate models revealed several significant improvements in simulating ENSO, IOD, and their relationship with winter and spring rainfall.

While our work has advanced our understanding of Australian climate drivers, it has also highlighted some key gaps and opportunities for future research. These include:

- Improving metrics to more reliably capture the onset of Australian droughts.
- Developing a more detailed understanding of the dominant mechanisms leading to droughts and quantifying the differences in impacts caused by flash droughts compared to conventional droughts, to understand how impacts amplify when droughts occur more rapidly.
- Using longer datasets to investigate trends in the occurrences of flash drought events.
- Quantifying the role of internal variability in observations and climate models. What are the relative roles of internal variability and climate change in recent decades and in the future?
- How do large-scale climate modes modulate the behaviour of smaller-scale synoptic weather systems, which impact short-lived rainfall events?
- Which processes need to be improved in climate models, in particular Australia's global climate model, ACCESS, to improve their overall simulation of the Australian climate?
- How can we reconcile the disparity between projected future warming patterns and the historical observed warming patterns?
- How can we improve our ability to translate coarse-resolution output from global climate models to useable, on-ground, local information?

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