Climate Systems

National Environmental Science Program

Where are we in 2021 and where to from here?

Understanding Climate Variability

This report summarises our current understanding of Australian climate drivers and recent advances in climate research.

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This project is supported with funding from the Australian Government under the National Environmental Science Program.

Please cite as: Chung CTY, Boschat, G, Lim E-P, McGregor S, Narsey S, Santoso A, Taschetto A, Wang G, Wheeler M (2022) *Understanding Climate Variability: Where are we in 2021 and where to from here?.* Climate Systems Hub. National Environment Science Program, Australia.

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The hub would like to acknowledge the contributions of David Jones, Pandora Hope, Jeff Jones, Roseanna McKay, and Tahnee Burgess.

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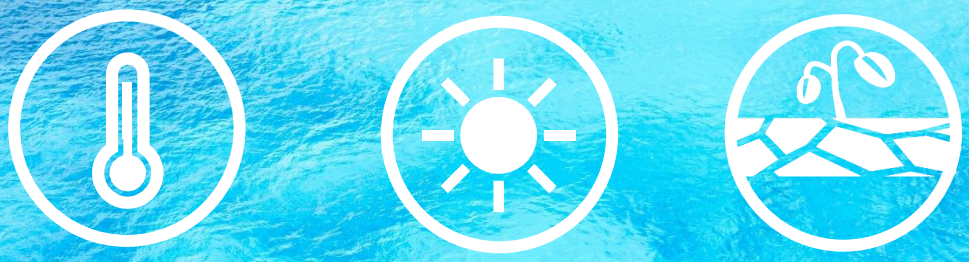


"Projected changes would result in overall less rainfall and warmer temperatures over Australia during winter and spring"

Executive Summary

This report summarises our current understanding of Australian climate drivers and recent advances in climate research, with a particular focus on topics covered by National Environment Science Program 2 (NESP 2) Project 1.4 (Understanding Climate Variability).

This project aims to improve our understanding of the impacts of the complex interplay between naturally occurring climate variability and anthropogenic climate change. **Combining analysis of state-of-the-art climate model output and observational data has given us new insights into the physical processes underlying the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM) and the Australian Monsoon.** ENSO variability is projected to increase over coming decades, along with more frequent extreme ENSO events. Strong positive IOD events are also projected to increase. **These projected changes would result in overall less rainfall and warmer temperatures over Australia during winter and spring.** Under high emissions scenarios, SAM is projected to experience a shift towards a positive state, associated with increased rain over eastern Australia. Long term projections of changes to the northern Australian monsoon remain uncertain. The researchers working within this project are working to refine our understanding of these projections and the physical processes behind the interaction and changes occurring in these climate drivers.

Introduction

Australia's size and location means that it experiences multiple large scale climate drivers, with many showing persistence and predictability owing to the large size of the Pacific and Indian Oceans. The long-lived coupled ocean-atmosphere ENSO and IOD phenomena lead to substantial year to variability, which is then reflected in other more local drivers including the SAM and Australian Monsoon. **While natural variability remains an important factor for Australia, anthropogenic climate change is now rapidly changing the mean climate state, and the ways in which natural drivers behave and interact**. Enhancing the work achieved during the previous hub (NESP 1), the researchers in this project have been focused on delving deeper into answering the questions that remain. These questions include the impact of internal variability on frequency of extreme ENSO and IOD events under greenhouse warming, how ENSO diversity impacts Australian rainfall, the predictability of SAM, and how these climate drivers and associated impacts are projected to change in the future.

In 2021, the Sixth Assessment Report of the International Governmental Panel on Climate Change (IPCC AR6) was released[1]. It was a global effort which summarised results from thousands of peer-reviewed climate publications. The first point in the summary for policy makers states "It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred."[2]. As with previous releases of IPCC Assessment Reports, AR6 was accompanied by a new, sixth, phase of the WCRP's Coupled Model Intercomparison Project (CMIP6) which comprised model runs from over 100 state-of-the-art climate models from global institutions[3]. Each submitted model was required to run core scenarios with specified greenhouse forcings, including:

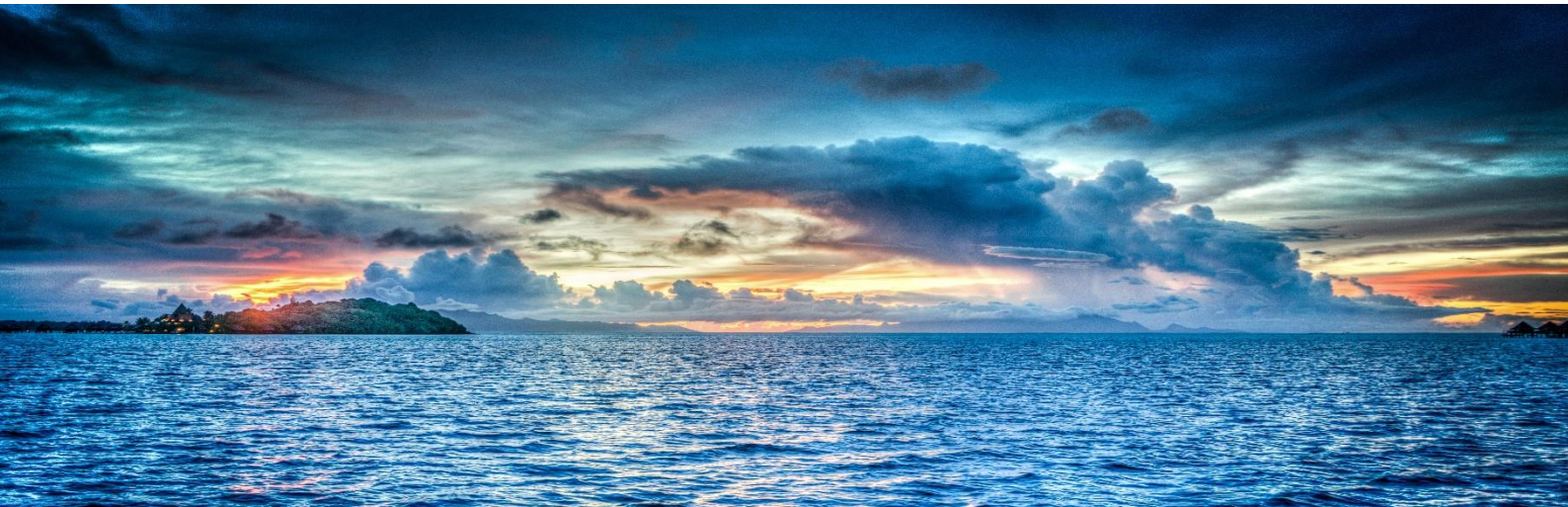
"It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred."

IPCC: Sixth Assessment Report

- Pre-Industrial, with greenhouse gases (GHGs) at 1850 levels,
- Historical, with GHGs varying from 1850-near present levels
- Future scenarios under Shared Socioeconomic Pathways (SSPs), with GHGs ranging from a low emissions scenario (SSP 126) to a high emissions scenario (SSP 585), varying from 2015-2100.

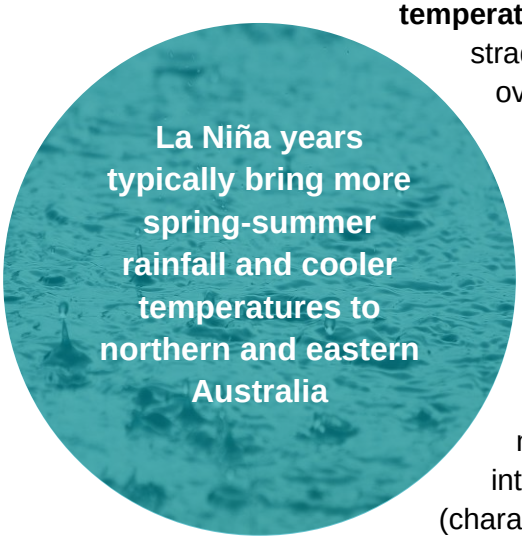
In Australia, recent events have highlighted the potential impacts of extreme events that occur when multiple climate drivers interact. For example, the devastating bushfires of 2019/2020 coincided with two consecutive years of a positive IOD and El Niño, together with negative SAM in late 2019. The implications of global warming on these climate drivers may further worsen future extreme events. Additionally, it is not just extreme events that need to be prepared for, but also the gradually changing mean state of the Australian climate – the 'new normal' which shifts the baseline against which variability occurs - and the change in the year-to-year variability that Australians experience.

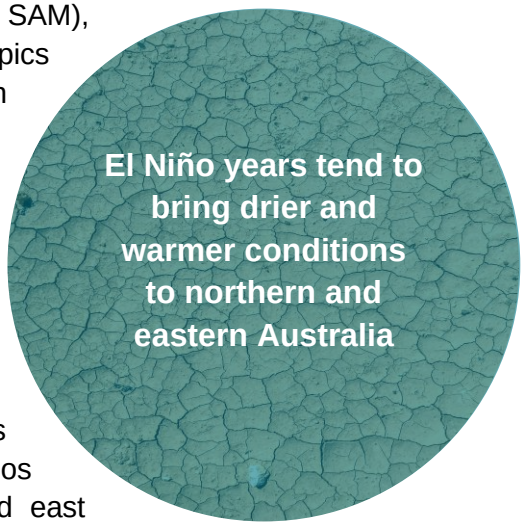
The following sections summarise our current understanding of the climate drivers most relevant to Australian climate, such as ENSO, the IOD, and SAM, with a focus on the research being done by project members.



El Niño Southern Oscillation and Pacific Ocean changes

Originating in the equatorial Pacific, the El Niño–Southern Oscillation (ENSO) has highly consequential global impacts, often leading to droughts during El Niño and floods during La Niña over eastern Australia, motivating the need to understand its responses to anthropogenic warming. **El Niño events are typically characterised by warmer than average sea surface temperatures** (SSTs) across the central to eastern equatorial Pacific, straddled by cooling to the north and south of this warming and cooling over the western equatorial Pacific. **During La Niña events, the opposite tends to occur,** with cooling across the central and eastern-equatorial Pacific. In the absence of any other climate drivers, La Niña years typically bring more spring-summer rainfall and cooler temperatures to northern and eastern Australia, while El Niño years tend to be drier and warmer. The strength of the relationship between ENSO and Australian rainfall is also modulated by the state of the Indian Ocean (characterised by the IOD), the atmospheric circulation over the Southern Hemispheric mid-latitudes (characterised by SAM), intraseasonal events in the tropics (characterised by the Madden Julian Oscillation), and the multi-decadal variability in the wider Pacific Ocean (the Interdecadal Pacific Oscillation), and so it is important to understand how all these climate drivers interact.





Furthermore, not all ENSO events are alike. **The sign and strength of El Niño-related teleconnections in Australia also vary depending on the El Niño 'flavour'** – where the Pacific sea surface temperature warming is concentrated[4,5]. For instance, Central Pacific (CP) El Niños can generate wet rainfall anomalies over the north and east regions of Australia during summer, and dry anomalies in autumn[5,6] and have a stronger impact on Australian rainfall than Eastern Pacific (EP) El Niños. CMIP6 models project a robust increase in ENSO variance, with 100% of 23 analysed models projecting an increase in EP variance and 65% in CP ENSO variance. Additionally, these models project an eastward shift and intensification of ENSO-related atmospheric teleconnections, resulting in potentially more intense ENSO-driven rainfall anomalies over the western hemisphere nations and west Antarctica. How the projected changes in ENSO diversity will affect Australian climate is not fully understood. However, given that a recent study suggests that strong CP El Niños increase summer rainfall in the Murray Darling Basin[5], projected changes in ENSO diversity may have important implications for Australian rainfall in the future.

Significant advances have been made in understanding how ENSO would respond to greenhouse warming (Fig. 1). In the past, CMIP models have yielded mixed projections on whether SST variability during ENSO events would increase or decrease, although projections of ENSO-related *rainfall* changes across the Pacific are robust[7]. These mixed projections, based on conventional ENSO indices (i.e., NIÑO indices which measure SST anomalies at

Variability: how something changes from year-to-year, or season-to-season.

fixed regions along the equatorial Pacific), remain in CMIP6 although with a higher inter-model consensus. However, by measuring CP and EP ENSO events separately, there is strong inter-model consensus in terms of a projected increase in ENSO SST variability, extreme El Niño, and extreme La Niña frequency across all emission scenarios[8].

Mean state: the long-term average.

In terms of disentangling the projected climate change signal from natural variability in the tropical Pacific, researchers have made an important distinction between detecting climate change signals in *variability*, and climate change signals in the *mean state.* The 'time of emergence' is when the changes due to climate change lie outside the expected range of natural variability. Researchers have found that the 'time of emergence' of ENSO-related rainfall variability occurs before the time of emergence for SST variability. However, the time of emergence of mean SST changes occurs before that of mean rainfall[8]. Researchers have also found that the ENSO-related SST variability response to greenhouse warming has a 'memory', and is strongly influenced by past internal (i.e. naturally occurring) variability[9]. Due to the nonlinearity of the ENSO system, weaker ENSO variability in the past would lead to a strong ENSO variability in the future. This highlights the importance of considering past observed climate variability in future projections. Given that the 2000-2019 period was one of relatively reduced ENSO variability, we might expect an increase in ENSO-related SST variability in the coming decades[9].

"The frequency of dry winter-spring seasons is projected to increase in all regions across Australia in the 21st century under a high emission scenario"

A 2020 study of how greenhouse warming would impact ENSO-related Australian rainfall 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[10]. The study found that under this scenario, **approximately 60% of years from 2010 to 2099 are projected to be drought years (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**. During this project this work is being updated using CMIP6 models.

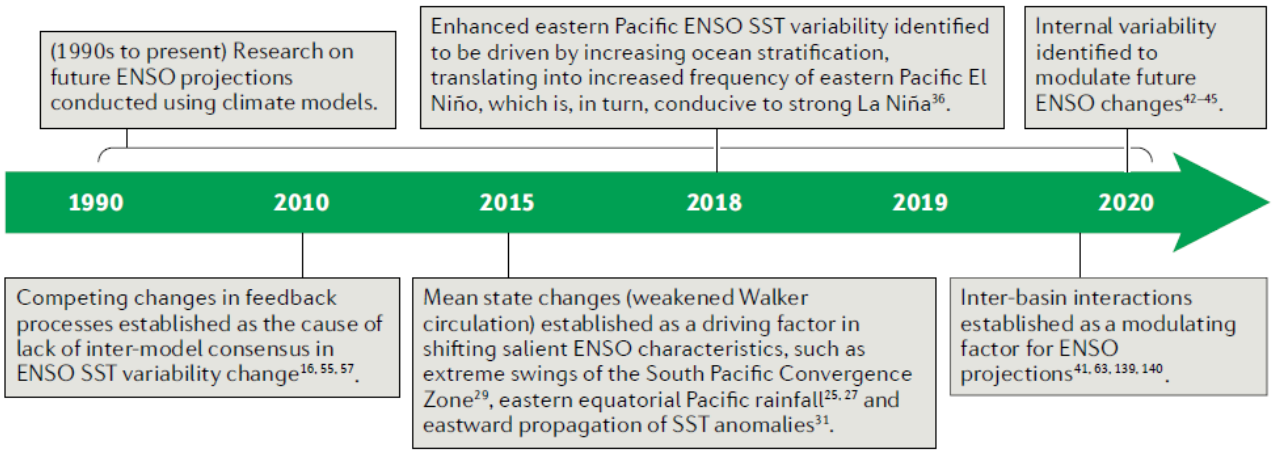


Fig. 1 | Key developments in understanding El Niño–Southern Oscillation response to greenhouse forcing. A timeline illustrating the evolution of thinking regarding El Niño–Southern Oscillation (ENSO) changes in a warming climate[8]. Each development is marked at an approximate time, starting in the 1990s, when coupled climate models were first used to study ENSO future projections.

"A positive Indian Ocean Dipole can promote the occurrences of floods in east African countries but droughts and bushfires in Indonesia and Australia"

"Consecutive IOD and El Niño events in 2018 and 2019 contributed to the extremely hot and dry conditions over south-eastern Australia leading up to the catastrophic 2019/2020 Australian Black Summer bushfires"

Indian Ocean Dipole and Indian Ocean changes

The Indian Ocean Dipole (IOD) is a climate phenomenon that impacts the Indian ocean and neighbouring regions, including southern Australia. **A positive phase of the IOD (pIOD), when the eastern and western Indian Ocean is respectively cooler and warmer than normal,** promotes occurrences of floods in east African countries but droughts and bushfires in Indonesia and Australia[11]. The extreme pIOD in 2019 led to devastating floods in east African countries affecting millions of people. In 2018 and 2019, two consecutive pIOD events occurred in conjunction with two consecutive CP El Niño events. These unique consecutive events (the first since observations began in 1911) contributed to the extremely hot and dry conditions over south-eastern Australia leading up to the catastrophic 2019/2020 Australian Black Summer bushfires[12,13]. These consecutive pIOD/CP El Niño events are projected to increase only marginally. However as mentioned above, ENSO-related winter-spring rainfall is projected to decrease across Australia[10], which would exacerbate the impacts of such events.

Understanding how IOD SST variability responds to greenhouse warming has remained a challenging issue. Climate models produce inconsistent results in assessment using a single index to characterise the IOD. Climate modellers are also working to improve the representation of the IOD in models, as some biases remain problematic. For example, CMIP6 models overestimate the strength and duration of the IOD and underestimate the skewness of the IOD (i.e. observations show that pIOD events are generally stronger than nIOD events, which many models are unable to reproduce[14]). A new study finds that there are nonlinear processes that generate two distinct regimes of the pIOD, i.e., strong and moderate pIODs

with distinct SST anomaly spatial patterns and dynamics[15]. Through the new approach in considering these two regimes, **SST variability associated with strong pIOD is projected to strengthen under greenhouse warming, whereas that of moderate pIOD is projected to weaken (Fig. 2).** These opposing changes translate into increased occurrences of strong pIOD events, but reduced occurrences of moderate pIOD events. The implication for Australia is that greenhouse warming is making strong pIOD events more likely, with implications for drought in southern Australia.

Recent experiments have also shown that the Indian Ocean, which is warming at a faster rate than other tropical ocean basins, can drive changes in the global atmospheric circulation patterns. These changes include drying over the tropical Atlantic and strengthening of a positive SAM pattern in winter[16]. The IOD and ENSO are also closely related, with ENSO events able to trigger IOD events, which in turn affect the evolution of the following year's ENSO activity[17,18].

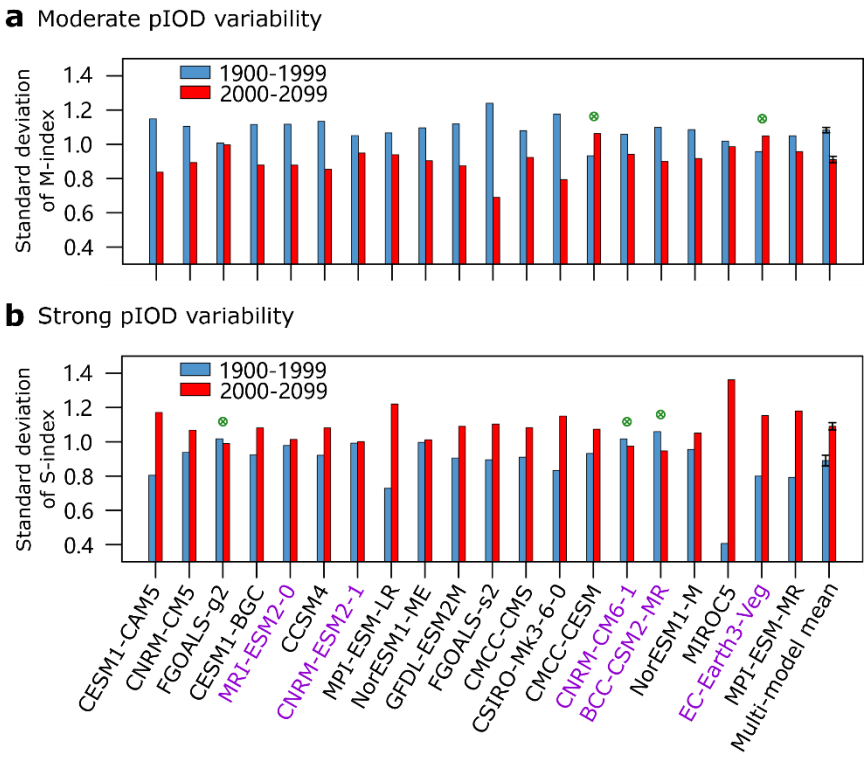


Fig. 2 | Projections show a decrease in moderate pIOD variability but an increase in strong pIOD variability[15]. A total of 18 out of the 20 selected models (90%) generate a reduction in moderate pIOD variability (depicted by the M-index) from the present-day (1900–1999, blue bars) to future (2000–2099, red bars) climate. The multimodel mean reduction of 16% is statistically significant above the 95% confidence level according to a bootstrap test. The error bars in the multimodel mean represent the 95% confidence level determined by a bootstrap test. **b**, A total of 17 out of the 20 models (85%) simulate an increase in variability of strong pIOD (described by the S-index) from the present-day to the future climate, with the exception of three models generating a decrease (indicated by green circles). The multimodel mean increase of 22% is statistically significant above the 95% confidence level according to a bootstrap test. Models from CMIP6 are indicated in purple.

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Southern Annular Mode

The Southern Annular Mode (SAM) represents the north-south shifts of the westerly wind belt that encircles the globe at around 50°S. It is associated with shifts in the extratropical Southern Hemisphere 'storm tracks' which carry heavy rainfall, and along which extratropical cyclones can form. These shifts can occur at weekly to centennial timescales,[19–25] occuring as both a natural mode of variability and also in response to climate drivers such as ENSO and global warming. **The positive phase of SAM (pSAM) is characterised by poleward shifts of the westerly jet and associated storm tracks, which result in wetter-than-normal conditions over Australia in spring and summer[26,27]**. The opposite happens during the negative phase of SAM (nSAM). Across Australia, pSAM is associated with lower rainfall over southwest Western Australia, Victoria and northern Tasmania in winter but higher rainfall over continental-wide subtropical Australia and eastern Tasmania in spring and summer[28,29].

While SAM typically has a lifespan of about two weeks, it can persist over a season in austral spring and summer thanks to its relationship with ENSO and the Antarctic stratospheric polar vortex (a polar cyclone strongest in winter, linked to the formation of the ozone hole).[30–32]. La Niña can promote the pSAM,[33–36] and conversely, El Niño can promote nSAM. **This linkage between SAM and ENSO can result in extreme Australian springtime rainfall anomalies[29]** and can also provide improved SAM predictability because strong ENSO events are skilfully predictable beyond a season in advance[34,37,38].

From October to January, SAM is also strongly driven by wind changes over Antarctica, which can be comparable to or more important than the ENSO forcing in spring.[31,39–41]. Chances of the occurrence of extreme high day-time temperatures and rainfall deficits which are directly linked to the elevated risks of bushfires, are significantly higher when the polar stratospheric vortex is significantly weaker than normal and the associated SAM is significantly negative41. This was particularly evident in late spring 2019 when very rare record-breaking stratospheric polar vortex weakening occurred. This

stratospheric wind event was a key driver of hot and dry conditions over southern Queensland and New South Wales. in October to December 2019. rare record-breaking stratospheric polar vortex weakening occurred. This stratospheric wind event was a key driver of hot and dry conditions over southern Queensland and New South Wales. In October to December 2019[32], worsening the already dry conditions due to the positive IOD and CP El Niño conditions mentioned above. Because the variability of the stratospheric polar vortex in spring is predictable from winter, this connection of SAM with the stratospheric polar vortex is another important source of predictability for the late spring season[32,40,42].

In the 1980s and 1990s, SAM showed a significant positive trend in austral late spring and summer largely because of a positive trend in the Antarctic ozone depletion (i.e., larger ozone hole) caused by human-induced ozone depleting substances (ODSs) such as chlorofluorocarbons (CFCs) and halons[43–45]. This positive trend in SAM drove a significant summer rainfall increase in regions such as Australia and southern Africa[26]. Thanks to the Montreal Protocol in 1987, the production of anthropogenic ODSs was reduced, and the positive trend in Antarctic ozone depletion has paused since 2000[46,47], resulting in a pause in the positive trend in SAM since 2000[43,48].

Questions regarding long-term trends in SAM still remain. Climate models project a continued positive trend in SAM due to increasing greenhouse gases[35,44,49,50]. However, their observed impact on the SAM trend in the past 50 years is not obvious. A recent study suggested that observed trends in SAM have been strongly influenced by internal climate variability during this multidecadal period[51]. Although the ozone forcing for pSAM has slightly reversed since 2000, the tropical Pacific has been in the negative phase of the Interdecadal Pacific Oscillation (for example, the background state has been La Niña-like) in the 2000s and 2010s. This may have contributed further to a positive SAM trend[52]. However, current climate models underestimate decadal climate variability[53,54], which is a major caveat for understanding the true impact of increasing GHGs on the climate, including the projection of SAM.

Overall, CMIP6 models have improved their representation of SAM compared to CMIP5[51,55]. These models project that the ozone hole will recover to 1980 levels by mid-21st century[48], which may cause a temporary pause in the positive SAM trend during summer. The term ‘tug-of-war' has often been used to describe the opposing effect of GHGs and ozone recovery on the SAM during the 21st century, the former driving a positive SAM trend, and the latter the opposite. However, by the end of the century under a high emission scenario, the effect of GHGs is expected to dominate and promote a positive SAM trend in all seasons[45,56]. The strengthening of the westerly winds at higher latitudes is projected for all seasons but is likely to be strongest in winter and spring, whereas the poleward shift is expected to be larger during summer and autumn, based on CMIP6 models[51]. In the case of a more moderate emission scenario where GHGs stabilize at a lower level, the ozone forcing is able to overcome the increase in GHGs and no significant trend is found in SAM (Fig 3).

Although the climate models have been extensively evaluated for their capabilities to simulate the realistic spatial structures and temporal characteristics of SAM and their changes with different levels of GHG and ozone concentrations, the assessments have not

been done in depth for the SAM-ENSO-Australian climate relationship[35] or the SAM-stratospheric vortex-ozone-Australian climate relationships either in the historical simulations or in the future climate change simulations. The latitude and strength of the midlatitude jet also shows some large regional differences across the Southern Hemisphere (SH), which are not accounted for in the conventional definition used for SAM. How realistically these interactions are simulated in different regions of the SH and how they will change in the future have significant implications for the predictabilities of the Australian climate extremes, which are yet to be explored.

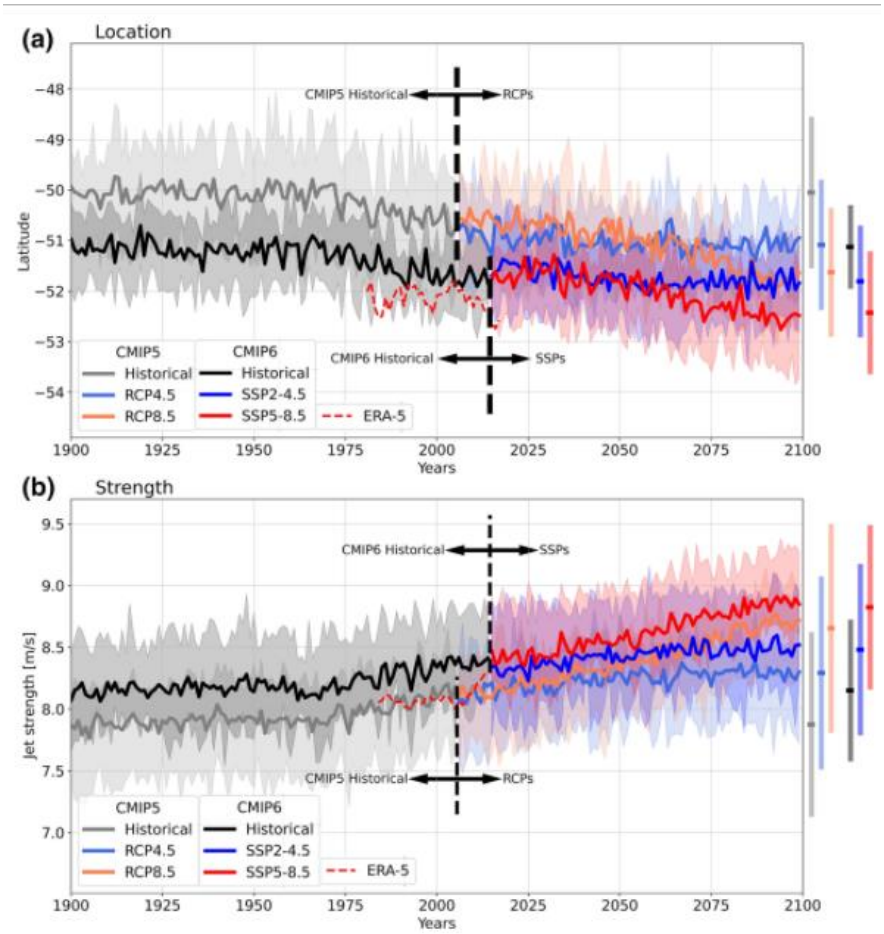

Fig. 3 | By the end of the century, increases in GHGs are expected to promote a positive SAM trend under high emissions scenarios[51]**.** Position (panel a) and strength (panel b) of maximum Southern Hemisphere surface westerly winds for CMIP5, CMIP6 models and ERA5. Thick lines represent multimodel mean and the shading indicates the interquartile range based on CMIP5 and CMIP6 ensembles. Red dotted line represents 5-year running mean jet latitude and strength from the ERA5 reanalysis from 1979 to 2019. Bars on the right represent one standard deviation model spread for historical (1901–1925 average) and future (2075–2099) for both CMIP5 and CMIP6 models and the thick line in the middle of the bars represent the multimodel mean.

Northern Australian Monsoon

The northern regions of Australia receive the majority of their annual rainfall in the summer months, associated with the Australian Summer Monsoon[57]. Variations in the monsoon on timescales from weeks to multiple years are related to several factors, including seasonal climate drivers and modes of variability that alter the large-scale atmospheric conditions over northern Australia[58]. **In order to plan for the future, climate change projections for northern Australia are essential.** However, long term climate change projections for the Australian monsoon are highly uncertain, and indeed have remained uncertain over multiple generations of state-of-the-art climate models including the most recent CMIP6 ensemble[59,60].

In addition to understanding how northern Australian rainfall responds to regional climate drivers, further research into how projected changes to the monsoon relates to large-scale tropical circulations will also help inform and eventually reduce the projection uncertainty. We propose a systematic evaluation of the large-scale tropical circulations and their teleconnection to northern Australian rainfall in global climate models.

Conclusion

Recent research has revealed that there is a projected increased occurrence of extreme El Niño and positive IOD events that can combine to bring intensified dry conditions to east and south-east Australia in winter and spring. Under a high emissions scenario, this projected response is occurring alongside a projected positive SAM trend which would result in wetter conditions over eastern Australia during summer. Together, this means climate variability is projected to increase in the future. How this increase in variability will impact Australian climate, in particular when two or more climate drivers have compounding effects, is an important question that is yet to be fully answered. More work is to be done, not only to get a better understanding of these interactions in the past and present, but also the projected future. Natural systems, water resources and communities currently have a limited capacity for managing the deep drys (and high fire danger) or extended wet driven by the current climate variability, so it is crucial that we make every effort to inform adaptive measures.

Lastly, the confidence in planning for the future in Northern Australia is limited by the uncertainties in the monsoon projections. This project will provide greater clarity around how large-scale processes are modelled to assist understanding of Northern Australian rainfall projections.

Over the course of this project, researchers will continue to seek clarity and understanding of these issues and answer pressing questions about Australia's climate drivers.

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

References

1. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2021).

2. IPCC. *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press., 2021).

3. Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).

4. Santoso, A. *et al.* Dynamics and Predictability of El Niño–Southern Oscillation: An Australian Perspective on Progress and Challenges. *Bull. Am. Meteorol. Soc.* **100**, 403–420 (2019).

5. Freund, M. B., Marshall, A. G., Wheeler, M. C. & Brown, J. N. Central Pacific El Niño as a Precursor to Summer Drought-Breaking Rainfall Over Southeastern Australia. *Geophys. Res. Lett.* **48**, e2020GL091131 (2021).

6. Taschetto, A. S., Ummenhofer, C. C., Sen Gupta, A. & England, M. H. Effect of anomalous warming in the central Pacific on the Australian monsoon. *Geophys. Res. Lett.* **36**, (2009).

7. Power, S., Delage, F., Chung, C., Kociuba, G. & Keay, K. Robust twenty-first-century projections of El Niño and related precipitation variability. *Nature* **502**, 541–545 (2013).

8. Cai, W. *et al.* Changing El Niño–Southern Oscillation in a warming climate. *Nat. Rev. Earth Environ.* **2**, 628–644 (2021).

9. Cai, W. *et al.* Butterfly effect and a self-modulating El Niño response to global warming. *Nature* **585**, 68–73 (2020).

10. Delage, F. P. D. & Power, S. B. The impact of global warming and the El Niño-Southern Oscillation on seasonal precipitation extremes in Australia. *Clim. Dyn.* **54**, 4367–4377 (2020).

11. Ashok, K., Guan, Z. & Yamagata, T. Influence of the Indian Ocean Dipole on the Australian winter rainfall. *Geophys. Res. Lett.* **30**, (2003).

12. Wang, G. & Cai, W. Two-year consecutive concurrences of positive Indian Ocean Dipole and Central Pacific El Niño preconditioned the 2019/2020 Australian “black summer” bushfires. *Geosci. Lett.* **7**, 19 (2020).

13. Abram, N. J. *et al.* Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Commun. Earth Environ.* **2**, 8 (2021).

14. McKenna, S., Santoso, A., Gupta, A. Sen, Taschetto, A. S. & Cai, W. Indian Ocean Dipole in CMIP5 and CMIP6: characteristics, biases, and links to ENSO. *Sci. Rep.* **10**, 11500 (2020).

15. Cai, W. *et al.* Opposite response of strong and moderate positive Indian Ocean Dipole to global warming. *Nat. Clim. Chang.* (2020). doi:10.1038/s41558-020-00943-1

16. Dhame, S., Taschetto, A. S., Santoso, A. & Meissner, K. J. Indian Ocean warming modulates global atmospheric circulation trends. *Clim. Dyn.* **55**, 2053–2073 (2020).

17. Izumo, T. *et al.* Influence of the state of the Indian Ocean Dipole on the following year’s El Niño. *Nat. Geosci.* **3**, 168–172 (2010).

18. Yue, Z., Zhou, W. & Li, T. Impact of the Indian Ocean Dipole on Evolution of the Subsequent

ENSO: Relative Roles of Dynamic and Thermodynamic Processes. *J. Clim.* **34**, 3591–3607 (2021).

19. Trenberth, K. E. Interannual Variability of the 500 mb Zonal Mean Flow in the Southern Hemisphere. *Mon. Weather Rev.* **107**, 1515–1524 (1979).

20. KAROLY, D. J., HOPE, P. & JONES, P. D. DECADAL VARIATIONS OF THE SOUTHERN HEMISPHERE CIRCULATION. *Int. J. Climatol.* **16**, 723–738 (1996).

21. Gong, D. & Wang, S. Definition of Antarctic Oscillation index. *Geophys. Res. Lett.* **26**, 459–462 (1999).

22. Thompson, D. W. J. & Wallace, J. M. Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. *J. Clim.* **13**, 1000–1016 (2000).

23. Marshall, G. J. Trends in the Southern Annular Mode from Observations and Reanalyses. *J. Clim.* **16**, 4134–4143 (2003).

24. Arblaster, J. M., Meehl, G. A. & Karoly, D. J. Future climate change in the Southern Hemisphere: Competing effects of ozone and greenhouse gases. *Geophys. Res. Lett.* **38**, (2011).

25. Yang, D., Arblaster, J. M., Meehl, G. A. & England, M. H. The Role of Coupled Feedbacks in the Decadal Variability of the Southern Hemisphere Eddy-Driven Jet. *J. Geophys. Res. Atmos.* **126**, e2021JD035023 (2021).

26. M., K. S., M., P. L., C., F. J. & M., S. Impact of Polar Ozone Depletion on Subtropical Precipitation. *Science (80-.).* **332**, 951–954 (2011).

27. Hendon, H. H., Lim, E.-P. & Nguyen, H. Seasonal Variations of Subtropical Precipitation Associated with the Southern Annular Mode. *J. Clim.* **27**, 3446–3460 (2014).

28. Hendon, H. H., Thompson, D. W. J. & Wheeler, M. C. Australian Rainfall and Surface Temperature Variations Associated with the Southern Hemisphere Annular Mode. *J. Clim.* **20**, 2452–2467 (2007).

29. Hendon, H. H., Lim, E.-P., Arblaster, J. M. & Anderson, D. L. T. Causes and predictability of the record wet east Australian spring 2010. *Clim. Dyn.* **42**, 1155–1174 (2014).

30. Thompson, D. W. J., Baldwin, M. P. & Solomon, S. Stratosphere–Troposphere Coupling in the Southern Hemisphere. *J. Atmos. Sci.* **62**, 708–715 (2005).

31. Lim, E.-P., Hendon, H. H. & Thompson, D. W. J. Seasonal Evolution of Stratosphere-Troposphere Coupling in the Southern Hemisphere and Implications for the Predictability of Surface Climate. *J. Geophys. Res. Atmos.* **123**, 2–12,12,16 (2018).

32. Lim, E.-P. *et al.* The 2019 Southern Hemisphere Stratospheric Polar Vortex Weakening and Its Impacts. *Bull. Am. Meteorol. Soc.* **102**, E1150–E1171 (2021).

33. Seager, R., Harnik, N., Kushnir, Y., Robinson, W. & Miller, J. Mechanisms of Hemispherically Symmetric Climate Variability. *J. Clim.* **16**, 2960–2978 (2003).

34. Lim, E.-P., Hendon, H. H. & Rashid, H. Seasonal Predictability of the Southern Annular Mode due to Its Association with ENSO. *J. Clim.* **26**, 8037–8054 (2013).

35. Lim, E.-P. *et al.* Interaction of the recent 50 year SST trend and La Niña 2010: amplification of the Southern Annular Mode and Australian springtime rainfall. *Clim. Dyn.* **47**, 2273–2291 (2016).

36. Lim, E.-P. *et al.* Continuation of tropical Pacific Ocean temperature trend may weaken extreme El Niño and its linkage to the Southern Annular Mode. *Sci. Rep.* **9**, 17044 (2019).

37. Hendon, H. H., Lim, E., Wang, G., Alves, O. & Hudson, D. Prospects for predicting two flavors of El Niño. *Geophys. Res. Lett.* **36**, (2009).

38. Lim, E.-P. & Hendon, H. H. Understanding and predicting the strong Southern Annular Mode and its impact on the record wet east Australian spring 2010. *Clim. Dyn.* **44**, 2807–2824 (2015).

39. Bandoro, J., Solomon, S., Donohoe, A., Thompson, D. W. J. & Santer, B. D. Influences of the Antarctic Ozone Hole on Southern Hemispheric Summer Climate Change. *J. Clim.* **27**, 6245–6264 (2014).

40. Seviour, W. J. M. *et al.* Skillful Seasonal Prediction of the Southern Annular Mode and Antarctic Ozone. *J. Clim.* **27**, 7462–7474 (2014).

41. Lim, E.-P. *et al.* Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex. *Nat. Geosci.* **12**, 896–901 (2019).

42. Byrne, N. J. & Shepherd, T. G. Seasonal Persistence of Circulation Anomalies in the Southern Hemisphere Stratosphere and Its Implications for the Troposphere. *J. Clim.* **31**, 3467–3483 (2018).

43. Fogt, R. L. & Marshall, G. J. The Southern Annular Mode: Variability, trends, and climate impacts across the Southern Hemisphere. *WIREs Clim. Chang.* **11**, e652 (2020).

44. Arblaster, J. M. & Meehl, G. A. Contributions of External Forcings to Southern Annular Mode Trends. *J. Clim.* **19**, 2896–2905 (2006).

45. Thompson, D. W. J. *et al.* Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nat. Geosci.* **4**, 741–749 (2011).

46. Salby, M., Titova, E. & Deschamps, L. Rebound of Antarctic ozone. *Geophys. Res. Lett.* **38**, (2011).

47. Susan, S. *et al.* Emergence of healing in the Antarctic ozone layer. *Science (80-.).* **353**, 269–274 (2016).

48. Banerjee, A., Fyfe, J. C., Polvani, L. M., Waugh, D. & Chang, K.-L. A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature* **579**, 544–548 (2020).

49. IPCC. *Climate change 2001: The scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change*. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2001). doi:10.1256/004316502320517344

50. Cai, W., Whetton, P. H. & Karoly, D. J. The Response of the Antarctic Oscillation to Increasing and Stabilized Atmospheric CO2. *J. Clim.* **16**, 1525–1538 (2003).

51. Goyal, R., Sen Gupta, A., Jucker, M. & England, M. H. Historical and Projected Changes in the Southern Hemisphere Surface Westerlies. *Geophys. Res. Lett.* **48**, e2020GL090849 (2021).

52. Yang, D. *et al.* Role of Tropical Variability in Driving Decadal Shifts in the Southern Hemisphere Summertime Eddy-Driven Jet. *J. Clim.* **33**, 5445–5463 (2020).

53. Luo, J. J., Wang, G. & Dommenget, D. May common model biases reduce CMIP5's ability to simulate the recent Pacific La Niña-like cooling? *Clim. Dyn.* **50**, 1335–1351 (2018).

54. Power, S., Delage, F., Wang, G., Smith, I. & Kociuba, G. Apparent limitations in the ability of CMIP5 climate models to simulate recent multi - decadal change in surface temperature : implications for global temperature projections. *Clim. Dyn.* **49**, 53–69 (2017).

55. Bracegirdle, T. J. *et al.* Improvements in Circumpolar Southern Hemisphere Extratropical

Atmospheric Circulation in CMIP6 Compared to CMIP5. *Earth Sp. Sci.* **7**, e2019EA001065 (2020).

56. Meehl, G. A. *et al.* Climate System Response to External Forcings and Climate Change Projections in CCSM4. *J. Clim.* **25**, 3661–3683 (2012).

57. TROUP, A. J. Variations in Upper Tropospheric Flow associated with the onset of the Australian Summer Monsoon. *MAUSAM* **12**, 217–230 (2021).

58. Wheeler, M. C. & McBride, J. L. Australian-Indonesian monsoon BT - Intraseasonal Variability in the Atmosphere-Ocean Climate System. in (eds. Lau, W. K. M. & Waliser, D. E.) 125–173 (Springer Berlin Heidelberg, 2005). doi:10.1007/3-540-27250-X_5

59. Brown, J. R., Moise, A. F., Colman, R. & Zhang, H. Will a Warmer World Mean a Wetter or Drier Australian Monsoon? *J. Clim.* **29**, 4577–4596 (2016).

60. Narsey, S. Y. *et al.* Climate Change Projections for the Australian Monsoon From CMIP6 Models. *Geophys. Res. Lett.* **47**, e2019GL086816 (2020).

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