A fiery wake-up call for climate science

To improve climate resilience for extreme fire events, researchers need to translate modelling uncertainties into useful guidance and be wary of overconfidence. If Earth system models do not capture the severity of recent Australian wildfires, development is urgently needed to assess whether we are underestimating fire risk.

Benjamin M. Sanderson and Rosie A. Fisher

The images from the Australian fires served as a bitter climax to a year that was already dominated by climate change and climate-related extreme events. A natural disaster of breathtaking scale unfolds as large fractions of Australia's east coast have burned to an extent not seen in living memory, releasing an estimated 350 million tonnes of CO_2 into the atmosphere in November and December[1], and causing the loss of thousands of homes and the death of hundreds of millions of animals[2].

The natural and human disaster has clear political resonance in a country with contentious climate politics, and the question of whether anthropogenic climate change has caused or exacerbated the fires has been a central topic of public debate. Scientists drawn into this debate are generally expected to provide 'hot takes', which are often distilled into strong attribution statements in the media[3,4] or explicitly make the case for a simple relationship between warming and fire behaviour[5–7]. But the relationship between fire and climate is notably complex[8], and blanket simplifying statements risk undermining expert authority. Worse, by failing to recognize and address knowledge gaps, we may leave society unprepared for potentially more extreme events in the future.

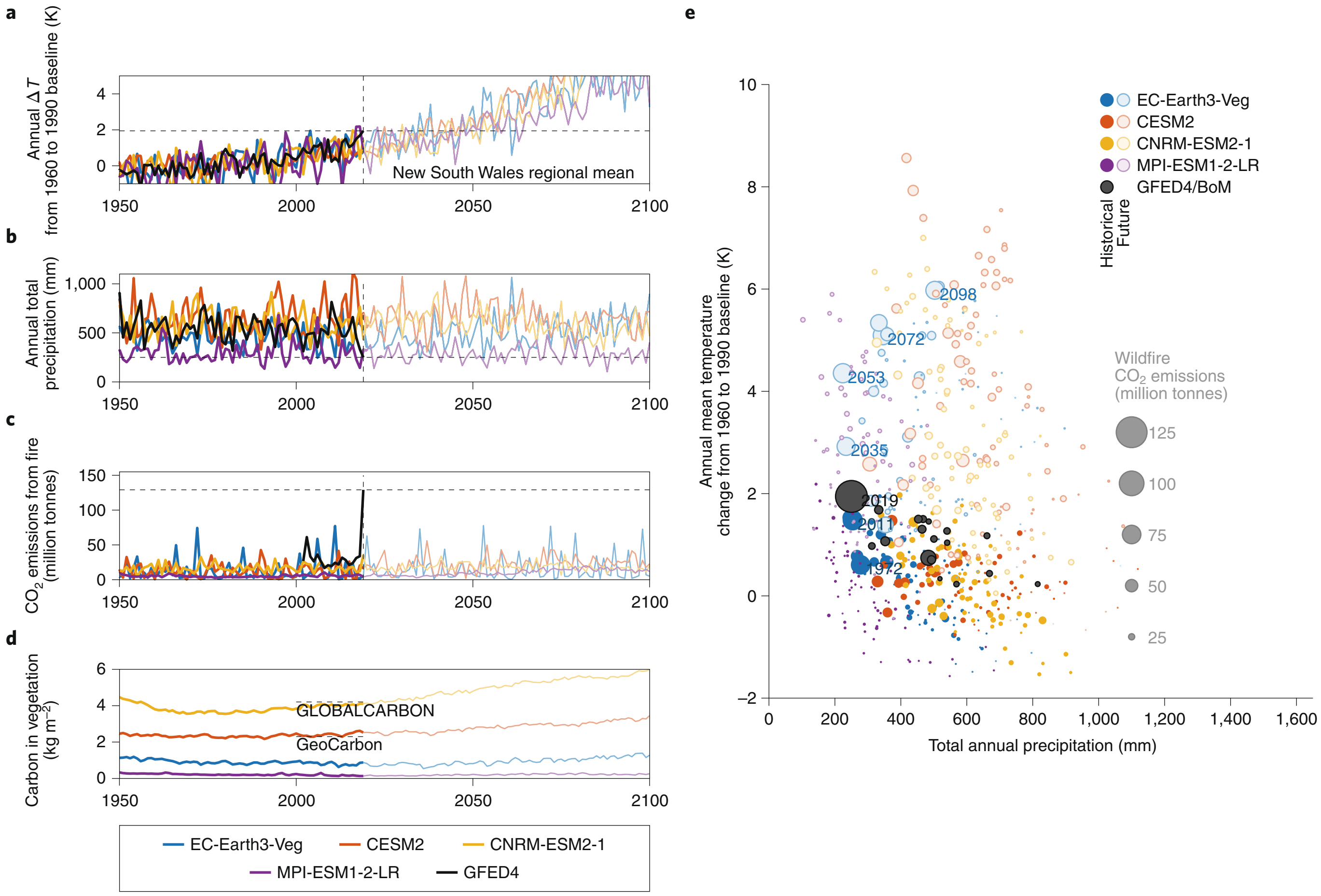

Fig. 1 | Observed and projection of historical and future climate in New South Wales, Australia. Projections are from four CMIP6 models that include fire model output in scenario projections. **a**–**d**, Evolution of the annual mean surface-temperature anomaly (from a 1960 to 1990 baseline); absolute precipitation; CO_2 emissions from fire; and vegetation biomass. **e**, Fire CO_2 emissions (illustrated by bubble size) as a function of both surface temperature anomaly and total annual mean precipitation. Future projections are shown in faded colours. Mean observed biomass estimates are from GLOBALCARBON[36] and GeoCarbon[37]. Temperature and precipitation data are from the Australian Bureau of Meteorology[38]. Fire emissions data are from the Global Fire Emissions Database (GFED)[1].

For an increasing number of catastrophes, strong attribution statements are justified. Mean warming levels are now sufficiently large that many high-temperature extreme events would be impossible without anthropogenic influence[9], and they can be reliably projected to become more intense in the future. In the case of recent events in Australia, there is no doubt that the record temperatures of the past year would not be possible without anthropogenic influence, and that under a scenario where emissions continue to grow, such a year would be average by 2040 and exceptionally cool by 2060 (Fig. 1a).

If all else is kept constant, higher temperatures will result in more fire-prone conditions[10]. This is represented in operational fire risk metrics used in forest management, which are calculated as functions of temperature, wind, moisture and fuel availability[11]. Such metrics, however, are calculated on historical datasets, and a premise that these relationships will hold in future climate is an extrapolation[12].

The complex dynamics of fuel accumulation, vegetation dynamics and their interactions with climate under transient CO_2 concentrations, as well as impacts of land management and human ignitions, are likely to result in fire behaviour patterns not represented in historical records. Thus, fire prediction over decadal to century timescales requires more mechanistic approaches, capable of capturing the numerous interacting system components that affect the evolution of fire risk[13,14].

Process-based global fire models based on these principles have progressed rapidly over the past decade[15–17]. Their use in fully coupled climate projections, however, is still not standard practice. Many Earth system models are thus omitting a potentially important component of the global carbon–climate feedback, while failing to deliver projections of one of the main facets of climate impacts on human society[18,19]. For those few CMIP6 models that do include prognostic fire (four unique models with future coupled projections: EC-Earth3-Veg, CESM2, CNRM-ESM2-1 and MPI-ESM1-2-LR), there can be large regional biases that make projections or formal attribution statements difficult.

For the case of New South Wales (the Australian state in which the fire extent is most unprecedented), the scale of the fires is unmatched in the CMIP6 simulations in either the present or the future (Fig. 1c; similar biases are evident in other Australian territories, as illustrated in the Supplementary Information). This is partly because 2019 was marked also by exceptionally low rainfall (Fig. 1b). For EC-Earth3-Veg (the one CMIP6 model that does simulate occasional mega-fires in southeast Australia), rainfall is a much stronger predictor of fire extent than temperature. Indeed, in that model, it is only at much greater regional warming levels — 4 °C above pre-industrial — that similar fire extents are seen in years without comparably low rainfall (Fig. 1e). Precipitation projections for southeast Australia remain highly uncertain and model-dependent[10], and assessing the changing probabilities of low-rainfall years like 2019 under climate change requires large ensembles that simulate many realizations of natural variability[20].

Fundamentally, modelling the cascade of climate, vegetation and anthropogenic feedbacks that lead to extreme fire events in semi-arid regions is challenging. In coupled Earth system models, biases in climate (or productivity) can mean that some models do not simulate enough vegetation to allow large burns to occur (for example MPI — purple in Fig. 1). Conversely, in systems that are wet or dominated by woody plants, vegetation- or fuel-mediated feedbacks may act to maintain systems in a fire-free state (both in models[21] and real life[22,23]). Simulation of transitional semi-arid vegetation is in itself difficult[24] on account of poorly understood phenology[25,26], root water access[27,28], grass/understorey dynamics[29], fuel dynamics[8] and heterogeneity. Fire ignition also requires parameterization and calibration. Fire models typically initialize burning events through both lightning-induced and anthropogenic ignitions, the latter based on a probabilistic function of human population density (as is the effectiveness of fire suppression activities)[30].

Recently published results of the first 'FireMIP' intercomparison project[17,31] have illustrated the capabilities of global fire models (and their host land-surface schemes) to capture these interactions when driven 'offline' with climate reanalysis data. They shed light on the causes of variability in model responses to climate and vegetation state[8], as well as illustrating the importance of appropriate representation of land use and human ignitions[30]. If we aspire to make useful projections of the future risk of catastrophic fires, entraining this new understanding into coupled Earth system simulations must be a high priority of upcoming model development efforts. At present, the inclusion of fire is arguably considered as an afterthought (or not at all) by many Earth system modelling efforts, representing a mismatch between resources dedicated to understanding this problem and the seriousness of its potential consequences.

It is critical that Earth system modelling is capable of informing the changing risk of potentially devastating events. The fact that Australia has experienced damages that go beyond what is currently simulated highlights that current syntheses may be missing major risks. Policymakers should take this as a warning that ongoing emissions will take us into an increasingly unpredictable climate space where impacts may be more extreme than projections. Scientists, on the other hand, need to tread a delicate line of underlining what is certain and providing appropriate guidance on what is not, while redoubling efforts to better represent climate impacts that most directly affect society.

Benjamin M. Sanderson[1,2] ✉ and **Rosie A. Fisher**[1]

[1]*CERFACS, Toulouse, France.* [2]*National Center for Atmospheric Research, Boulder, CO, USA.*
✉*e-mail: sanderson@cerfacs.fr*

https://doi.org/10.1038/s41558-020-0707-2

References

1. Giglio, L., Randerson, J. T. & van der Werf, G. R. *J. Geophys. Res. Biogeosci.* **118**, 317–328 (2013).
2. *University of Sydney News* (8 January 2020); https://go.nature.com/3aBhTyu
3. Eggleton, M. *National Geographic* (15 November 2019); https://go.nature.com/38MEJSl
4. Rice, D. *USA Today* (8 January 2020); https://go.nature.com/36xAvfA
5. Mann, M. *The Guardian* (1 January 2020); https://go.nature.com/30WmreF
6. Law, T. *Time* (7 January 2020); https://go.nature.com/2RwgBxx
7. Abram, N. *Scientific American Blog Network* https://go.nature.com/3aNFI6o (2019).
8. Forkel, M. et al. *Biogeosciences* **16**, 57–76 (2019).
9. Sippel, S., Meinshausen, N., Fischer, E. M., Székely, E. & Knutti, R. *Nat. Clim. Change* **10**, 35–41 (2020).
10. Kirchmeier-Young, M. C., Zwiers, F. W., Gillett, N. P. & Cannon, A. J. *Climatic Change* **144**, 365–379 (2017).
11. Van Wagner, C. E. & Canadian Forestry Service. *Development and Structure of the Canadian Forest Fire Weather Index System.* Forestry Technical Report 35 (Canadian Forestry Service, 1987).
12. Clarke, H. & Evans, J. P. *Theor. Appl. Climatol.* **136**, 513–527 (2018).
13. Hoffmann, W. A. et al. *Austr. Ecol.* **37**, 634–643 (2012).
14. Shuman, J. K. et al. *Environ. Res. Lett.* **12**, 035003 (2017).
15. Thonicke, K. et al. *Biogeosciences* **7**, 1991–2011 (2010).
16. Hantson, S. *Biogeosciences* **13**, 3359–3375 (2016).
17. Hantson, S. et al. *Geosci. Model Dev*. https://doi.org/10.5194/gmd-2019-261 (2020).
18. Liu, Y., Goodrick, S. & Heilman, W. *For. Ecol. Manag.* **317**, 80–96 (2014).
19. Arora, V. K. et al. *Biogeosci. Discuss*. https://doi.org/10.5194/bg-2019-473 (2019).
20. Norris, J., Chen, G. & Neelin, J. D. *J. Clim.* **32**, 5397–5416 (2019).
21. Scheiter, S., Moncrieff, G. R., Pfeiffer, M. & Higgins, S. I. *Biogeosci. Discuss*. https://doi.org/10.5194/bg-2019-415 (2019).
22. Staver, A. C., Archibald, S. & Levin, S. A. *Science* **334**, 230–232 (2011).
23. Forkel, M. et al. *Environ. Res. Commun.* **1**, 051005 (2019).
24. Whitley, R. et al. *Biogeosciences* **14**, 4711–4732 (2017).
25. Dahlin, K. M., Fisher, R. A. & Lawrence, P. J. *Biogeosciences* **12**, 5061–5074 (2015).
26. Dahlin, K. M., Ponte, D. D., Setlock, E. & Nagelkirk, R. *Ecography* https://doi.org/10.1111/ecog.02443 (2017).
27. Williams, M., Law, B. E., Anthoni, P. M. & Unsworth, M. H. *Tree Physiol.* **21**, 287–298 (2001).
28. Kauwe, M. G. D. et al. *Biogeosciences* **12**, 7503–7518 (2015).
29. Whitley, R. et al. *Biogeosciences* **13**, 3245–3265 (2016).
30. Teckentrup, L. et al. *Biogeosciences* **16**, 3883–3910 (2019).
31. Rabin, S. S. et al. *Geosci. Model Dev.* **10**, 1175–1197 (2017).
32. Neubauer, D. et al. HAMMOZ-Consortium MPI-ESM1.2-HAM model output prepared for CMIP6. https://doi.org/10.22033/ESGF/CMIP6.5016 (2019).

33. Seferian, R. CNRM-CERFACS CNRM-ESM2-1 model output prepared for CMIP6 CMIP. https://doi.org/10.22033/ESGF/CMIP6.1391 (2018).
34. EC-Earth Consortium (EC-Earth). EC-Earth-Consortium EC-Earth3-Veg model output prepared for CMIP6 ScenarioMIP. https://doi.org/10.22033/ESGF/CMIP6.727 (2019).
35. Danabasoglu, G. NCAR CESM2 model output prepared for CMIP6 ScenarioMIP. https://doi.org/10.22033/ESGF/CMIP6.7768 (2019).
36. Liu, Y. Y. et al. *Nat. Clim. Change* **5**, 470–474 (2015).
37. Ge, Y., Avitabile, V., Heuvelink, G. B. M., Wang, J. & Herold, M. *Int. J. Appl. Earth Obs.* **31**, 13–24 (2014).
38. Australian Government Bureau of Meteorology. Climate change — trends and extremes. http://www.bom.gov.au/climate/change (accessed 8 January 2020).

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.

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

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