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Acknowledgements

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output, with specific contributions from MPI[32], CNRM[33], ECMWF[34] and NCAR[35]. B.M.S. is supported by the French National Research Agency, ANR-17-MPGA-0016.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-020-0707-2.

The role of climate variability in Australian drought

Much of Australia has been in severe drought since at least 2017. Here we link Australian droughts to the absence of Pacific and Indian Ocean mode states that act as key drivers of drought-breaking rains. Predicting the impact of climate change on drought requires accurate modelling of these modes of variability.

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Australia has an exceptionally variable climate[1], with periods of drought punctuated by heavy rainfall events that can cause widespread flooding. This prevalence of floods and droughts is likely to have been typical of Australia's long-term climate[2] and is relatively common in instrumental observations over the past century or so. Droughts ranging from a year or two to more than a decade in length (such as the Millennium Drought of 1997–2009) have tended to be broken by widespread heavy rains (such as in 2010–2012, when rain brought devastating floods to Queensland) rather than simply a return to average rainfall conditions. Recently, there has been considerable discussion around the causes of the ongoing drought in southeastern Australia, including the possible influence of human-induced climate change. Here we contend that the primary reason for the long-lasting dry conditions is a recent lack of La Niña and negative Indian Ocean dipole (IOD) events in the Pacific and Indian Oceans, respectively.

Unprecedented multi-year drought

Large swaths of Australia, and in particular the Murray–Darling Basin (MDB) region of southeastern Australia, have been in drought since 2017. The MDB is a crucial agricultural region, sometimes described as the 'food bowl' of the country. Drought in this region has consequences for food and cotton prices as well as cascading effects on the regional and national economy. In addition, dry conditions can exacerbate the risk of bushfires in terms of how likely they are to occur and how difficult they are to control. Bushfires in eastern Australia in spring 2019, which have continued into the summer, have been widespread and intense because of the dryness of the fuel load in association with ongoing drought.

Drought may be analysed using a multitude of different methods and indices. In Australia, the Bureau of Meteorology measures drought based on rainfall deficiencies across different temporal scales[3]. Here we focus on rainfall, acknowledging that other variables influence the nature of drought.

The winter of 2016, which preceded the current drought, was particularly wet in southeast Australia and ranked as the fourth wettest for the MDB since 1900, the start of the instrumental record. This was associated with a negative IOD event, whereby anomalously warm sea surface temperatures in the east Indian Ocean gave rise to dynamic and thermodynamic conditions conducive to widespread rainfall[4]. Since then, there have been unusually dry conditions in the MDB with 12 consecutive seasons of below-average rainfall, the longest such period since 1900 (Fig. 1a). Specifically, the occurrence of three consecutive dry winters since 2017 — all in the lowest decile of observed values — is unprecedented since 1900. This has had severe impacts on crop harvests and water security, with several major regional centres on the brink of running out of water.

Looking through the instrumental record, we observe other periods of persistently dry conditions, such as during the Federation, Second World War and Millennium Droughts (Fig. 1a). Palaeoclimate reconstructions suggest that other multi-year droughts have occurred in previous centuries, but also that recent drying in southern Australia is unusual in a multi-century context[2]. Rainfall in the MDB is marked by very high variability, and there is no statistically significant trend towards higher or lower annual rainfall totals since 1900[5].

Drivers of MDB rainfall variability

Short-term rainfall variability in the MDB is related to the Southern Annular Mode (SAM), the Sub-Tropical Ridge and the passing of individual weather systems (Fig. 1b). On the interannual timescales relevant to the ongoing MDB drought, ENSO and the IOD are well-established drivers[6]. The IOD modulates MDB rainfall during austral winter and early spring, whereas ENSO plays a strong role during austral spring[7,8]. There are highly significant correlations between sea surface temperature indices representing ENSO and the IOD and

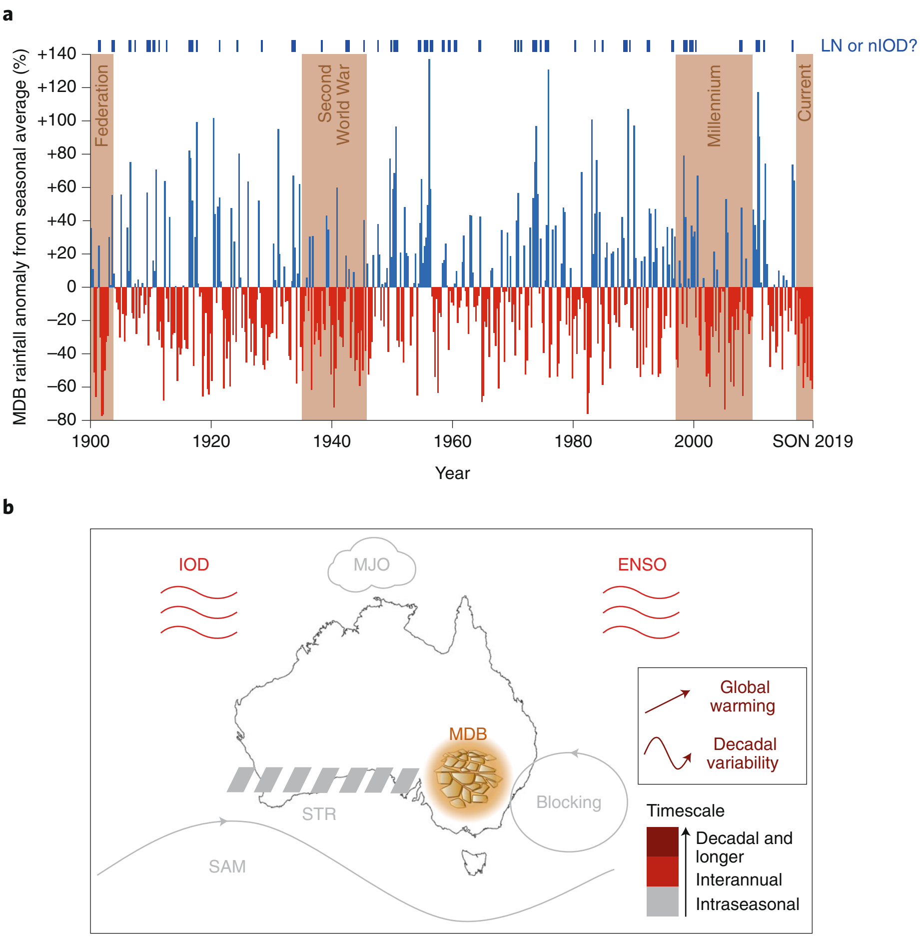

Fig. 1 | The recent drought in context and the drivers of seasonal rainfall variability in the Murray–Darling Basin of Australia. a, Observed seasonal rainfall departures as a percentage of the respective seasonal 1961–1990 climatology. The brown bars mark the times of significant multi-year drought defined following ref. [2]. The dark blue bars above the graph indicate whether the season in question is categorized as either La Niña (LN) or negative IOD (nIOD). **b**, Schematic image showing the climate modes related to rainfall variability in the MDB. Climate modes are coloured by the timescale on which they exhibit variability. STR, Sub-Tropical Ridge (belt of high pressure).

seasonal MDB rainfall anomalies (Fig. 2a,b). It is also noteworthy that the relationships between these climate modes and MDB rainfall are not always linear. On average, rainfall totals in El Niño seasons and ENSO-neutral seasons are similar, whereas La Niña seasons are often substantially wetter (Fig. 2a). Although this was known previously[9], it is highly relevant in the context of drought, as drought-breaking rainfall is considerably more likely to occur during a La Niña season than either an El Niño or ENSO-neutral season. The IOD–rainfall relationship is almost linear (Fig. 2b), but the probability of high rainfall totals is substantially greater during negative IOD events than in either neutral or positive IOD conditions for the MDB.

Without a La Niña or a negative IOD event, it is difficult for wet conditions to occur on a large spatial scale across a season in the MDB or much of eastern Australia. This is particularly clear in spring, when seven of the ten wettest seasons in the MDB since 1900 occurred during strong La Niña or negative IOD conditions, and the three remaining events fall just short of being categorized as La Niña.

These results suggest that the Australian drought should be examined through a different lens. Rather than considering only the causes of the dry conditions, analysis of the drought should include a focus on the lack of wet conditions that break it.

Dynamics that bring rain

Considering the accumulated rainfall anomaly since a La Niña or negative IOD event has occurred (Fig. 2c), we find that, typically, the more time that has passed since a La Niña or negative IOD event, the greater the rainfall deficits over the MDB. To the end of 2019, the accumulated MDB rainfall deficit is over 450 mm — the greatest running deficit since a La Niña or negative IOD event. In the instrumental record, when 6 months have passed since a La Niña or negative IOD event, 67% of the time (32/48 cases) there was an accumulated rainfall deficit in the MDB. Similarly, for events that were 12, 18 and 24 months after a La Niña or negative IOD event, the MDB experienced an accumulated rainfall deficit 76% (25/33), 81% (22/27) and 90% (19/21) of the time, respectively.

Major multi-year drought events are difficult to reliably contextualize using the instrumental record since 1900. Nevertheless, the major Australian droughts of the past 100 years have coincided with several of the longer-lasting periods when La Niña and negative IOD events did not occur. The Second World War Drought from 1935 to 1945 includes two unusually long periods when neither a La Niña nor a negative IOD event occurred, from 1934 to 1938 and 1939 to 1942. Indeed, the 1938–39 La Niña brought temporary relief with wetter-than-average conditions in the MDB in the early part of 1939. The Millennium Drought from 1997 to 2009 included periods from 2001 to 2004 and 2004 to 2007 without a La Niña or negative IOD event when rainfall deficits substantially worsened.

Although there is a general pattern towards rainfall deficits accumulating between the La Niña and negative IOD events that increase the probability of widespread heavy rainfall, there are exceptions to this pattern. For example, two long time windows without either La Niña or negative IOD events in the twentieth century were associated with small rainfall surpluses in the MDB during the early 1960s and mid-1990s (blue lines in Fig. 2c). The wettest months in these outlier series occurred in summer and were associated with positive SAM conditions, in which the midlatitude storm track is unusually far south and there are more frequent moist easterly winds over southeast Australia related to atmospheric blocking in the Tasman Sea[10,11]. There are other occasions when positive SAM conditions fail to produce large-scale rainfall events in the MDB owing to the seasonality of the SAM influence and its interaction with other climate modes[7]. Thus, the modes of variability do not provide a definitive guide to rainfall over the MDB, owing to natural variability and synoptic-scale weather systems. Although the length of time since a La Niña or negative IOD event does not necessarily imply drought, it does increase

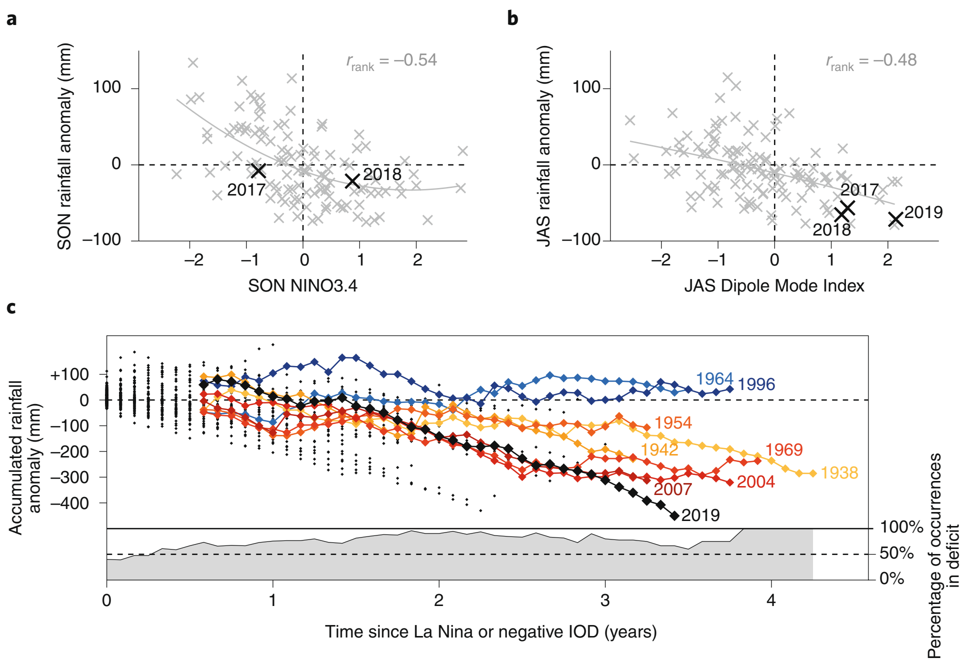

Fig. 2 | A lack of recent La Niña or negative IOD conditions is contributing to the ongoing drought in the Murray–Darling Basin. a, Scatter of September–November (SON) Niño3.4 index against concurrent MDB rainfall anomalies. **b**, Scatter of July–September (JAS) Dipole Mode Index against concurrent MDB rainfall anomalies. **a**, **b**, Second-order polynomial best fits are plotted (grey; as in ref. [9]). Spearman rank correlation coefficients (r_{rank}) are shown, and the most recent seasons of data are displayed as black crosses. **c**, Graph of accumulated rainfall anomalies during the time since a La Niña or negative IOD event has occurred. For series greater than 3 years in length, the period from 6 months onwards is coloured and marked by the end year. In the case of 2019, this is to the end of the year. The grey shaded region shows the percentage of occurrences for each time duration since a La Niña or negative IOD event when the accumulated rainfall anomaly was in deficit. See Supplementary Information for further details.

the probability of drought because of the reduced chance of widespread rain.

Focus on interannual variability

While Australia is no stranger to drought, the southeast of the continent is experiencing a particularly severe event at the time of writing. Droughts in Australia have wide-ranging impacts from large economic costs[12] to increased mental health disorders[13] and suicide rates[14]. Individual farms may experience some drought relief due to local storm events, but southeast Australia is in urgent need of widespread heavy seasonal rainfall. Our analysis suggests that the probability of widespread drought-breaking rains is associated with La Niña or negative IOD events.

To understand the risks of human-induced climate change on the security of Australia's water supplies, its agriculture, the prevalence of droughts and the intensity of bushfires will therefore require accurate projections of the future frequency of La Niña and negative IOD events in a warming world. These events may be increasing as the world warms[15,16], but there remains uncertainty in projections due to model deficiencies. In particular, climate models overstate the amplitude of the IOD[17] and struggle with the spatial and temporal extent of La Niña[18]. This leaves Australia in a challenging position in terms of how to prioritize investment in climate adaptation, because it is unclear how the IOD and ENSO will change in the future and whether these changes will exacerbate drought conditions. Clearly, a continent as vulnerable to drought as Australia has a vested interest in accelerating research that addresses the present and future role of the IOD and La Niña in explaining large-scale rainfall. ❐

Andrew D. King[1,2] ✉, Andy J. Pitman[2,3], Benjamin J. Henley[1,2,4], Anna M. Ukkola[2,5] and Josephine R. Brown[1,2]

[1]*School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia.* [2]*ARC Centre of Excellence for Climate Extremes, University of New South Wales, Kensington, New South Wales, Australia.* [3]*Climate Change Research Centre, University of New South Wales, Kensington, New South Wales, Australia.* [4]*School of Earth, Atmosphere and Environment, Monash University, Clayton, Victoria, Australia.* [5]*Research School of Earth Sciences, Australian National University, Canberra, Australian Capital Territory, Australia.*
✉*e-mail: andrew.king@unimelb.edu.au*

Published online: 24 February 2020
https://doi.org/10.1038/s41558-020-0718-z

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Acknowledgements

We thank the Bureau of Meteorology, the Bureau of Rural Sciences and CSIRO for providing the Australian Water Availability Project data. Several authors received funding through the Australian Research Council: A.D.K. (DE180100638), and A.J.P. and A.M.U. (CE170100023). B.J.H. received funding from an Australian Research Council Linkage Project (LP150100062), which was co-funded by Melbourne Water and the Victorian Department of Environment, Land, Water and Planning, and supported by the Australian Bureau of Meteorology.

Author contributions

A.D.K. conceived the study and performed the analysis. All authors contributed to the methodological design and the writing of the paper.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-020-0718-z.

nature climate change

SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41558-020-0718-z

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The role of climate variability in Australian drought

Andrew D. King[1,2] ✉, **Andy J. Pitman**[2,3], **Benjamin J. Henley**[1,2,4], **Anna M. Ukkola**[2,5] and **Josephine R. Brown**[1,2]

[1]School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia. [2]ARC Centre of Excellence for Climate Extremes, University of New South Wales, Kensington, New South Wales, Australia. [3]Climate Change Research Centre, University of New South Wales, Kensington, New South Wales, Australia. [4]School of Earth, Atmosphere and Environment, Monash University, Clayton, Victoria, Australia. [5]Research School of Earth Sciences, Australian National University, Canberra, Australian Capital Territory, Australia. ✉e-mail: andrew.king@unimelb.edu.au

The role of climate variability in Australian drought:

Supplementary Information

Andrew D. King, Andy J. Pitman, Benjamin J. Henley, Anna M. Ukkola, Josephine R. Brown

Data

This analysis was performed using observational data only. The rainfall timeseries for the Murray-Darling Basin region (MDB; http://www.bom.gov.au/climate/change/about/rain_timeseries.shtml) is derived from the Australian Water Availability Project (AWAP[1]). This is a daily rainfall product that extends back to 1900 and is on a regular 0.05° grid. Here, monthly data averaged over the Murray-Darling Basin were downloaded from the Bureau of Meteorology website (http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi) for January 1900-November 2019. Monthly and seasonal anomalies were calculated from a 1961-1990 climatology.

The Niño-3.4 index and Dipole Mode Index (DMI[2]) were calculated from the Met Office observational sea surface temperature (SST) dataset (HadISST[3]) for January 1900-October 2019. The Niño-3.4 area-average SST was calculated within the box [5°N-5°S, 170°W-120°W]. The DMI was calculated as the difference in area-average SST between the western Indian Ocean [10°N-10°S, 50°E-70°E] and the eastern Indian Ocean [0°N-10°S, 90°E-110°E]. Both the Niño-3.4 and DMI indices were calculated by detrending the respective area-average SST timeseries. The detrending was performed by calculating anomalies from a 30-year centred moving window with the detrending calculated for each calendar month individually. The detrending for the DMI was performed after the difference between western and eastern Indian Ocean SSTs was calculated. A sensitivity test was performed by not detrending the DMI at all and this produced broadly similar results. Both indices were also standardised for subsequent analysis with anomalies calculated from a 1961-1990 mean.

Methodology

Scatter plots of the Niño-3.4 and DMI indices were plotted against MDB area-average rainfall anomalies for September-November and July-September respectively. These periods were chosen for exhibiting particularly strong ENSO and IOD relationships with MDB rainfall[4,5]. A second-order polynomial was fitted to both the ENSO-rainfall and IOD-rainfall scatter plots as in Power et al.[6] and Spearman rank correlation coefficients were calculated due to the non-Gaussian nature of seasonal rainfall totals and the non-linear relationship identified between ENSO and MDB rainfall.

To analyse the effect of a lack of La Niña or negative IOD conditions on MDB rainfall, La Niña and negative IOD events were first identified in the observational record. These were defined as events where the Niño-3.4 index (for La Niña) and DMI (for negative IOD) were greater than one standard deviation below average for a given month. The robustness of results to the choice of threshold was tested and found to be strong to changes of up to 0.25 of a standard deviation in the threshold. La Niña events were only identified for calendar months from June-February and negative IOD events were only identified for calendar months from May-October as these are periods when ENSO and IOD are most active and strongly related to Australian climate. For Figure 1, where seasons with La Niña or negative IOD are marked, these are for La Niña events are identified in June-August, September-November, and December-February, and for negative IOD events in June-August and September-November only.

In Figure 2c, rainfall anomalies were accumulated for all time durations in the 1900-2019 timeseries since either a La Niña or negative IOD event had occurred. Periods without a La

Niña or negative IOD exceeding three years in length were identified and examined more closely. The percentage of rainfall accumulations in deficit for each time duration since a La Niña or negative IOD had occurred was also calculated.

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