Earth Systems and Climate Change Hub

National Environmental Science Programme

Exploring drivers of Australia's variable and changing climate

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REPORT SUMMARY

Climate variability and change impact all sectors of Australia's economy, our communities and unique ecosystems. The Earth Systems and Climate Change Hub has conducted world-class climate change research to increase understanding and knowledge on how our variable climate is likely to change under increasing greenhouse gas concentrations. This includes, for example, investigating how the frequency of extreme El Niño and positive Indian Ocean Dipole events may change in the future, and the impact this change will have on Australia's climate system. This new understanding and knowledge will arm Australian decision-makers and researchers with the best available information, data and tools to assess and manage climate risks across Australia.

Key findings:

- Earth System and Climate Change hub researchers have investigated two of Australia's dominant climate drivers: El Niño-Southern Oscillation and the Indian Ocean Dipole. These climate phenomena, and their interactions with each other, significantly affect Australia's climate.
- Increasing greenhouse gas concentrations, which lead to global warming, are projected to impact the frequency and variability of these climate drivers. New research has shown that the rate of warming and the change in variability may be better predicted when taking into account the state of the Pacific Ocean over the preceding decades.
- Research under the Hub has led to new knowledge and understanding of these important climate drivers, including:
    - Better understanding of the way that different El Niño and Indian Ocean Dipole events manifest, including new ways to define and characterise extreme El Niño events.
    - New projections which indicate that extreme El Niño and positive Indian Ocean Dipole events, two key drivers of drought in parts of Australia, are likely to increase in frequency under climate change due to rising sea surface temperatures. Projections also suggest an increase in the frequency of dry winter-spring seasons across Australia over the 21st Century, primarily due to a shift in long-term average rainfall towards drier conditions which exacerbates the impacts of El Nino events.

- Research into changing climate risks associated with extreme El Niño events, such as disrupted rainfall patterns over the Pacific leading to some regions experiencing droughts, and others experiencing flooding. These risks may already have increased due to greenhouse gas emissions over the past century. If global temperature increase is stabilised at 1.5 degrees Celsius, the risks associated with extreme El Niño events are still likely to persist up to a century from the time of stabilisation. However, the risks associated with extreme La Niña events and positive Indian Ocean Dipole events may stabilise within years of the stabilisation of global temperatures.

- The rate of global warming is modulated by decadal variability in the Pacific Ocean. Given that the Pacific Ocean has recently experienced several decades of a 'La Niña-like' background state of relatively cooler sea surface temperatures across the central-eastern Pacific, and is likely to be entering an 'El Niño-like' state, research into decadal variability in the Pacific Ocean indicates that it is likely that we are now entering a phase of accelerated warming.

1 Introduction

Climate variability and change impact Australians on all socio-economic levels, from agricultural and water management sectors to financial and insurance bodies to local community groups and individuals.

Climate variability refers to any deviation from long-term average climate conditions. Variability can occur on multiple timescales (from months to decades) and is naturally occurring, although the characteristics of this variability are changing with the warming climate. Australian climate variability is influenced by many phenomena such as El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM) and the Australian monsoon. These operate on various timescales, peak during different seasons and impact different regions of Australia. For example, ENSO is the dominant influence on spring-summer rainfall across much of Australia, while the IOD influences south-east Australia's rainfall during spring. The positive IOD phase is usually linked to dry conditions.

Climate change is a trend occurring over many decades, which gradually alters the long-term average climate conditions. Since the 1850s, the continuous increase in greenhouse gas concentrations has led to an increase in average global temperatures of over 1°C. This may not sound like much, especially since the temperature fluctuations at regional scales caused by climate variability can be much larger. However, as this warming combines with naturally occurring variability, climate change can manifest as an increase in the impacts of extreme events such as IOD and ENSO, through droughts and bushfires.

Climate phenomena like the IOD and ENSO play a large role in climate extremes, and it is critical to explore how these phenomena are changing under a warming climate. For example, the recent devastating bushfires in Australia's south-east during 2009 and 2019-20 occurred during positive phases of the IOD. The frequency of positive IOD events has increased since 1960, and the 2019 positive IOD was the strongest on record

Against a backdrop of steadily warming global temperatures, how well we prepare for the impacts of these phenomena depends on the answers to some fundamental questions, including: how the IOD and ENSO impact Australian climate; how ENSO and the IOD are likely to change in the future; how well ENSO and the IOD are captured in climate models; and how their representations in climate models could be improved.

Research under the Earth Systems and Climate Change (ESCC) Hub of the Australian Government's National Environmental Science Program focused on advancing our understanding of ENSO, the IOD, the interaction between the two phenomena and the impact of global warming on Australia's climate. Information and knowledge gained from this research aims to arm decision makers with the best knowledge available to better prepare for the increased risks of extreme events, to manage resources as the climate system shifts to new long-term averages and to highlight the need to reduce greenhouse gas emissions to reduce long-term climate risks where possible.

By combining analysis of observational data and climate model output, research by the ESCC Hub has used climate models to simulate how the ocean, atmosphere and land respond under a range of historical and future greenhouse gas scenarios.

On shorter timescales, improving seasonal prediction of ENSO and the IOD remains an ongoing challenge. An increased understanding of the physical processes behind these phenomena benefits the continued improvement of operational climate services, such as seasonal forecasts and climate driver updates.

This report summarises the advances in understanding on two climate phenomena key to Australia’s climate variability and change made under the ESCC Hub *Project 5.2: Climate variability and change: past, present and future* as well as key knowledge gaps that are yet to be addressed.

Information box: Using climate models

To understand how climate variability has occurred in the past, observations of climate variables, such as sea surface temperature and rainfall, are used. While temperature and rainfall observations across Australia have existed since the early 20th century, there was sparse coverage in some parts of the world before the advent of satellite observations in the 1970s. Climate models can assist researchers to fill in these gaps by simulating physical processes which occur in the atmosphere, oceans and land, and quantifying the climate variables at each grid point globally. Climate models are also the best available tool we have to study multi-decadal processes and project future changes to the climate system. Running simulations of the Earth's climate under given scenarios allows us to study how individual climate processes impact the climate system as a whole.

Climate scientists around the world contribute models and simulations to a global database called the Coupled Model Intercomparison Project (CMIP). This year, the sixth iteration of this database, CMIP6, came online. Australia’s contributions to CMIP6 are the ACCESS-CM2 and ACCESS-ESM1.5 models. This was led by ESCC Hub Project 5.1: ACCESS evaluation and Application.

Hub researchers have analysed up to about 20 different CMIP6 models, including ACCESS-CM2, focusing on two main objectives: improving our current understanding of ENSO and the IOD and analysing their future projections. They also examined how historical and projected ENSO and IOD variability change on decadal time scales. This work builds on previous research conducted under the ESCC Hub.

2 What have we learnt about El Niño-Southern Oscillation?

The unique El Niño of 2015/16 posed unforeseen challenges in ENSO predictability and raised questions on the fundamental nature of ENSO variability. As ENSO is a major driver of Australian rainfall, this phenomenon was a key focus of climate variability and change research conducted under the ESCC Hub.

2.1 The flavours of El Niño

Although El Niño and La Niña can be thought of as opposite states of the Tropical Pacific, they are not mirror images of each other. There exist two distinct types of El Niño (and to a lesser extent, La Niña): the Central Pacific and Eastern Pacific El Niños. These El Niño types have unusually warmer waters concentrated on either the central or eastern Pacific, respectively, and impact Australian rainfall differently (see Figure 1).

- Central Pacific (CP) El Niños, while generally weaker in terms of sea surface temperature deviations, are associated with more widespread drying and warming over Australia, possibly due to warmer sea surface temperatures being located closer to Australia.

- Eastern Pacific (EP) El Niños, on the other hand, have more limited impact on Australian temperatures and rainfall, but cause severe and extensive rainfall disruptions elsewhere, such as in South America[1]. Stronger warming along the equatorial eastern Pacific during EP events has also led to loss of marine life and mass coral bleaching[2].

Of the three extreme El Niños which have occurred in the last century, two (1982/83 and 1997/98) have been EP El Niños and one (2015/16) was classified as a mixed CP/EP El Niño[3].

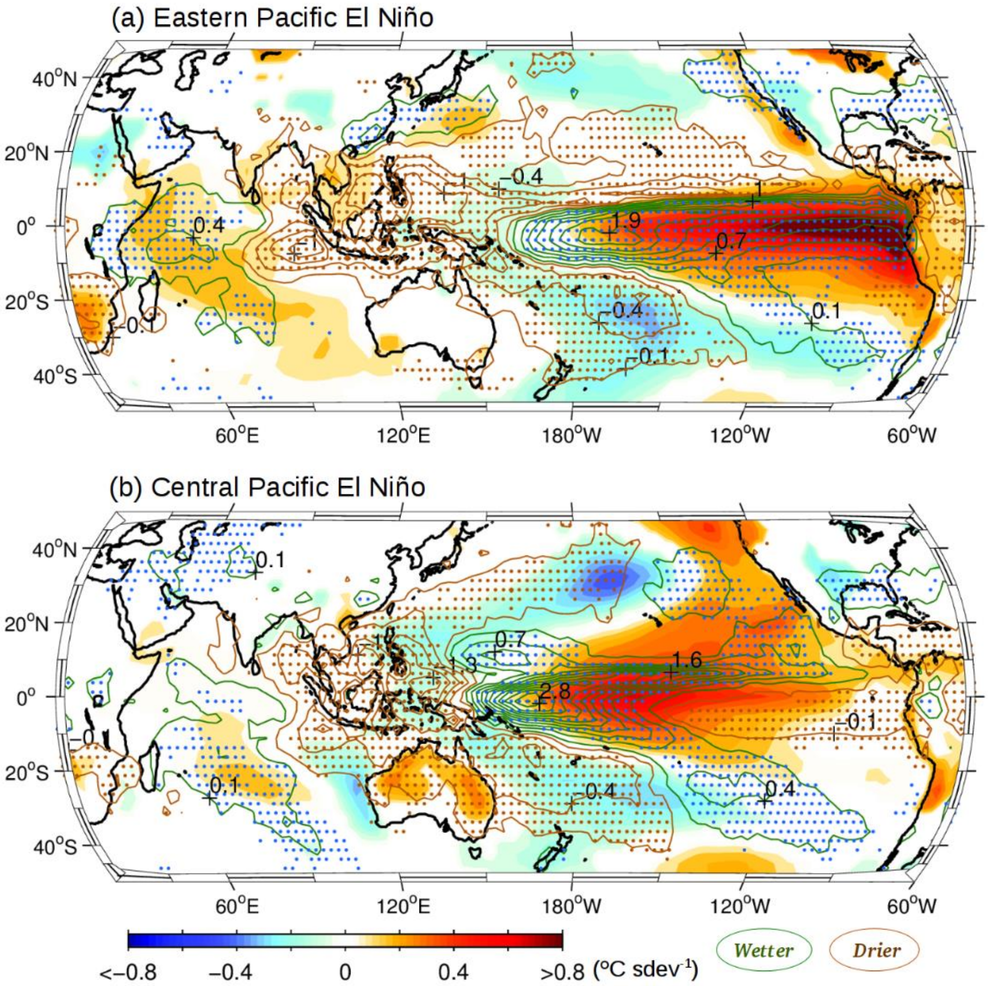

Figure 1. December-February surface air temperature anomaly (colour shading) and rainfall anomaly (contours) patterns associated with Eastern Pacific ENSO (top panel) and Central Pacific ENSO (bottom panel). Temperatures that are warmer than usual are indicated by orange-red shading, while areas where rainfall is lower than usual are outlined with brown contours. Stippling indicates regions where rainfall is statistically significant different from usual (above 95% confidence level)[4].

2.2 Case study: The 2015/16 El Niño

In 2015/16, Australia experienced an unusually extreme El Niño, during which reduced rainfall over northern and eastern Australia contributed to an early start to the fire season as well as the most severe recorded coral bleaching event for the Great Barrier Reef. It also contributed to the very dry conditions and low sea level in the Gulf of Carpentaria that led to one of the worst mangrove dieback events recorded globally. Not only was this extreme El Niño preceded by a 'false alarm' in 2014 (i.e. with many forecast models predicting a strong El Niño which did not eventuate), it was also established as the first extreme El Niño of the 21st Century with distinctly different characteristics from previous extreme El Niño events.

Hub researchers conducted a detailed examination of the characteristics and mechanisms of this event[3,5]. During the 2015/16 event, sea surface temperatures were warmer than usual and extended from the tropical Pacific to the central *and* eastern Pacific. Therefore, the event was classified as a 'joint' CP/EP El Niño.

The combined CP/EP El Niño event in 2015 made researchers rethink previous methods of defining extreme ENSO events. Hub researchers[6] compared two definitions of extreme El Niños using either the magnitude of sea surface warming in the Tropical Pacific or the amount of rainfall over the Eastern Pacific. While the three previous extreme El Niño events fall under both these categories (sea surface temperature-based- and rainfall-based), climate models project that these two types of extreme events respond differently to increasing greenhouse gases.

Under increasing emissions, sea surface temperature-based extreme El Niño events are not likely to be affected as much as rainfall-based extreme El Niño events, which are projected to increase by almost 400% by the end of the 21st century. Extreme El Niño events which fall under both categories are also projected to increase by about 70% over the century.

The unusual evolution of the 2015/16 El Niño also raised questions on the predictability of such events on interannual time scales[4]. The ability to predict an extreme El Niño event is of great value to Australian industries, sectors and communities who are likely to bear the brunt of the impacts of such events. Understanding more about whether such extreme events will become easier or harder to predict as the climate continues to warm is therefore important and has been a focus of research under the Hub.

2.3 ENSO research key gaps and challenges

Hub research has identified key challenges and gaps in ENSO research relevant for managing future climate risks in Australia. These include:

- To better understand of the causes and predictability of extreme ENSO events.
- To improve ENSO representation in climate models.
- To improve operational predictive capability of ENSO, including decadal predictability.
- To re-evaluate ENSO response to greenhouse gas forcing in the latest generation of models and identifying where model biases have reduced compared to older models.
- To improve understanding of decadal variability and trends.

3 What have we learnt about the Indian Ocean Dipole?

Over the last decade, the role of the Indian Ocean Dipole (IOD) on Australia's springtime temperature and rainfall has been of great interest. For example, the positive IOD in 2019 contributed to the driest Australian spring on record, contributing to the precursor conditions for the disastrous southeast Australian bushfires. These fires were severe in many respects, including their early seasonal commencement, large spatial coverage and large number of burning days. Research was conducted by the ESCC Hub into the roles that greenhouse warming, the positive IOD and El Niño played in the bushfires. This helps us understand the likelihood of similar events occurring in the near-term.

3.1 Case study: Climate precursors of the 2019/2020 bushfires

In 2018 and 2019, two consecutive positive IOD events occurred in conjunction with two consecutive CP El Niño events. Hub researchers[7] found that these unique consecutive events (which have occurred only once since 1911) contributed to the record dry and hot anomalies preceding the bushfires (Figure 2).

CMIP5 and CMIP6 climate model-based projections indicate that the frequency of such consecutive positive IOD/CP El Niño concurrences would increase only marginally under a warming climate. However, projected rainfall under warming indicates future drying trends across Australia, which implies that the impact of such consecutive concurrences would be exacerbated.

The magnitude of this projected drying trend was estimated in an investigation into how global warming and changes to ENSO would impact Australian rainfall[8]. In this study, Hub researchers found that the frequency of dry winter-spring seasons is projected to increase in all regions across Australia in the 21st century under a high emissions scenario (RCP8.5). Under such a trajectory, approximately 60% of years from 2010 to 2099 are projected to be drought years (i.e. receiving less than 10% of usual rainfall) in Perth, 35% in Adelaide, 30% in Melbourne, and approximately 20–25% of years in Sydney, Canberra and Brisbane.

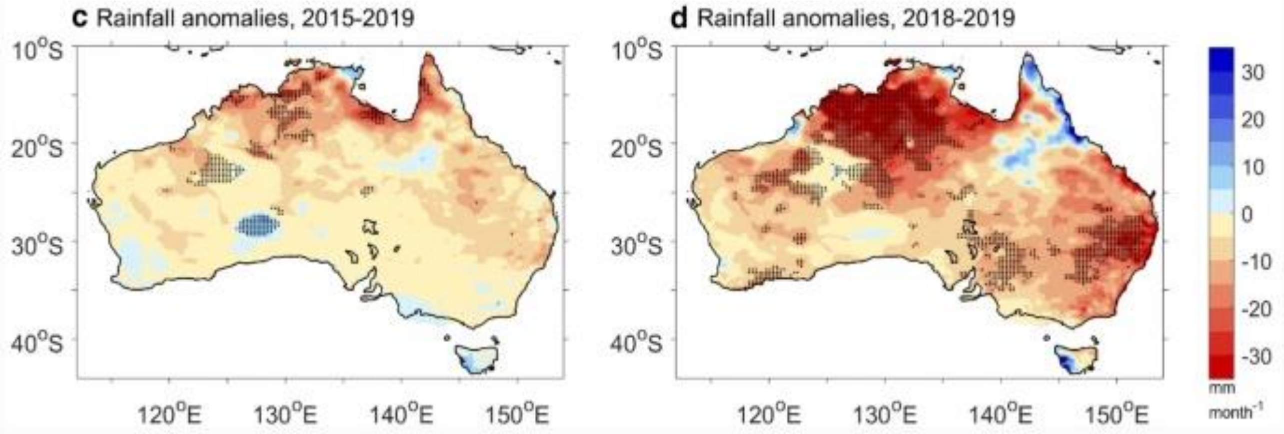

Figure 2. The consecutive concurrences of CP El Niño and positive IOD events and the recent severe drought over Australia. Left: Mean monthly rainfall anomalies (departures from a baseline period or average) over the recent five years, (2015 to 2019). Right: The same, but over the recent two years (2018 to 2019). Data are detrended and dotted areas indicate regions where the anomalies are greater than a 2.0 standard deviation value of the 5 year and 2 year running time series at each grid-points in the left and right panels, respectively[7].

3.2 How are ENSO and IOD likely to change in the future?

Robust climate change projections depend on improvements in the understanding of climate processes and continuous improvements in the ability of climate models to simulate climate variations. The CMIP5 and CMIP6 climate model database includes simulations of past, current and future climate run under several future emission scenarios, ranging from low to high emissions scenarios. These climate model simulations are invaluable for research into gaining a clearer picture on how ENSO and the IOD are likely to change into the future.

Capabilities to project future ENSO have advanced, although further research is needed to examine the effects of model biases[9]. Hub research has found a projected future increase in the frequency of EP El Niños and CP El Niño events in response to rising greenhouse gases. The frequency of strong EP El Niño events is projected to increase by up to 47% by 2100 under a high emissions scenario[10]. Additionally, new research has shown how variability in precursor decades may affect how ENSO responds to greenhouse warming. Climate models indicate that a system experiencing weaker ENSO variability for several decades (as has been the case between 1998-2018) would experience an increase in ENSO variability under greenhouse warming, and vice versa. Under these projections, ENSO variability may increase by up to 37% in the coming decades.

Hub research into the recent 2019 positive IOD event showed that the pattern in which the sea surface temperatures are warming over the Indian Ocean gave rise to unusually strong winds over the Indian Ocean. This was the first time such wind anomalies were observed in an extreme positive IOD event[12].

As most climate models project this sea surface temperature warming trend to continue, extreme positive IOD events like that in 2019 may occur more frequently in the future[13].

3.3 Indian Ocean Dipole research key gaps and challenges

Hub research has identified key challenges and gaps in IOD research relevant for managing future climate risks in Australia. These include:

- To improve the representation of the IOD in climate models[12,14].
- To better understand interactions between the IOD and other climate processes such as ENSO, and their response to greenhouse warming.
- Re-evaluation of projections from CMIP6 models, particularly seasonal forecasts of ENSO, IOD, and their interactions.

4 A global view

4.1 Tracking the impact of the Paris Agreement temperature targets on future extreme El Niño and positive IOD events

ESCC Hub research investigated what the Paris Agreement temperature targets would mean for future extreme El Niño and positive IOD events. Researchers found that even if global mean temperatures stabilise at the 1.5 degree warming target set by the Paris Agreement, there would still be an increased risk of extreme El Niño events up to a century beyond that stabilisation[15]. That is, the maximum risk of these events occurs long after stabilisation of global temperatures, although the risk of extreme La Niña is reduced. In contrast, the increase in extreme positive IOD frequency stabilises with the global mean temperature[16]. An increased frequency of extreme El Niños and positive IODs can lead to more frequent severe drought over eastern and south-eastern Australia.

4.2 Changes to global rainfall patterns

Hub research[17] has also shown that although sustained reductions in 21st century human-caused greenhouse gas emissions can greatly moderate the likelihood of major disruptions to rainfall levels and patterns over the Pacific (such as droughts in some regions and flooding in other regions), elevated risk of major disruption appears locked in now for at least the remainder of the 21st century. Increased emissions to date may have already contributed to some of the major rainfall disruption experienced in the late 20th century by increasing the likelihood and exacerbating the large El Niño events that occurred at that time.

4.3 Tropical ocean basin interactions

The global climate is an inter-connected system. The state of ENSO and the tropical Pacific influences the climate of the entire planet and can in turn be influenced by processes occurring in other regions. ESCC Hub researchers led a major review into how the three tropical ocean basins interact, and how these interactions affect climate prediction and modelling[18,19]. Hub researchers also explored how the interactions between the Indian and Pacific Oceans impact various regions across the world, and how these interactions will change in the future. For example, researchers demonstrated that Indian Ocean warming at the peak of El Niño dampens the impact of El Niño on air temperature across North Africa and South Asia[20]. On the backdrop of these interactions is a long-term rapid warming of the Indian Ocean which impacts large-scale and regional climate trends[21]. Experiments using ACCESS-CM2 were also conducted to investigate the links between the South and Tropical Pacific[22].

4.4 Changes to ENSO across the world

The diversity of ENSO events has important implications for regional climate outside of Australia as well, such as over South America. For example, the impact of the eastern Pacific El Niño on Peru rainfall is opposite to that of central Pacific El Niño, and these impacts are likely to intensify under greenhouse warming[1].

However, Hub researchers[23] also found that under a high-emissions scenario (RCP8.5), projected rainfall changes during El Niño or La Niña years in most regions around the world would be mostly due to mean-state changes. This means rainfall changes are primarily because of the climate system shifting to a 'new' normal rather than because of changes to ENSO variability.

Aside from ENSO and the IOD, which vary on timescales of 2-5 years, the climate system also fluctuates naturally on decadal time scales. Approximately every 15-30 years, the Pacific Ocean switches between positive (El Niño-like) and negative (La Niña-like) phases of the Interdecadal Pacific Oscillation (IPO). The state of the IPO modulates the rate of global warming, with the recent global warming 'hiatus' (1998-2012) occurring during a negative IPO phase. Hub research shows that projections of multi-decadal temperature are improved by preparing forecasts with the observed IPO phase. When decadal forecasts were prepared with a negative IPO, the *subsequent* decade showed accelerated warming, whereas when prepared with a positive IPO the *subsequent* decade showed slowed warming. It is therefore likely that since the IPO was in a negative phase over the last decade, we are now entering a phase of accelerated warming[24]. New Hub research also shows that increased warming may make decadal variability in the North Pacific less predictable, posing an additional challenge to the field of decadal predictability[25].

5 Conclusions

Being able to quantify the impacts of climate change on phenomena like the IOD and ENSO and learn how these changes manifest in our everyday experience of temperature and rainfall is crucial for better understanding our climate risks and how they can be managed into the future.

Research under the Earth Systems and Climate Change Hub has provided increased understanding of the fundamental processes that impact our variable climate, and insights into how these might change in the future. This knowledge has the potential to assist policymakers and other sectors in their efforts to mitigate emissions and adapt to the changing climate.

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