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High impact compound events in Australia

ARC Centre of Excellence for Climate Extremes

- Compound events are combinations of weather and climate hazards that have the potential to cause more severe socio-economic impacts than hazards occurring in isolation.
- Australia has experienced a variety of compound events that have led to loss of life and negatively impacted the Australian economy over the past decades.
- Future climate change will lead to an increase in prolonged hot and dry compound events over all of Australia which is likely to exacerbate fire risk and have negative impacts on agricultural productivity and human health.
- Current climate models project an increase in wet and windy compound events in the northern parts of Australia dominated by tropical cyclones and thunderstorms, and a decrease in events in the south where fronts and frontal systems are the dominant drivers of extreme wind and rain.
- The ARC Centre of Excellence for Climate Extremes is leading research that will ultimately help businesses and governments better assess the risks posed by compound events.

This is the third in a series of briefing notes on compound events. The broad area of compound events science was addressed[1,2], in March 2022, followed by a global-scale assessment of how compound events might respond to climate change in April 2022[3,4].

This report focuses on Australia, at a higher level of spatial detail than is possible globally, and utilises data sets that are specific to Australia. By focusing on Australia, areas of confidence and uncertainty can be more clearly identified. Future work to resolve weaknesses in model agreement is highlighted at the end of this briefing note.

Compound events in Australia

Many major catastrophic events in Australia have characteristics typical of compound events. While climate scientists have tended to focus on single drivers of events (what was the role of La Niña, is rainfall intensifying, how is the risk of heatwaves increasing?), almost all catastrophic events are the consequence of multiple drivers acting together. There is growing awareness that assessment of single meteorological drivers in isolation will not fully capture the potential changes in extreme weather and climate events as the climate shifts. To do so will require an assessment of the risk of multiple hazard events occurring concurrently or consecutively.

Compound events are highly diverse in terms of their characteristics. They may arise from multiple hazards or drivers, they may be a succession of hazards, or be hazards in multiple connected locations,
or they may be simply a more severe event as the result of preconditioning[5].

Compound events involve multiple elements of weather and climate jointly causing an impact on a socioeconomic or ecological system.

One of the first compound events identified in Australia exhibited both temporal and spatial compounding: the simultaneous occurrence of the 2009 heatwave in Victoria, which culminated in the Black Saturday bushfires, and two tropical cyclones making landfall in Western Australia and Queensland, bringing strong winds and heavy rainfall leading to infrastructure damage and localised flooding. All three events arose because atmospheric processes were connected by large-scale atmospheric dynamics related to atmospheric waves[6,7], (Figure 1).

Similarly, there is a large variety of known connections between atmospheric processes that are likely responsible for up to half of summertime rainfall in the northwest of the continent[8], heatwaves over south eastern Australia[9], and the formation of east coast lows, which can bring extreme rainfall to the eastern seaboard of Australia[22]. When analysing climate hazards, an insurance company might think cyclones occurring in one part of Australia are independent of heatwaves and fire occurring in another part of Australia, but in fact these can be connected through the atmosphere and are not independent.

Some compound events are of the type where multiple drivers combine to lead to a major event. An example was the Black Summer bush fires of 2019/20 in southeast Australia. These were linked with widespread landscape dryness, likely associated with the extended period since the occurrence of a La Niña event and a negative phase of the Indian Ocean Dipole[10]. Together with strong winds, clear skies causing additional drying, and high fuel loads[11] they allowed the occurrence of fires with impacts of the unprecedented extent seen during that summer.

Similarly, the extreme rainfall in New South Wales in 2021/22 combined strong on-shore moisture flow, a blocking high-pressure system over the Tasman Sea, Rossby wave breaking, and a range of important synoptic-scale features. Added to these weather-scale features was a double-dip La Niña which meant that catchments were saturated before the latest and very extreme rainfall occurred[12]. This was a compound event where a series of synoptic-scale mesoscale rainfall features happened to occur sequentially in the same geographic location, and antecedent conditions were important (Figure 1).

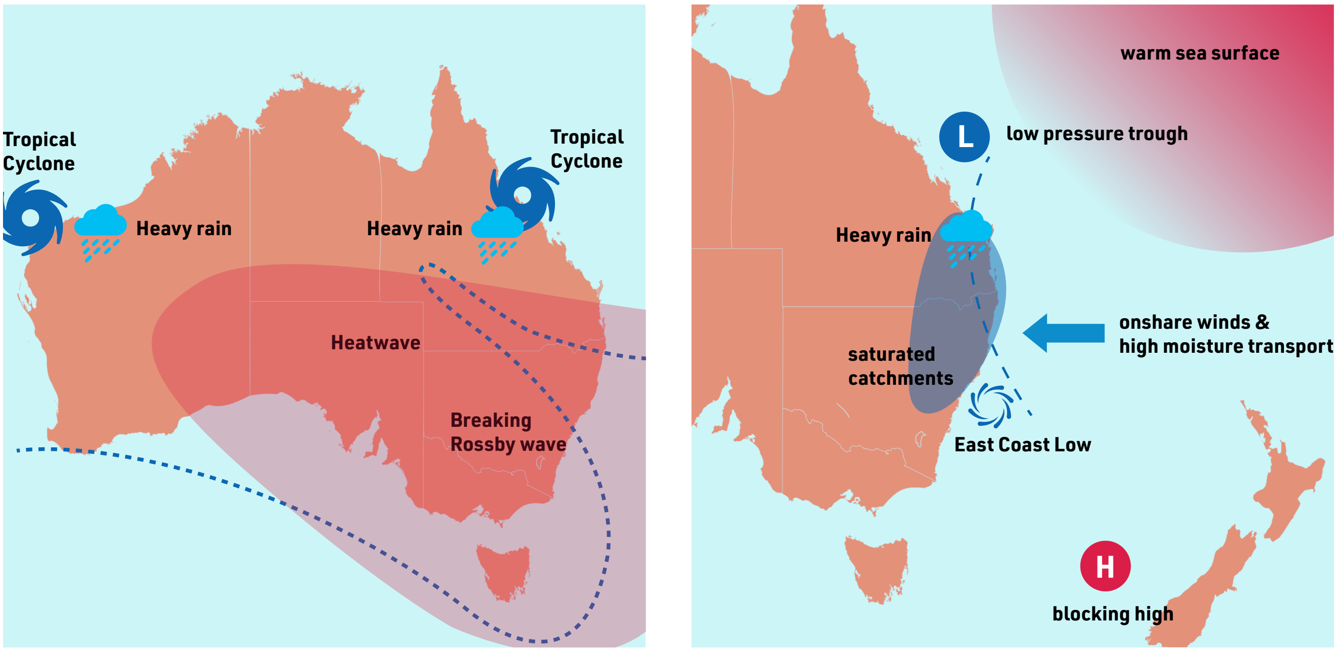

Fig. 1. Schematic of the conditions preceding the February 2009 Black Saturday Bushfires (left), and the conditions that lead to the devastating floods in Queensland and Northern New South Wales in February/March 2022 (right).

These sorts of events are experienced in many regions of Australia. The Australian Royal Commission into National Natural Disaster Arrangements (2020)[13] noted that some communities will have to cope with the effects of multiple natural hazard events immediately, with the prospect of being affected by further hazard events before recovery efforts have been completed. In addition, they noted that to properly manage natural disasters of national scale and consequence, it was necessary to assess the risk of multiple hazard events occurring concurrently or consecutively. Looking ahead, the Australian Prudential Regulation Authority (APRA[14]) has instructed businesses to assess "the impact of multiple extreme weather events arising concurrently" when assessing future climate risk (APRA, 2021). In effect, the Royal Commission and APRA have asked for a clear focus on compound events.

Compound events are a key focus area at the ARC Centre of Excellence for Climate Extremes. In recent research, we examined the current and future projected frequency of two important compound events in Australia; the joint occurrence of hot and dry, and wet and windy conditions. We also discuss how our science can inform businesses around the risk of these events in the future.

What do observations tell us about Australian compound events?

The examples above illustrate that compound events can arise from numerous phenomena in a multitude of possible combinations, and from interactions on a wide variety of temporal and spatial scales. From this large set of possible combinations and scales of interaction,

> we focused on two compound events that have had significant impacts on the Australian socioeconomic system over the past: the joint occurrence of wet and windy, and prolonged hot and dry, conditions over roughly three decades (1980–2014).

We used a combination of observations and reanalysis data. For rainfall and temperature, we used daily data from the Australian Bureau of Meteorology via the Australian Water Availability Project (AWAP; Jones et al., 2009). These data are based on in-situ rain gauge and thermometer measurements and are provided as a gridded dataset at 0.05° × 0.05° spatial resolution (approximately 5 km × 5 km).

We obtained 3-hourly wind speed from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) global reanalysis dataset (Hersbach et al., 2020). Because the ERA5 reanalysis uses satellite data for records from 1979, we limited our analysis to the period from 1980 onwards.

Our analysis focused on relatively mild extremes. This is necessary to provide a sufficiently large sample size to allow statistically significant analyses. Thresholds for wind and rainfall were set at their respective 99th percentiles, which represents an event that occurs roughly 3 times a year. Hot events were defined as three consecutive days with daily temperatures above the 95th percentile of the climatological mean of those days, while dry events were those months with 3-month rainfall of −1.3 standard deviations below the climatological mean. Figure 2 shows the resulting observed return period (the average time between events) for the co-occurrence of hot and dry, and for wet and windy conditions.

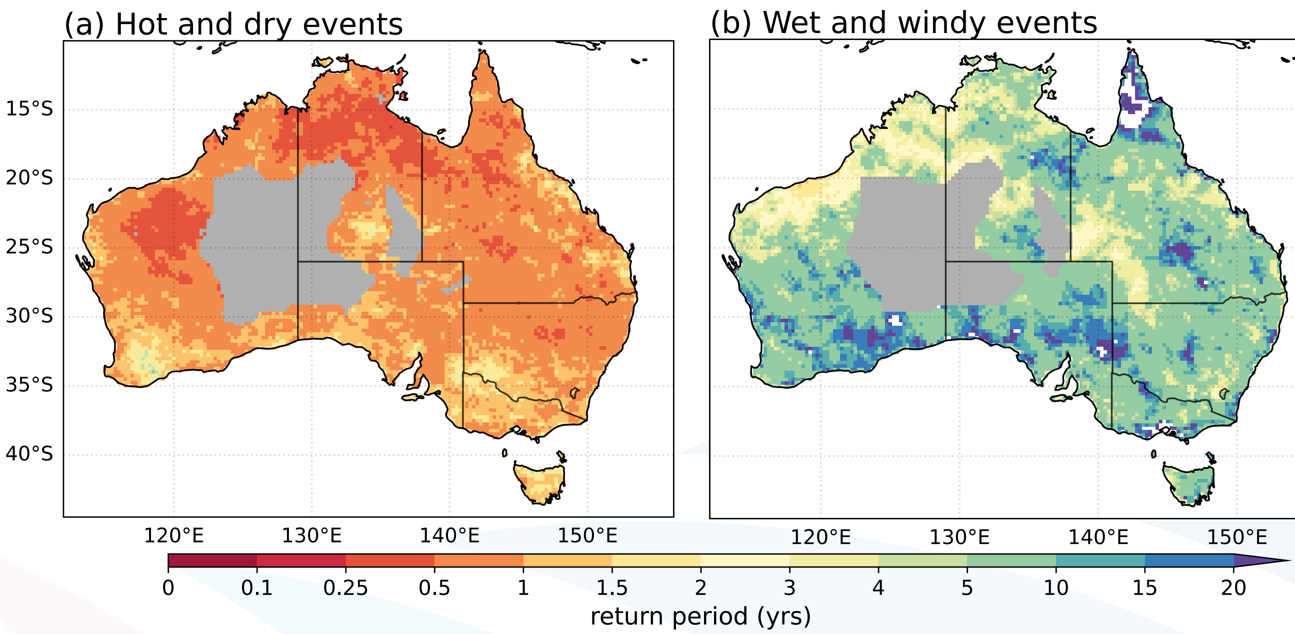

Fig. 2. Observed climatology for (a) hot and dry events and (b) wet and windy compound events derived from the Australian Water Availability Project (AWAP) temperature and precipitation, and ERA5 wind speed, for the time period 1980–2014. Grey areas mask regions where AWAP precipitation data has more than 10% of missing data. Note that the climatology is limited to return periods of less than 35 years due to limiting the datasets to the satellite era, and the statistical method used to determine event likelihood.

Under current conditions, hot and dry events display shorter return periods (they occur more frequently, several times a year) in the north, becoming longer (they occur less frequently, every 2-3 years) in the south. Wet and windy compound events show short return periods along the north-west coast with longer return periods to the south and east.

How will this picture change in the future?

Global climate models can be used to explore this question, and Figure 3 shows the results for a medium emissions scenario (SSP2-4.5). The medium emissions scenario is a plausible trade-off between the low emissions scenario that is more likely to be an infeasible future and the high emissions scenario with changes that are unlikely to be adaptable to. SSP2-4.5 results in global mean warming of 2.1–3.5°C above pre-industrial levels by 2100.

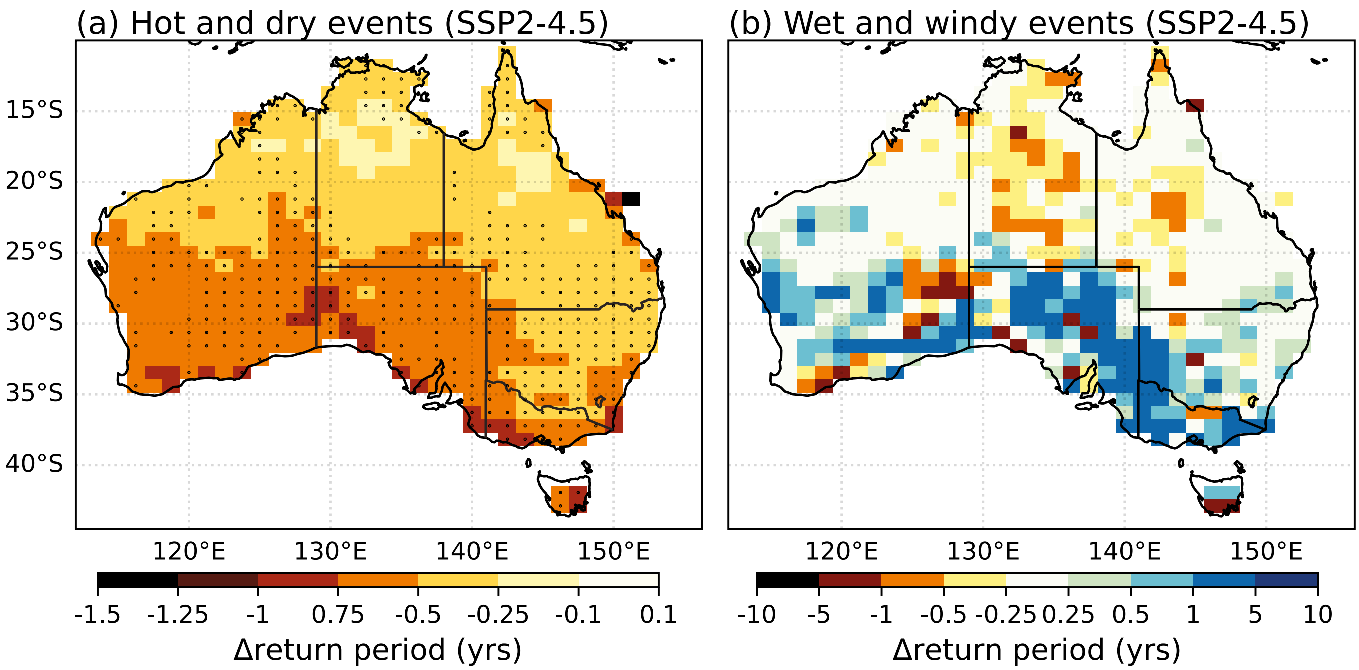

Fig. 3. Multi-model median change in return period for hot and dry, and wet and windy events in 2066–2100 compared to 1980–2014 following a moderate (SSP2-4.5) emissions scenario. The black dots indicate regions where the models produce a reasonably robust result.

Figure 3 illustrates two major features of this future scenario. First, hot and dry events increase everywhere in Australia, indicated by the negative changes in return period. A negative change in return period means an event of a given size that occurs at present, will occur more frequently in the future. The changes in the return period are mostly around 0.5 to 0.75 years, representing a substantial increase in risk. Second, for wet and windy events the changes are generally quite small over the continent as a whole. However, there is an increase in the return period over Victoria, South Australia, and to a lesser degree over Western Australia and New South Wales. At present, these regions experience roughly one wet and windy event every 5 to 20 years (Figure 2b). This is projected to increase by roughly 1 to 5 years on average. There are places where the return periods are projected to decrease but these are scattered across the continent, and may well be unreliable and associated with noise in the climate projections.

To infer information about localised changes, it is not advisable to extract data at a single pixel from this analysis – one cannot infer a signal from just a few pixels. Instead, conclusions should be drawn based on broader spatial patterns that are more likely to be robust. From Figure 3a the result is clear, with the risk of hot and dry compound events increasing for all of Australia. From Figure 3b there is an increase in the return periods for wet and windy events across much of the southern half of Australia, with either no clear signal or a slight reduction in return periods over the northern parts of the continent.

Why do these compound events appear to change in the future?

Hot and dry compound events

The reductions in the return periods for hot and dry events are largely the result of higher mean temperatures over Australia in the future, a trend that has been observed over the last several decades and which can be directly attributed to increasing concentrations of greenhouse gases in the atmosphere. The larger reductions in return periods over the southern half of Australia are consistent with a global-scale analysis of drought intensity and duration. This reduction in return periods, and more frequent hot and dry events, points to a deterioration of conditions for agriculture in the future[15].

The reliability of these results is closely connected to the ability of climate models to represent the two hazards contributing to this compound event. Therefore, an analysis of the skill of the current generation of global climate models to simulate the major drivers of heat extremes in Australia - such as atmospheric blocking, soil moisture variability and land-atmosphere coupling[16] - would be beneficial, combined with an updated analysis of model skill in simulating drought.

Crucial to simulating drought is the ability to capture long-term persistence of dryness, but also the role of the El Niño Southern Oscillation and the Indian Ocean Dipole. These have been shown to be significant climate drivers for the occurrence of hot and dry events. These large-scale processes are captured with useful skill in many, but not all, global models. The reasonable degree of agreement between models on increasing drought intensity and duration and heightened heatwave risk[17] suggests that it is necessary to plan for the changes shown (at the large scale) in Figure 3.

> The results for hot and dry compound events have a range of implications for important socioeconomic sectors in Australia.

More frequent hot and dry events across a continent that is already hot and often dry, offers no obvious benefits but implies considerable costs. Figure 3 shows that the reduction in return periods under a moderate emissions scenario will likely affect major agricultural areas (the wheat belt of Western Australia, and major wine-growing regions in Western Australia, South Australia, Victoria and Tasmania) and most major population centres. Under a high emissions future, these circumstances will worsen to include most of the Murray Darling Basin.

Why do these compound events appear to change in the future?

Wet and windy compound events

The contrasting patterns of future change for wet and windy events (Figure 3b) between the northern and southern regions of Australia suggests changes in the contributions from different weather systems. For example, Dowdy and Catto (2017)[18] show that between 2005 and 2015, univariate wind and precipitation extremes in northern Australia were commonly caused by cyclones and thunderstorm activity, while frontal systems and fronts with thunderstorms caused extremes in the south-west and south-east of Australia. The current generation of climate models currently use spatial resolutions that preclude the simulation of these smaller-scale weather phenomena which are potentially a major driver of changes in the risk of such compound events. Consequently it is not surprising that the contrasting north-south pattern in the change of wet and windy events is not necessarily robust, given that the degree of correspondence between the models is poor (note the lack of black dots indicating model agreement in Figure 3b).

Regions where cyclones and thunderstorms are the major driver of strong winds and heavy rain, i.e. in the northern parts of Australia, are shown as areas where the return periods for wet and windy events shorten in the future (Figure 3b).

The large increases in wet and windy return periods over southern Australia shown in Figure 3b are likely associated with regions where fronts are the key driver. An older generation of climate models tended to capture winter front frequency well, but simulated too high a frequency of frontal precipitation with too low an intensity[19]. Examining the changes in the two components of wet and windy for the CMIP6 models would be very useful, but this research has not been undertaken to date.

The above drivers are very challenging for CMIP6 models to resolve. As such, the current generation of climate models generally show lower skill for combined wet and windy conditions compared with hot and dry events.

To improve skill in simulating the detail of these meteorological events likely requires the development of weather-resolving climate models[20,21], that explicitly resolve, rather than parameterise, key processes such as convection.

Conclusions

The acknowledgement in Australia by the Royal Commission (2020) and the Australian Prudential Regulation Authority (APRA) of the need to consider compound events is welcome. Our results provide the first Australian-specific evaluation of how CMIP6 models project the future risks of two important types of compound events. We note, however, that our results need to be interpreted with care.

> The results in Figure 3 show broad-scale future changes which may be robust in the case of hot and dry events but are much more uncertain, with little agreement across the CMIP6 models, for wet and windy events.

A tendency has emerged to utilise climate models for decision-making in ways for which the models were never designed for[22]. To avoid potential misuse of our results, we emphasise that these give broad continental-scale indications of how the risk of two types of compound events might change in the future. It would be inappropriate and inadvisable to extract details from small groups of pixels from our results and use them to inform future risk at the local or urban scale.

The advice from APRA that businesses should consider compound events is appropriate and the acknowledgement by the Royal Commission (2020) to assess the risks of compound events is correct. However, the skill of climate models for simulating the change in the risk of almost all types of compound events is very limited. Earlier, we discussed three compound events and we reflect on these to highlight the limits of future projections at this time.

The 2009 heatwave in Victoria, the Black Saturday bushfires, and the tropical cyclones making landfall in Western Australia and Queensland are physically linked via atmospheric processes, Rossby wave breaking and small-scale synoptic processes. At present, global climate models cannot capture fire weather, tropical cyclones or the synoptic scale processes, and whether the models properly connect these phenomena is unknown. The ARC Centre of Excellence is currently examining whether climate models can make these links.

Further, the Black Summer bushfires of 2019/20 in New South Wales required a very long period of extreme dryness linked to long periods since a La Niña event and a negative phase of the Indian Ocean Dipole, together with strong winds, clear skies causing additional drying, and high fuel loads. Our current climate models struggle with capturing long dry periods, and they do not simulate fuel loads. The ARC Centre of Excellence for Climate Extremes is addressing these aspects of ocean and atmospheric variability to determine why climate models struggle to simulate persistent dry periods. In the meantime, the risks of future conditions like 2019/2020 are unlikely to be reflected in our models, and may be underrepresented in future simulations.

The extreme rainfall in New South Wales in 2021/22 combined strong on-shore moisture flow, a blocking high-pressure system over the Tasman Sea, Rossby wave breaking, and a range of important synoptic-scale features combined with two consecutive La Niña events. Our climate models lack the spatial detail to capture all these elements well.

> The ARC Centre of Excellence for Climate Extremes is assessing the drivers of the extreme rainfall event to determine what we can, and cannot, say about the risk of these kinds of events in the future.

Compound events over Australia do represent significant risks and are fundamental to many major disasters. At present, however, we urge considerable caution in using global climate models, which do not resolve weather-scales, as part of the risk assessment process in disaster management, business risk, etc. Rather than using climate model output, we suggest using climate models to inform scenarios, storylines[23,24], and stress testing, or using climate models to modify the statistics represented in current-day catastrophe modelling. These approaches can help break the false assumption that the numerical precision in climate models equates to accuracy at a granular level. In many ways, this echoes the need to take climate models seriously, but not literally[25].

Created By:

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