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LETTER

Controlling factors of wildfires in Australia and their changes under global warming

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Abstract

This study investigates a fire weather index (FWI) and its associated components in Australia using the downscaled projects for the Coupled Model Intercomparison Project phase 6 dataset, aiming to understand how they respond to global warming, particularly associated with different phases of the El Niño-Southern Oscillation (ENSO). In the historical simulation, multimodel mean composite results show positive anomalies of FWI during El Niño and negative anomalies during La Niña over most of Australia relative to the neutral year. At the end of the 21st century under the Shared Socioeconomic Pathways (SSP585 scenario), FWI anomalies increased across Australia; however, ENSO wildfire teleconnections weakened (−4.4%) during El Niño but strengthened (+6.0%) during La Niña, especially in northern Australia. Further examination of the contribution from individual environmental variables that enter the FWI shows that increased temperature and drought conditions with warming in La Niña strengthen positive FWI anomalies, thus making fire more favorable in north and central Australia. The impacts of relative humidity and wind speed anomaly changes also favor fire activity toward the north. These results suggest a more robust modulation of FWI in northern Australia by ENSO in a warmer climate; future efforts to predict wildfire will depend on the model's ability to predict local climate conditions.

1. Introduction

The Australian wildfire season of 2019–2020 was unprecedented in many ways. This wildfire season was distinct in its intensity and spatial and temporal distribution (Boer *et al* 2020), with devastating consequences for lives and property, especially in the southeast of the continent (Wintle *et al* 2020). The emission from such wildfires further increases the atmospheric concentrations of CO_2 and other greenhouse gases (Khaykin *et al* 2020, Hirsch and Koren 2021). Modeling studies showed that biomass aerosol emitted from Australian wildfire causes clouds and radiation responses similar to those simulated for a major volcanic eruption that significantly impacts climate responses (Fasullo *et al* 2023). This Black Summer event was just the latest in a series of similar events that have impacted Australia in the past decades. The wildfire conditions exhibit variability on a broad range of time and spatial scales in Australia (e.g. Abram *et al* 2021), so understanding what processes control these variations is relevant to regional and large-scale climate variability, natural hazards, and local resource management.

Meteorological conditions have undoubtedly made significant impacts on the ignition and spread of wildfires (e.g. Simard *et al* 1985, Carmona-Moreno *et al* 2005, Mooney *et al* 2011, Sharples 2022). Previous research found that fires are highly sensitive to atmospheric conditions and regional land surface changes that control fuel drying (Forkel *et al* 2019, Bui *et al* 2022), implying the importance of understanding how air temperature, moisture, and wind speed can influence fire spread (Yu *et al* 2020). Toward this end, various fire weather indices (FWI) were developed and continually improved to study the environmental conditions leading to wildfire occurrence. The current study focuses on the modified Fosberg FWI (Fosberg 1978, Goodrick 2002), an index with global applicability in assessing fire weather conditions in many places around the globe (see more detail in the Methods section). Analyzing the FWI helps identify processes to which fires are particularly sensitive; knowledge of FWI, such as its temporal and spatial variation/distribution and changes, provides insight into the mechanisms that modulate fire weather conditions and thus helps to improve their representation in climate models in order to advance prediction.

In this study, we examine the relationship between FWI and the leading large-scale climate variabilities that influence Australia on interannual to decadal timescale—the El Niño-Southern Oscillation (ENSO; Walker 1924). The warm phase of the ENSO, or El Niño, is characterized by an anomalous and widespread warming of central and eastern tropical Pacific Ocean sea surface temperature (SST) of up to several degrees. El Niño has been known to be associated with a planetary-scale redistribution of heat, precipitation, and winds (McPhaden *et al* 2006), generally producing anomalous drier and warmer conditions over much of Australia, especially in the southeast (e.g. Wang and Hendon 2007, King *et al* 2013). On the other hand, the cold phase of the ENSO, or La Niña, usually brings anomalous wetter and colder conditions over the Australian continent (Chung *et al* 2023). However, it is important to note that recent studies have shown a non-linear relationship between ENSO and Australian weather/climate (Chung and Power 2017). While northern Australia feels the direct effect of ENSO via changes in surface temperature, ENSO influences southeast Australian rainfall via zonally asymmetric Rossby wave-trains (Gillett *et al* 2023b). Importantly, the connection between ENSO and Australian weather is not straightforward but rather complex, varying across seasons and regions (e.g. Cai *et al* 2001, Pui *et al* 2012, Tozer *et al* 2023, among many others). Despite the extensive research on the impacts of ENSO on wildfires (e.g. Cai *et al* 2001, Harris *et al* 2008, Murphy and Timbal 2008, Hill *et al* 2009, Risbey *et al* 2009, Mariani *et al* 2016, Virgilio *et al* 2019, Abram *et al* 2021, Canadell *et al* 2021), there is still a need to quantify the contributions from each environmental factor impacting fire weather conditions.

Given the current global warming (Intergovernmental Panel on Climate Change (IPCC) 2022) and its associated impact on the climate variables (e.g. Vecchi *et al* 2006, Chou *et al* 2009), one would expect such changes to manifest in the wildfires. Most climate models project an increase in wildfires due to greenhouse warming (e.g. Canadell *et al* 2021, Clark *et al* 2021a, 2021b, Jones *et al* 2022, among others); however, fewer studies focused on assessing the changes in controlling factors of wildfires and their coupled with atmosphere-ocean conditions in a warmer climate. Understanding the response of wildfires and their controlling factors to interannual climate variability and climate change is essential for mitigating and protecting socio-economic systems, which may also explain the recent wildfires in Australia and around the globe.

To study the controlling factors of wildfire in Australia and their changes under global warming, we use the latest climate simulations from the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projects (NEX-GDDP) of the Coupled Model Intercomparison Project phase 6 (CMIP6; Eyring *et al* 2016, Thrasher *et al* 2022). We aim to (1) quantify the contribution of climate conditions to the FWI, (2) investigate how El Niño and La Niña modulate these factors, and (3) assess how the FWI and its components are expected to change under global warming. The NEX-GDDP-CMIP6 dataset provides high-resolution and bias-corrected climate change projections that help evaluate climate change impacts on processes on a finer scale. This dataset is also helpful for examining driving impacts and adaptation, given the higher spatial and temporal resolution compared to other climate data products (Thrasher *et al* 2022).

2. Data and methods

2.1. Data

We use the following datasets, which were re-gridded to a $0.25^\circ \times 0.25^\circ$ latitude-longitude grid resolution prior to subsequent processing.

2.1.1. NEX-GDDP-CMIP6 model outputs

To understand the controlling factors of wildfires in Australia, we utilized the NASA Earth exchange global downscaled projects for several CMIP6 models (Eyring *et al* 2016, Thrasher *et al* 2022). A brief description and the spatial resolution of the 15 models, which provide daily data necessary for FWI diagnosis, are given in table S1 in the supplementary materials. The historical and the shared socioeconomic pathways (SSP) with fossil-fueled development combined with an 8.5 W m^{-2} forcing scenario (SSP585; O'Neill *et al* 2016) are used in our analysis. The present and future climate are defined using 1981–2010 in the historical and 2071–2100 in SSP585 simulations, respectively. In most of this paper, we focus on multimodel means, although results from individual models are shown for some key quantities and figures to examine the model spread. Individual models, as might be expected, produce noisier patterns than the multimodel means, as well as different amplitude distributions, although the overall conclusions on the sense of the pattern are consistent with the multimodel mean.

2.1.2. Reanalysis

- *European Center for Medium-Range Weather Forecasts reanalysis version 5 (ERA5;* Hersbach

2018): This reanalysis was used for comparison with the model simulations. We analyzed the forest fire danger index from the ERA5 during the time period of historical simulation from 1981 to 2010 (see figure S1(b) in supplementary materials).

- *Global Fire Weather Database (GFWED)*: Our analysis also included an examination of the FWI from the GFWED (see figure S1(c)). The GFWED comprises different sets of FWI estimated from the NASA Modern Era Retrospective Analysis for Research and Application version 2 (MERRA-2; Rienecker *et al* 2011). It is worth noting that the smaller magnitude of the NEX-GDDP-CMIP6 relative to GFWED is because the field is averaged across multiple models with peak variability in slightly different places, thus resulting in a smaller multimodel mean composite amplitude.

2.1.3. Observational dataset

We also compared our FWI from the model with the observed fire emission and burned area data set from the Global Fire Emissions Database version 4 (GFED4; Giglio *et al* 2013, Randerson *et al* 2017; also see figures S1(d) and (e)). The GFED4 combines satellite information on fire activity and vegetation productivity to estimate burned areas and emissions. Admittedly, the observed fire emissions from GFED4 are governed not just by area burned and fire counts but also by fuel load and fuel type, such as the vegetation burned by fire. The emission data also have limitations since they were obtained by redistributing monthly emissions with other fire information (Van der Werf *et al* 2017). Hence, they could not be directly compared to FWI. Nevertheless, the fire emission (from 2003 to 2022) and the burned areas (from 1997 to 2016) are analyzed for reference purposes, revealing qualitative similarities in the spatial distribution despite the noisy detailed structure, given the short-term record of the data.

2.2. Methods

2.2.1. FWI

As mentioned in the Introduction, we have chosen to use a FWI in the current study to help us understand the impact of climate/environmental conditions impact on fire weather conditions. It is important to note that FWI is only a proxy of fire weather, not the specific fire behavior, and different indices may yield slightly different results (e.g. Sharples 2022), but do not change the conclusions (Dowdy 2018). Generally, larger values of FWI are associated with extended flame lengths and spread. There are several fire weather indices featured in the wildfire literature [see a review of Sharples (2022)]. In this study, we will focus on the Fosberg FWI (Fosberg 1978) because it has been widely used to assess fire weather conditions in many places around the globe (Goodrick 2002). The index was further modified by Goodrick (2002) to assess the fire weather conditions in Australia, which includes not only temperature, relative air humidity, and wind speed but also precipitation in the form of drought factor (Goodrick 2002, Sharples *et al* 2009). This global applicability of the modified Fosberg FWI makes it a useful tool for wildfires studies. For simplicity, we refer to this modified Fosberg FWI as FWI throughout the entire paper:

$$\mathrm{FWI} = \left(0.000002 \cdot \mathrm{KBDI}^2 + 0.72\right) \cdot \frac{\left[1 - 2 \cdot \left(\frac{\mathrm{EMC}}{30}\right) + 1.5 \cdot \left(\frac{\mathrm{EMC}}{30}\right)^2 - 0.5 \cdot \left(\frac{\mathrm{EMC}}{30}\right)^3\right] \cdot \sqrt{1 + U^2}}{0.3002} \tag{1}$$

where U is the wind speed (mph), EMC is the equilibrium moisture content (mm). The Keetch Byram Drought Index (KBDI) is calculated based on Keetch and Byram (1968) that represents the soil moisture deficit and requires daily temperature and precipitation as input:

$$\mathrm{KBDI} = Q + \frac{(800 - Q) \cdot \left(0.968 \cdot e^{0.0486 \cdot T} - 8.30\right) \cdot \Delta t}{1 + 10.88 \cdot e^{-0.0441 \cdot P}} \cdot 10^{-3} \tag{2}$$

where Q is the previous day's KBDI minus net rainfall (inch/100), T is air temperature (°F), Δt is time increment (one day), and P is mean annual precipitation (inch). Note that the daily FWI was first calculated using daily data before averaging into monthly data to examine the ENSO impacts.

2.2.2. Source of FWI

The following method, designed for practical application, is used to assess the individual importance of the variables that comprise the FWI for determining the FWI anomalies. First, the FWI is calculated where all four variables (i.e. humidity, temperature, wind speed, and drought factor) are allowed to vary fully. Then, we recomputed the FWI such that three out of the four variables are allowed to vary but with the climatological annual cycle of the remaining variable input. This quantity can then be subtracted from the FWI calculated using all variables to assess the importance of the variable of interest. This allows more nonlinearity in the calculation than setting all variables to the climatological mean. The method, therefore, provides a better quantitative estimate of the relative importance of the different factors to the variability of FWI anomalies, which is similar to the approach used by Bui and Maloney (2022) for the tropical cyclone genesis potential index.

2.2.3. ENSO modulation

To classify ENSO events, we begin by calculating the Niño 3.4 index using monthly SST anomalies (i.e. removing a 30 year climatology) over the region of 5° N–5° S and 170° W–120° W for both historical and SSP585 simulations. El Niño and La Niña months are defined when Niño 3.4 index exceeds the threshold of $+1\sigma$ or -1σ, respectively. Neutral ENSO months are defined as all months that are left once the El Niño and La Niña months are classified, an approach similar to previous studies (e.g. Santoso *et al* 2017, Gillett *et al* 2023, Liu *et al* 2023b).

The teleconnections during El Niño and La Niña are examined using composite analysis. To highlight the impacts of different ENSO phases, we calculate the differences between El Niño and La Niña relative to the neutral ENSO (Liu *et al* 2023b, Santoso *et al* 2017). It is important to note that we perform such a composite for all seasons to avoid complications due to the strong seasonality of ENSO (Min *et al* 2013), where the tropical SST gradient/anomalies can modulate fire anomalies for every season in different regions in Australia (Harris and Lucas 2019).

2.2.4. Significant test

All the calculations in this paper are done for individual models separately before calculating the ensemble mean. The results are significant when more than two-thirds of the models (i.e. more than 10 out of 15) agree with the multimodel mean. We also perform a Student t-test between the future and historical simulations to assess the significant impacts of global warming (figures S8 and S9).

3. Results

3.1. Connections between ENSO, atmospheric, terrestrial forcings, and wildfire activities

The FWI shows a significant difference between El Niño and La Niña in comparison to the neutral ENSO cases (figures 1(a)–(c)). Specifically, during El Niño, the multimodel mean shows significantly positive anomalies of FWI in southern Australia and negative anomalies in the north (figure 1(b)). Conversely, during La Niña, FWI indicates significantly negative anomalies in southern Australia (figure 1(c)) and positive anomalies in the northern region (despite insignificance). Our model's FWI aligns well with results from the observed FWI from the Global Fire Weather Database (GFWED) and the fire danger index from the fifth generation of the European Center for Medium-Range Weather Forecasts (ERA5) reanalysis (see figure S1). The discrepancies between ENSO phases highlight the impact of SST anomalies on wildfire anomalies in Australia, particularly the modulation of wildfire in southeast Australia during El Niño, consistent with previous studies (e.g. Murphy and Timbal 2008, Risbey *et al* 2009, Mariani *et al* 2016, Harris and Lucas 2019).

Notably, previous studies have shown that, in northern and central Australia, fire activity is mainly fuel-driven and controlled by the amount of fuel available, given that grasslands dominate this region (e.g. Harris *et al* 2008), while in southern and eastern Australia, fire usually occurs in forested regions where it needs an extended period of dry conditions or drought to burn (Harris *et al* 2008, Williams *et al* 2009, Sullivan *et al* 2012). Impacts from land cover to wildfires have been documented in various regions of the world (e.g. Jensen *et al* 2018, Liu *et al* 2018, Junaidi *et al* 2021), although we leave further investigation of this behavior in Australia to future modeling sensitivity studies where we can alternately test the role of land surface conditions versus atmosphere-ocean changes for mediating the wildfire response. Regardless of the impacts of the land surface, in the next section, we will further quantify the contribution of each environmental condition, or top-down controls, to the variation of FWI.

3.2. Sources of FWI variability

To understand the pattern of FWI anomalies, we further decompose these into the contributions from each environmental variable: relative humidity, drought factor, maximum temperature, and wind speed (figure 2; see Methods and figure S3 for details). The result of adding the four contributions calculated this way produces a similar anomaly pattern to the total field shown in figure 1, with the maximum peak of FWI in central and western Australia during neutral ENSO (cf figure 1(a) and the first column in figure S3). Drought is the most dominant factor contributing to FWI anomalies across Australia, except for Tasmania, where temperature contributes the most (figure 2(a)). On the other hand, relative humidity and wind speed contribute the least to FWI in the central and southeastern regions, respectively, compared to the other variables (figure 2(d)). Lower relative humidity might lead to increased fires, but wind speed effects may only be important during fire aggregation processes (Wu *et al* 2018). The result thus highlights the importance of dynamic and thermodynamic factors that influence the fire weather conditions and suggests a close relationship between hydroclimate conditions and wildfires in Australia (Dowdy 2018, Harris and Lucas 2019).

When the central-eastern tropical Pacific is warmer than usual (i.e. during El Niño), the maximum contributions come from temperature and

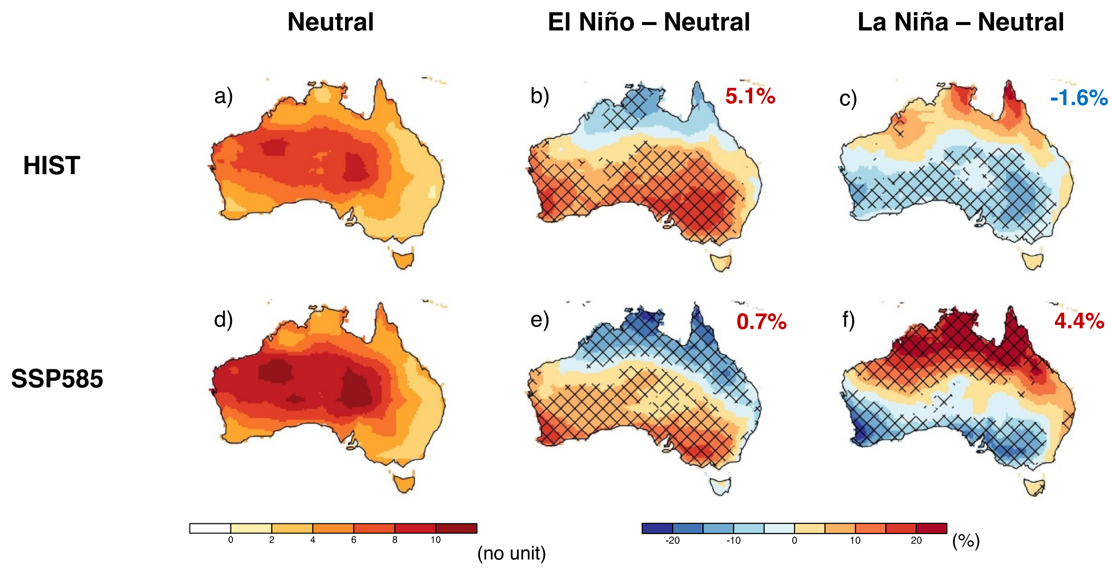

Figure 1. (a) Multimodel mean historical simulation (1981–2010) of FWI (no unit) from the NEX-GDDP-CMIP6 during the neutral ENSO phase. (b), (c) Multimodel mean FWI deviation from the neutral phase of the El Niño and La Niña cases, respectively (shaded, units are %). (d)–(f) Similar to (a)–(c) but for the multimodel mean SSP585 (2071–2100) simulations. The value on the top-right corner of the second and third columns shows the percentage difference relative to the neutral ENSO averaged over Australia (red shows an increase while blue shows a decrease). Cross-hatching indicates regions where two-thirds of models (i.e. more than 10 out of 15) show the same sign with the multimodel mean. The 15 NEX-GDDP-CMIP6 models used to construct the multimodel mean are indicated in table S1 in the supplementary materials. See figure S1 for the FWI from the Global Fire Weather Database (GFWED), the fire danger index (FDI) from the reanalysis ERA5, and the observed burned area and fire emission from the Global Fire Emissions Databases (GFED).

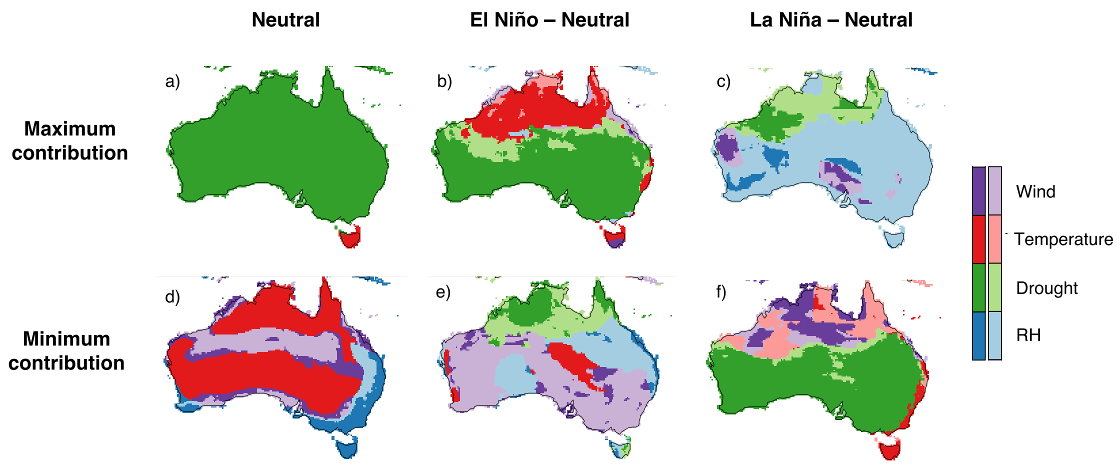

Figure 2. (a)–(c) Color-coded maps show the maximum contribution of the environmental variables [surface wind speed (Wind), maximum temperature, Keetch Byram Drought Index (Drought), and relative humidity (RH)] to FWI in historical simulation during the (a) neutral ENSO, (b) El Niño, and (c) La Niña relative to neutral ENSO. Dark colors represent the significant contribution (i.e. more than two-thirds of models agree with the multimodel mean), while the associated light colors represent the insignificant contribution. (d)–(f) Similar to (a)–(c) but shows the minimum contribution. See figure S3 for the spatial distribution of each environmental variable and figure S4 for the contribution from precipitation and temperature to KBDI.

drought in northern and southern Australia, respectively (figure 2(b)). The maximum contribution of drought shows a similar pattern to the total FWI anomalies (cf figure 1(b)), with positive anomalies in central and southern Australia and negative anomalies in the north, suggesting its strong linkage to fire activities. On the other hand, surface wind speed exhibits a small contribution to FWI, particularly in southeast Australia (figure 2(e)). The contributions from relative humidity, although small, support the anomalous pattern of FWI across the continent (figure S3(a)).

In contrast to El Niño condition, the drought component during La Niña exhibits the smallest contribution to FWI across central and southern Australia (figure 2(f)). A closer comparison with the anomalous FWI pattern shows that the anomalous drought conditions may contribute to the positive FWI anomalies in northern Australia, whereas the relative humidity anomaly is more important in

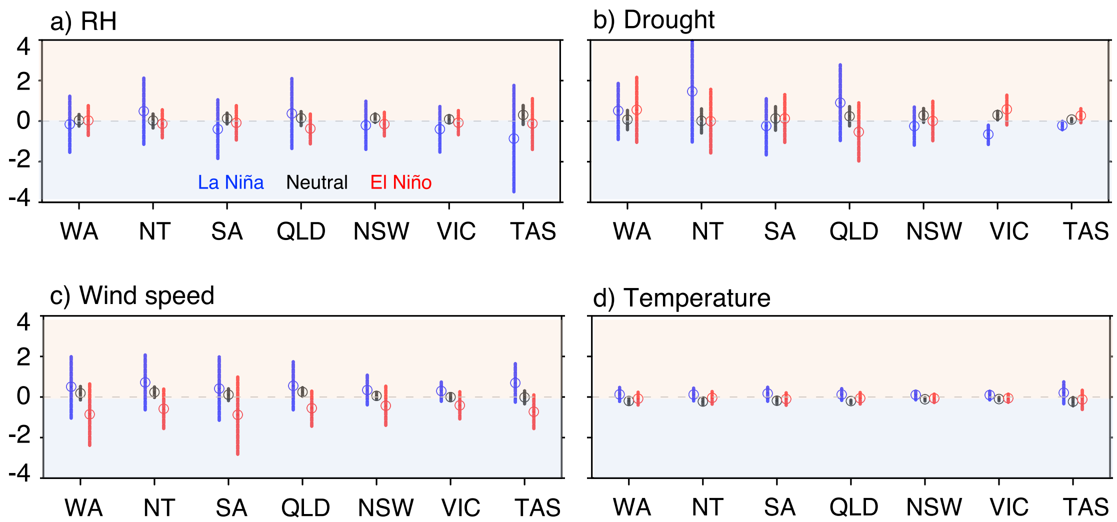

Figure 3. Changes (SSP585 minus historical simulation) of each environmental variable that enters the FWI (no unit; *y*-axis) for each state in Australia (*x*-axis; Western Australia (WA), Northern Territory (NT), Southern Australia (SA), Queensland (QLD), New South Wales (NSW), Victoria (VIC), and Tasmania (TAS)). See figure S2 for the Australian map with the administrative states' borders. (a) Relative humidity (RH), (b) Keetch Byram Drought Index (KBDI or Drought), (c) Surface wind speed, and (d) Maximum temperature. Black is neutral ENSO, while red and blue are El Niño and La Niña relative to neutral ENSO, respectively. The bars represent the standard deviation calculated across all models. Also, see figures S5–S9 for the detailed maps of these variables.

southern Australia in suppressing fires during La Niña (figure 2(c)). Compared to El Niño condition, temperature and wind speed during La Niña show a small insignificant contribution to the FWI anomaly. Further elaboration on the contribution factors to drought conditions shows that the increased drought is caused by the comparable contributions from the temperature anomalies and reduced precipitation anomalies components (figure S4).

It is worth noting that, besides the impacts of these four environmental variables entering the FWI, soil moisture may also contribute to fire conditions (O *et al* 2020). A previous study on the feedback of soil moisture on precipitation in Australia suggests that soil moisture is proportional to the time before fire ignition (Bui *et al* 2024a). In summary, we have quantified the contribution of individual environmental factors to FWI, in which temperature and drought conditions are key factors contributing to FWI anomalies.

3.3. Responses to global warming

Under the influence of global warming, the neutral ENSO condition shows a substantial increase in FWI across most regions of Australia, with an average increase of about 22.2% compared to historical simulation. This effect is particularly pronounced in the central and western regions, which currently experience the highest FWI (cf figures 1(a) and (d)). These findings, which align with previous results from the CMIP5 and weather research and forecasting (WRF) downscaling datasets (Dowdy *et al* 2019), reveal a pattern resembles to the 'rich-get-richer' pattern. Notably, the ENSO modulation, when compared to the contemporaneous neutral phase, shows a significant decrease in FWI during El Niño in most regions of Australia, especially in the central-north-eastern regions (figure 1(e)). Conversely, during La Niña, FWI is projected to increase across central and northern Australia and decrease in the south-east (figure 1(f)).

- Changes in the source of FWI

To understand the changes in the pattern of FWI anomalies, we first examine the changes in environmental factors in controlling FWI (figure 3; see also figures S5–S9). During the neutral ENSO, the increased FWI across Australia is primarily due to the increase in drought (figure 3(b)), while the influence of temperature is diminishing (figure 3(d)). The contribution from wind speed and relative humidity is projected to slightly increase in the future (figures 3(a) and (c)). This result is in agreement with previous studies showing an increase in drought under global warming (Nicholls 2004, King *et al* 2017). The result also confirms the strong relationship between wildfires and drought, as discussed above.

During El Niño, the decreased FWI anomaly across the southwestern states is likely caused by a reduction in wind speed (figure 3(c)) in compensation for the increase in drought (figure 3(b)). Figure S8 provides additional information on these changes. The contributions from other factors only show a small change. Notably, drought contribution is significantly increased in Victoria (figure 3(b)), resulting in an increase in FWI anomaly (figure 1(e)), hence implying an enhancement of wildfires over this

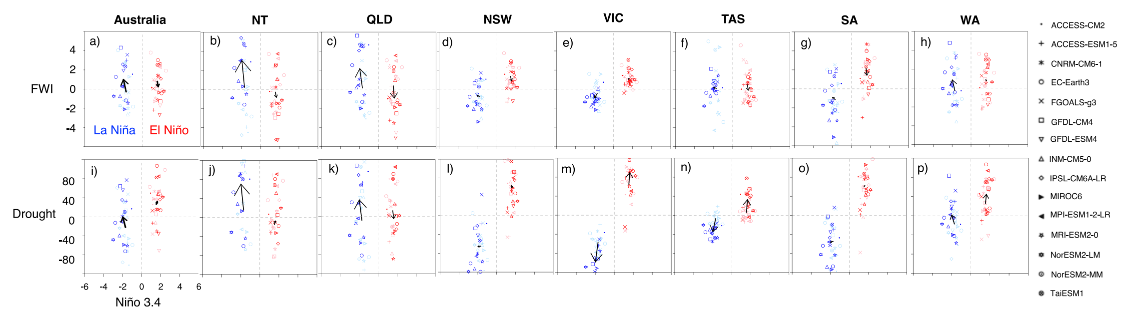

Figure 4. (a)–(h) Scatterplot of Nino 3.4 index (x-axis, units are °C) and FWI (y-axis, no unit) averaged over (a) Australia continent and (b)–(h) each state of Australia, including (b) Northern Territory (NT), (c) Queensland (QLD), (d) New South Wales (NSW), (e) Victoria (VIC), (f) Tasmania (TAS), (g) Southern Australia (SA), and (h) Western Australia (WA) from 15 models. See figure S2 for the Australian map with the administrative states' borders. The historical and SSP585 simulations are shown in dark and light colors, respectively. Reds are for El Niño, and blues are for La Niña cases. The black arrow shows the changes in multimodel mean from historical to SSP585 simulations. (i)–(p) Similar to (a)–(h) but for the Keetch Byram Drought Index (KBDI or Drought, y-axis, no unit).

region in a warmer climate. Unlike El Niño, La Niña brings about an increase in drought, wind speed, and temperature contributions across states under the influence of global warming (figure 3 and the third column in figure S8). In terms of the changes in drought conditions, the increased drought is caused by the comparable contributions from the temperature anomalies and reduced precipitation anomalies components (see figure S9). The result underlines the potential increase of FWI under global warming and suggests that the increase of drought during La Niña could lead to more wildfires over the central-northern regions of Australia in a future warmer climate, a situation that demands attention and action to mitigate the potential impact.

- Changes in ENSO teleconnections

In addition to changes in environmental factors in controlling FWI, we also examine changes in ENSO teleconnections under global warming (figure 4). The multimodel mean across Australia projects a decrease in FWI during El Niño and an increase in FWI during La Niña in a warmer climate (figure 4(a); also see figure 1), consistent with the projected changes in the drought condition (figure 4(i)). This result suggests a dampening of future ENSO teleconnections impact on FWI in Australia. However, it is important to note that the ENSO teleconnections changes over Australia currently do not show strong intermodal agreement, highlighting the complexity of ENSO impacts and the uncertainty of model physics and thermodynamics in simulating future ENSO teleconnections as discussed before (e.g. Delage and Power 2020, also see the review of Yeh *et al* 2018).

Nevertheless, several regions/states exhibit a significant signal in the emergence of model projections, such as the Northern Territory (figure 4(b)) and Queensland (figure 4(c)). This result, where models show a significant increase in FWI during La Niña and a decrease in FWI during El Niño, suggests an amplification of the ENSO teleconnection under global warming. It is worth noting that changes in ENSO teleconnections under global warming will depend on changes in the mean state and ENSO characteristics (e.g. patterns and amplitude). Given the nonlinear interaction between ENSO teleconnections and local/regional climate conditions (e.g. McGregor *et al* 2022), it is crucial that more analysis on this topic should be explored in future work.

The increase in FWI shown here is an intriguing result, and there may be a combination of both internal and external forces. For instance, the Atlantic Multidecadal Oscillation has been shown to modulate the ENSO and fire weather relationship in Australia (Liu *et al* 2023a). Additionally, future changes in both the mean state and variability would also be expected to cause wildfires to intensify and expand their region of influence in response to anthropogenic emissions. Quantifying the contributions of these forcings by employing the ensemble-wise analysis on large-ensemble climate simulations has been documented for other climate phenomena (O'Brien and Deser 2023, Deser *et al* 2024), although we leave further investigation of such contribution to the wildfires to future modelling sensitivity studies where we can alternately test the role of each forcing for mediating the wildfires response. Regardless, the increase of fire weather conditions under global warming in Australia, especially during La Niña, due to the increase of drought has profound implications for seasonal prediction over the next several decades, particularly in the central-northern regions. This underscores the critical need for future modelling sensitivity studies that will provide insights for future wildfires management and mitigation strategies.

4. Concluding remarks

While many previous studies have examined the interannual variability of wildfires in Australia, including its relationship with ENSO (e.g. Mariani *et al* 2016, Chen *et al* 2017, Abram *et al* 2021, Dong *et al* 2021, Zhao *et al* 2022), our current study goes a step further. We investigated the contribution of the individual components of the FWI (e.g. drought, wind speed, temperature, humidity) to the present and future fire weather conditions, as well as their association with ENSO phases. We found a clear contrast in the pattern of FWI between the northern and southern regions of Australia, which is associated with different ENSO phases. We also found that drought and temperature are the main factors contributing to the fire weather condition anomalies in Australia. Relative humidity and wind speed also contribute to the FWI, although their contributions are smaller than those of the other two components. These results reveal new insights into the dynamics of wildfires in Australia and help improve the parameterizations of fire in climate models.

It is important to note that the FWI results presented here, while they do shed light on the changes in fire weather conditions due to global warming, do not encompass all the factors that could influence wildfire changes. For instance, we do not anticipate the FWI here to fully explain wildfire changes such as fire count, burned area, or fire emissions. While our study does demonstrate how environmental factors impact FWI variabilities in Australia, there is still a significant gap in our understanding of how large-scale climate variability influences local-scale wildfires, especially considering that fire depends strongly on local conditions such as vegetation type. More work is needed to understand wildfires in the Australian continent and other regions.

- First, although the FWI used in the current analysis is widely used and includes several weather conditions, such as temperature, relative humidity, wind speed, and drought, we emphasize that the contribution of these components to FWI is nonlinear and might be dependent on the fire indices. Examining whether and how different FWI exhibit similar contributions is subject to further analysis.
- Second, even though there is a strong relationship between El Niño and La Niña and fire weather conditions in southeast and central Australia, ENSO only explains ~15%–30% of the year-to-year variance in FWI (Lucas 2005, Lucas *et al* 2007). ENSO activity is projected to intensify in recent decades (Grothe *et al* 2020) and in a warming climate (Power *et al* 2013, Cai *et al* 2014, 2015), how much the ENSO amplitude/pattern change will further feedback to local environmental factors and wildfires. The projected El Niño-like global warming (Bui *et al* 2019, Bui *et al* 2024b, Lopez *et al* 2022) might amplify drought in the southeastern region of Australia, which potentially favors fire activity in response to anthropogenic climate change in this region (Hennessy *et al* 2005). However, if the future climate resembles 'La Niña-like' conditions as suggested by previous studies (Kohyama *et al* 2017, Seager *et al* 2022), our result suggests a more favorable fire condition in northern Australia.
- Third, the impacts of other climate modes on wildfire are not examined in the current study. For instance, the positive phase of the Indian Ocean Dipole is known to be associated with drier and warmer climate conditions in Australia, potentially influencing fire activity (Cai *et al* 2009, Abram *et al* 2020).
- Finally, model biases, such as those in humidity (Simpson *et al* 2024) and wind speed simulation (e.g. Fasullo 2020), can significantly impact FWI calculations. Therefore, it is imperative that we need to analyze observational remote sensing fire datasets with complete spatial and temporal coverage. This will help examine the regional ocean-atmosphere-land-fire relationships and their responses to global warming.

Data availability statement

We thank the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) for providing the data, which can be downloaded at www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6. The ERA5 data were obtained from https://doi.org/10.24381/cds.adbb2d47. The GFWED data were obtained from https://data.giss.nasa.gov/impacts/gfwed/. The Global Fire Emission Database (GFED) can be downloaded at https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1293. The NCL code to calculate the fire indices is available online at https://github.com/NCAR/fire-indices.

All data that support the findings of this study are included within the article (and any supplementary files).

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