~~Limiting global warming to 1.5°C minimisesminimizes projected global increases in fire weather days, but adaptation to new fire regimes is still needed~~Future fire weather projections show the importance of ~~bothh~~ mitigation and adaptation for dynamic fire management

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Abstract

Understanding future shifts in fire weather (FW) risk across peak-season, transitional, and off-season periods is crucial for adapting fire preparation and management to climate change. Fire management planning depends not only on reducing~~how much~~ fire risk~~ is reduced~~ through climate change mitigation, but also on how residual risk evolves under different warming pathways, ~~including at~~including low levels of global warming. Additionally, while most FW~~fire weather~~ projections focus on peak-season severity and length, fire management decisions - including prevention, preparedness, and controlled burning- are made throughout the annual cycle. This creates a growing information gap between climate-driven shifts in fire risk under different mitigation scenarios and year-round fire management frameworks. To address this, we explore future climate-driven FW~~fire weather~~ projections using the McArthur Forest Fire Danger Index (FFDI) and a large perturbed-physics ensemble, enabling a systematic assessment of uncertainty and confidence in projected changes globally and across three focus regions: Australia, Brazil, and the United States of America. We evaluate future FW~~fire weather~~ across all phases of the annual cycle relative to both a historical baseline (1986–2005) and a recent reference period (2004–2023), under three Global Warming Levels (1.5 °C, 2.0 °C, and 4.0 °C) and two emissions scenarios (RCP2.6 and RCP8.5). In addition to changes in season length and peak FFDI, we quantify transitions between meteorological FW~~fire danger~~ periods and shifts in low FW~~fire weather~~ windows, linking projected climate change impacts directly to the timing and feasibility of Integrated Fire Management (IFM) activities. We project a global rise in FW at all GWLs, with the largest increases in Australia, then Brazil and the USA. At 1.5°C, the area exposed to Very High FW (FFDI ≥ 24) globally expands by 31% (25%–36%) relative to 1986 - 2005. Higher GWLs drive further increases, with more than a threefold rise in days with Very High FW from 2.0°C to 4.0°C. The transition from preparation periods to fire

season advances by 7-36 days (Australia), 12–32 days (Brazil), and 5–36 days (the United States of America) at 2.0°C. Low FW windows persist, providing crucial opportunities for out-of-season preparation, though they become narrower with warming. Our findings highlight the dual need for mitigation and adaptation~~ive~~ strategies, including accounting for changes in out-of-season fire risks. We offer an initial step toward a more dynamic form of IFM by illustrating how climate projections, impact metrics and seasonal diagnostics can be combined to inform preparedness, flexible planning, and providing a foundation for operational dynamic IFM.

~~We explore model projections of future fire weather using the McArthur Forest Fire Danger Index (FFDI) and a large, perturbed physics ensemble (PPE), to assess uncertainty in global and regional fire-weather projections for Australia, Brazil, and the USA. warmings , including. Thesealignwithin (IFM), Also,FMrely oncreating measuresUnderstanding future shifts in fire weather risk, including peak season, transitional and off-season, will be crucial for reshaping fire preparation and management in order to adapt to climate change. (FW)GWLs,) phasesThis study explores future climate-driven projections of fire weather using the McArthur Forest Fire Danger Index (FFDI) across, three Global Warming Levels (GWLs) (1.5°C, 2.0°C, 4.0°C) with two future emissions scenarios(1.5°C, 2.0°C under both RCP2.6, and RCP8.5, and 4.0°C under RCP8.5). Using a large, perturbed physics ensemble, we assess uncertainty in fire weather projections globally and for three regions: Australia, Brazil, and the USA. In Aadditionally to season length and peak FFDI, we evaluate transitions in meteorological fire danger periods and shifts in low FW-fire weather windows to inform IFMfire management throughout the annual cycle. We project a global rise in fire weatherFW days and severity at all GWLs, with the largest increases in Australia, thenfollowed by Brazil and the USA. At 1.5°C, the area exposed to Very High fire weatherFW (FFDI ≥ 24) expands by 31% (25%–36%) relative to a baseline of 1986-2005. Higher GWLs drive further increases, with more than a threefold rise in days with Very High fire weatherFW days from 2.0°C to 4.0°C, emphasising the mitigation benefits of limiting global warming to well below 2.0°C as intended by the Paris Agreement. The transitions from High to Very High FFDI, (a proxy for the start of the fire season), advances, by 9–12 days (in Australia), 16–22 days (in Brazil), and 8–24 days (in the United States of America). Despite these changes, Llow -fire weather FW windows persist, providing crucial opportunities for out-of-season preparationthey such as controlled burns. Our findings highlight the the need for mitigationboth emissions reductions and adaptive strategies, including accounting for~~

~~changes in out-of-season fire risks when employing management techniques that rely on pre-fire season preparations.IFM , ,and IFM~~

1 Introduction

Wildfires, defined as unusual or extraordinary free-burning vegetation events, can be destructive to ~~both~~ human society and ecosystems (UNEP et al., 2022) ~~(UNEP et al., 2022)~~, ~~and~~with ~~t. Their~~ impacts ~~of wildfires~~ ~~are~~ experienced over a range of timescales. The immediate consequences may include loss of life, wildlife, habitat, ~~and~~ crops and carbon, and destruction of property and infrastructure. L~~The l~~onger-term impacts can include environmental degradation~~amage~~, reduced air quality contributing to health effects, mental ill health and decreased well-being, economic damage and increased greenhouse gas emissions (Head et al., 2014; Sharples et al., 2016) ~~(Head et al., 2014; Sharples et al., 2016).~~. Fire weather (FW) extremes driving these events~~associated with these fires~~ are already becoming more frequent and intense(Dowdy, 2018; Sharples et al., 2016) ~~(Dowdy, 2018; Head et al., 2014),~~,. ~~, High fire weather seasons are lengtheninlengtheningg (Jones et al., 2022; UNEP et al., 2022), and wildfire events are increasing~~ extending ~~high risk~~high-risk fire seasons and increasing wildfire occurrence ~~(Jones et al., 2022; UNEP et al., 2022).~~, R~~with r~~ecent wildfire events demonstrate the consequences of elevated fire danger,~~s~~ providing~~ing~~ a glimpse of the devastation that a future ~~fire~~ increase could bring (Jones et al., 2024a; Kelley et al., 2025). ~~(Jones et al., 2024).~~

~~Recent extreme wildfire events provide a glimpse of the consequences of these trends.~~ The Black Summer fires of 2019/2020 in Eastern Australia, for example, were unprecedented in recorded history (Boer et al., 2020), causing~~resulting~~ at~~in the direct loss of at~~ least 34 deaths~~lives~~, the destruction of ~~almost~~ nearly 6000 buildings, hazardous air quality levels and an estimated ~~loss of up to~~ 1.5 billion wild animals killed (Jan Van Oldenborgh et al., 2021; Ward et al., 2020)~~.~~. Similarly, the western USA has also seen a series of recent extreme wildfire events (Higuera and Abatzoglou, 2021), with the ~~recent LA~~ 2025 Lons Angeles fires explicitly linked to climate change and causing severe impacts in the region (Kelley et al., 2025). ~~, while~~ Canada's 2023 fire season burned over 150,000 km^2, ~~triggering~~forcing the evacuation~~s~~ of 232,000 people and causing degraded air quality across North America (Jain et al., 2024; Jones et al., 2024a). Increased ~~burning~~wildfires have~~s~~ also been observed across parts of South America, including extreme levels of burning in the Pantanal wetlands in 2020 and 2024, and widespread fires across Amazonia during 2023/2024, driven by drier conditions, seasonal shifts, and land-use change (Ferreira Barbosa et al., 2021; Kelley et al., 2021; Silveira et al., 2020).

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~~The recent events with the highest associated cost have tended to occur in vegetated areas at the urban/wildland interface that experience drought and/or extreme heat conditions, often associated with fire risk. The Black Summer fires of 2019/2020 in Eastern Australia, for example, were unprecedented in recorded history (Boer et al., 2020),~~

~~resulting in the loss of at least 34 lives, almost 6000 buildings, hazardous air quality levels and an estimated loss of up to 1.5 billion wild animals (van Oldenborgh et al., 2020; Ward et al., 2020). This event highlights the far-reaching impacts of a wildfire season that was longer than normal, more widespread and reached into areas that do not historically burn (van Oldenborgh et al., 2020). The western USA has also seen a series of recent extreme wildfire events (Higuera and Abatzoglou, 2021), and the unprecedented fires Canada experienced in 2023 saw over 150,000 km² burned, prompting evacuations of 232,000 people and poor air quality across North America (Jain et al., 2024; Jones et al., 2024). Both events were, again, characterised by a shift in fire season alongside an increase in extreme fire behaviour. Much of the forested areas in South America have also seen increases in burning (Ferreira Barbosa et al., 2021; Kelley et al., 2021; Silveira et al., 2020), with widespread fires in northwestern South America in 2023/2024 including parts of Amazonia (Mataveli et al., 2024) largely driven by drier weather conditions and seasonality alongside changes in land use (Jones et al., 2024).~~

~~A recent assessment of fire risk due to climate change found that the frequency and severity of fire weather have increased globally, alongside with an increase in High fire weather season length (Jones et al., 2022; UNEP et al., 2022), particularly in areas where we have seen recent extreme events and seasons (Jones et al., 2024). Climate change's influence over wildfire's and fire weather is beginning to emerge from natural variability in some regions, including Amazonia and the western USA (Abatzoglou et al., 2019; Abatzoglou and Williams, 2016; Jolly et al., 2015; Kelley et al., 2019; Williams et al., 2019). Even in other regions, such as Australia, where the climate change signal is more difficult to isolate from natural variability (Udy et al., 2024), attribution studies are finding that temperature risesincreases have resulted in at least a 30% increase in severe fire weather since 1979, in severe fire weather over the region impacted by the 2019/20 fires (van Oldenborgh et al., 2020).~~

~~Looking ahead, t~~The frequency and intensity of ~~The rise in these se~~ destructive wildfires are ~~areare is~~ projected~~set~~ to continue rising. UNEP et al. (2022)~~, with UNEP et al. (2022),~~ estimate~~ing~~ an 8-14% ~~worldwide increase in extreme wildfire events in~~increase~~ worldwide~~ in extreme wildfire events in ~~over~~ the next decade~~10 years~~ and 31-57% by 2100, with regions such as s~~. S~~outheast Australia, s~~S~~outhern Amazon, and, under higher emissions scenarios, w~~W~~estern USA expected~~is are projected~~ to experience~~see~~ significantly larger~~more than average~~ increases. ~~These projections include substantial rises even with efforts to cut emissions to limit global warming to 1.5°C above pre-industrial levels, with global impacts on forest cover and carbon sequestration occurring from as early as 1.0-1.3°C (Burton et al., 2024b) - i.e., already (Betts et al., 2023). The~~While the Paris Agreement ~~under the United Nations Framework Convention on Climate Change~~ aims to limit~~keep the~~ global ~~average temperature rise~~warming to well below ~~-~~2.0°C~~, pursuing efforts to limit warming to 1.5°C above pre-industrial temperatures~~ (UNFCCC, 2015) ~~Paris Agreement of the United Nations Framework Convention on Climate Change aims to keep the global average temperature rise to well below 2.0°C, aiming for 1.5°C above pre-industrial temperatures (UNFCCC, 2015),~~ UNEP projections indicate that~~of future fire indicate~~ substantial increases in wildfires~~ events~~ are likely even under scenarios of 1.5°C~~consistent with~~ (UNEP et al., 2022)~~(UNEP, 2022)limiting warming to 1.5°C~~. Achieving~~These projections include substantial rises even with efforts to cut emissions to limit global warming to 1.5°C above pre-industrial levels, with global impacts on forest cover and carbon sequestration occurring from as early as 1.0-1.3°C (Burton et al., 2024b) - i.e., already (Betts et al., 2023). . However, despite global commitments to reduce emissions,~~

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this target~~current trends suggest that limiting warming to 1.5°C~~ will be ~~exceedingly~~highly challenging, and many regions are already experiencing ~~climate~~climate-driven~~caused~~ fire impacts at lower levels of warming, with g~~.~~ ~~G~~lobal effects~~impacts~~ on forest cover and carbon sequestration possible~~, for example, could occur from as~~ at just~~early as~~ 1.0-1.3°C of warming (Burton et al., 2024b)~~°C.~~. ~~– i.e., already (Betts et al., 2023). .~~ Exceeding 1.5°C, 2.0°C, or higher thresholds is expected to further increase extreme wildfires, emphasizing the urgent need for adaptive fire management strategies.

~~Exceeding 1.5°C, 2°C, or even higher thresholds is thereforethese thresholds is expected to bring more frequent and severe wildfire events, underscoring and we will requirethe need for adaptive strategies in wildfire management, even in the face of efforts to mitigate climate change.~~

Despite this threat, there has been little progress linking climate, ecological, and fire ~~management~~ research with fire management ~~(Hamilton et al., 2024)~~ (Hamilton et al., 2024). This lack of progress has been identified as the biggest bottleneck for developing effective and future-proof fire management plans (Jones et al., 2024a; UNEP et al., 2022). ~~(Jones et al., 2024; UNEP et al., 2022).~~

Integrated Fire Management (IFM) is widely promoted as the framework for coordinating mitigation, preparedness, response, and recovery across the full fire cycle (UNEP et al., 2022). It recognizes fires ~~adopts a holistic approach to wildfire risk, recognising fire~~ as both a natural ecological process and a societal hazard, ~~and~~ seek~~ing~~s to balance prevention, fuel management, suppression, and post-fire recovery across ecological, climatic and socio-economic contexts~~. In principle, IFM, therefore, integrates ecological, climatic, and socio-economic contexts, coordinating actions across agencies, land managers, and communities~~. In practice, many operational activities~~spects~~, such as ~~scheduling~~ fuel-reduction burns, training, and preparedness~~ activities~~, still rely on historically stable seasonal windows, though ~~. However,~~ some modern approaches increasingly ~~recognise these windows as shifting and~~ incorporate adaptive, climate-informed planning (Oliveras Menor et al., 2025)~~to account for shifting fire risks~~.

~~These seasonal windows underpin key IFM activities:~~ F~~f~~uel -reduction burn~~sing~~ are~~is~~ often conducted ~~undertaken~~ during ~~defined~~ off-season periods, while preparatory actions occur ~~are scheduled~~ ahead of peak fire weather~~FW the onset of more dangerous fire-weather~~ conditions to reduce fuel loads and mitigate later wildfire severity (Burrows and McCaw, 2013; Morgan et al., 2020; Moura da Veiga et al., 2025; da Veiga and Nikolakis, 2022)~~. Such preparedness often includes adapting controlled-burn practices to safely reduce fuel loads and mitigate wildfire severity later in the fire season~~. ~~In regions with long-established fuel-management programs, these activities are closely aligned with predictable seasonal fire-weather patterns.~~ In Australia, ~~for example,~~ controlled burns are concentrated in cooler months~~widely used to manage fuel loads, with operations typically concentrated during cooler months~~ to minimise risks to people~~human safety~~ and biodiversity, while~~. Similarly,~~ in the western United States of America (USA), prescribed burning and mechanical thinning are scheduled during low wind periods~~standard practices for reducing fuel loads~~, particularly ~~in fire-prone areas~~ near the wildland–urban interface

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(Stephens et al., 2012)~~ (WUI), and are often undertaken during periods of low wind activity to limit fire spread~~.

~~These measures are often conducted during periods of low wind activity to limit fire spread. However, an earlier onset of high-fire weather on top of a longer associated fire season may shift these safe operating control burn windows, potentially leaving areas more vulnerable to intense fires. ~~By contrast, in Brazil, controlled burning has historically been~~ played a more~~ limited, ~~ role in natural ecosystems, ~~with fire management~~ largely~~ focused on suppressing agricultural and pasture fires to prevent their spread into protected or ecologically sensitive regions such as~~ the~~ Amazonia rainforest and Pantanal wetlands.

~~Although considerable effort is directed toward preventing deforestation and illegal burning, rising temperatures and prolonged dry periods are increasing the frequency and intensity of fires in ecosystems that were previously less fire-prone [ref]. In response, integrated fire management policies in parts of the Cerrado are beginning to incorporate early dry-season fuel management and controlled burns to reduce the risk of more intense fires later in the year (Santos et al., 2021; Schmidt et al., 2018; da Veiga and Nikolakis, 2022).~~

Across these~~e contrasting~~ contexts, effective IFM~~ should adapt to the expected fire season and~~ depends on the availability and total duration of low-risk~~, off-season~~ periods for safe fuel management, training, and preparedness. An earlier onset of high ~~fire weather~~fire weather~~FW~~ and~~, combined with~~ a longer fire season, may shift or shorten these operational windows,~~ potentially~~ constraining~~ preparedness~~ activities, particularly for part-time,~~ or~~ volunteer, and community-based firefighting~~ fire~~ services,~~, as~~ common~~ly used~~ in Australia, the USA~~nited States~~ and~~ and Brazil, or for community/indigenous firefighting, as in~~ Brazil~~, that rely on predictable seasonal lulls~~. Climate-driven changes in the timing and duration of these windows is as important as the length and intensity of periods of high fire weather~~FW fire weather therefore~~ for effective IFM, ~~-~~and ~~, reshaping the windows available for both preparation and early-season management.~~

~~With this increasing emphasis on preparation for fire seasons rather than solely focusing on suppression during the season itself (UNEP et al., 2022), rrf thisis critical for~~evidence of how these windows may change is needed to prepare for potential future ~~alig~~realignment of seasonal~~ning~~ management actions.~~in duration is essential. Such information is critical for understanding how fire risk evolves across the off-season, transition season, and peak season, and for assessing the implications of these shifts for management actions that currently depend on predictable preparatory windows, or for informing the need to update more recent adaptive IFM approaches.With an increasing emphasis on preparation for fire seasons rather than solely focusing on fire suppression during the season itself (UNEP et al. 2022), Such information is essential for understanding how fire risk evolves across the off-season, transition season, and peak season, and for assessing the implications these shifts have for management actions that currently depend on predictable preparatory windows.it is particularly important to gather evidence on how fire seasons may shift or change in duration and the implications this has for fire risks during the preparatory periods, outside of the current fire season. Integrated Fire Management (IFM) provides a framework that combines mitigation, preparedness, response, and recovery in a coordinated cycle, with a strong emphasis on planning based on seasonal fire risk and local ecological and social contexts (UNEP et al., 2022). In practice, many components of~~

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~~IFM still assume relatively stable seasonal timings – for example, that preparatory actions such as fuel reduction can be carried out safely during a predictable off-season. However, climate-driven shifts in fire weather may reduce or reshape these windows, highlighting the need for climate-informed evidence on how fire danger evolves throughout the year.~~

Here, w~~We~~e present a~~ A promising~~ new way of assessing~~A crucial too to assess we present here that could inform~~ how wildfire~~the~~ management cycle~~s~~ might need to adapt under climate change~~, change is~~~~through the~~ combin~~ing~~ed ~~use of~~ future climate projections with~~and~~ year-round fire~~ -~~weather~~I to bridge this gap is the combined use of future climate projections in conjunction with fire weather~~ danger indices. ~~Several factors, including meteorological conditions, fuel availability and moisture content, topography, human land use, and landscape/fire management, all influence the level of danger and severity of fires (Yeo et al., 2015). Climate change affects both meteorological conditions and suitable climate conditions for fuel (Flannigan et al., 2016).~~ ~~“Fire weathe~~Fire weather~~Wr”~~ describes~~refers to the~~ short-term atmospheric conditions, including~~such as~~ temperature, humidity, drought and wind, that influence fire ignition and spread, and~~ which~~ are~~ themselves~~ shaped by longer-term climate conditions (Flannigan et al., 2016; UNEP et al., 2022)~~The weather and longer-term climate conditions that a fire needs to burn if ignited with available fuel are often referred to as "fire weather", with climate change affecting both current and long-term weather and fuel conditions~~, ~~(Flannigan et al., 2016).~~ Fire weather indices~~ (FWI)~~, such as the ~~McArthur Forest Fire Danger Index (~~FFDI (Noble et al., 1980)~~) (Noble et al., 1980)~~, integrate these~~ combine~~ meteorological conditions~~, including high temperature, dry air (low relative humidity), dry fuel and ground (due to lack of rain and low soil moisture), and wind,~~ to quantify~~provide~~ fire danger and capture the direct influence of climate variability and change on wildfire risk. Wildfire risk encompasses fire danger, exposure, and vulnerability, where fire danger represents the hazardous fire weather~~FW~~ conditions that enable fire ignition and spread. Here, we focus on fire danger as quantified by fire weather~~FWI~~, while using fire risk to refer to the broader impacts of wildfire on society and ecosystems

~~an index that can quantifiesy the direct meteorological impact, including from climate change, on fire weatherrisk.~~ Fire weather~~W~~ indices~~IIndices such as the FFDI~~ are particularly useful in ecosystems with abundant fuel, such as temperate and tropical forests, where meteorological conditions~~factors~~, rather than fuel availability~~,~~ drive fire occurrence and severity, especially for~~ particularly for the more~~ extreme events (Jolly et al., 2015; Kelley and Harrison, 2014)~~fires (Jolly et al., 2015; Kelley and Harrison, 2014)~~. ~~In these regions, fire indices are a useful proxy for chchanges in the number of fire weather days and season lengths, offering insights into when and where wildfires might occur when other conditions, such as fuel, are met, giving a much cleaner and more identifiable signal than other, more stochastic fire measures, such as burnedt area (Jones et al., 2022). In regions such as Southeast Australia, parts of the USA and much of Brazil, where vegetation and fuel loads are ample, fire weather~~

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~~indices are critical for predicting fire risk and are used to manage wildfire response. Conversely, in fuel-limited systems, such as arid grasslands or sparsely vegetated areas, fire weather is less dependent on weather and more on fuel accumulation, which complicates the use of FFDI in these contexts (Kelley and Harrison, 2014).~~ In regions including southeast Australia, and parts of the USA, these indices are widely used to support wildfire preparedness and response. In such contexts, fire weather~~FW~~ indices ~~FWI~~ provide a robust proxy for changes in fire season length and the frequency of dangerous conditions, offering a clearer signal than more stochastic fire metrics such as burned area (Jones et al., 2022) ~~(Jones et al., 2022)~~. ~~Their applicability is more limited in fuel-constrained systems, where fire occurrence depends more strongly on fuel accumulation than on weather alone (Kelley and Harrison, 2014). In regions such as Southeast Australia and parts of the western USA, where vegetation and fuel loads are ample, fire weather indices are critical for predicting fire risk and are used to manage wildfire response. Conversely, in fuel-limited systems, such as arid grasslands or sparsely vegetated areas, fire weatherrisk is less dependent on weather and more on fuel accumulation, which complicates the use of FFDI in these contexts (Kelley and Harrison, 2014).~~

~~While~~~~A~~Although a~~a wide~~ range of models exist to simulate physical fire behaviour, including burnt area and fire intensity (Haas et al., 2022; Hantson et al., 2016; Kelley et al., 2019), the stochastic nature of fire mean these approaches are often less suited to informing management~~-relevant questions~~ about timing, duration, and seasonal change. Such models ~~Despite rapid improvement, physically based fire models~~ continue to~~still~~ exhibit substantial ~~disagreement and~~ uncertainty (Burton et al., 2024a; Hantson et al., 2020), particularly when applied across regions and under ~~when applied to~~ future projections (Kloster and Lasslop, 2017; Li et al., 2024). By contrast, ~~fire weather indices such as the FFDI~~fire weather~~FW~~ indices provide a simple and transparent representation of the meteorological conditions that underpin fire danger, without introducing the stochasticity inherent in modelling ignition, spread,~~Is simple and~~ or~~,~~ suppression processes~~, and specific fire behaviours~~. ~~Their~~However, fire weather~~FW~~ indices ~~appl~~applicability is more limited in fuel-constrained~~icability is more limited in fuel constrained~~ systems, where fire occurrence depends more strongly on fuel accumulation than on weather alone (Kelley and Harrison, 2014) ~~(Kelley and Harrison, 2014)~~.

~~This makes them particularly well-suited to examining changes in fire season length, frequency of dangerous fire weather, and the timing of transitions between low- and high-risk periods. By extrapolating short-term climate–fire relationships, fire weather indices can therefore inform longer-term fire management strategies, including planning, structure, and preparedness, with a particular emphasis on preparedness as advocated by UNEP et al. (2022). The FFDI's ability to integrate multiple fire weather drivers and track seasonal changes in fire danger makes it a valuable tool for identifying how management-relevant operational windows — such as those used for fuel reduction, training, and preparedness — may shift under climate change.~~

The FFDI can ~~also~~ be calculated from standard ~~using components regularly output by~~ climate model outputss, and thereby can be used to assess~~enabling their application~~~~which are used to explore~~ different future emissions pathways. ~~While a single climate model provides insight into one possible future, uncertainty in how Earth's complex system will respond to increased greenhouse gas emissions makes using multiple climate models, or variations of a single model, preferable to sample a broader range of potential futures~~ Given uncertainty in the climate system response to greenhouse gas forcing, ensembles of climate projections are required to sample a

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plausible range of futures~~. This approach increases the likelihood of capturing the actual future within the modelled scenarios, reducing unexpected "surprises" (Booth et al., 2013; Boulton et al., 2017)~~ . ~~A~~ Perturbed Physics Ensemble (PPE) address this ~~samples uncertainty~~ by varying key physical parameters within a single climate ~~-~~model framework, generating a large number of internally consistent climate projections (Booth et al., 2013; Lambert et al., 2013). This approach complements multi-model ensembles such as CMIP6 by providing a much denser and ~~more~~ controlled exploration of uncertainty in~~how the climate system — and in particular~~ the climate system, particularly in temperature, humidity, wind and fuel dryness ~~— may respond to global warming~~. Because all ensemble ~~e all PPE~~ members share the same model structure ~~and land–atmosphere processes~~, differences between members can be ~~interpreted~~attributed ~~as the influence of~~primarily to physical uncertainty, making PPEs valuable for analyzing compound metrics such as the FFDI and for assessing how incremental warming alters fire weather~~FW~~ seasonality.

~~rather than structural differences between models. This coherence is particularly valuable when analysing compound metrics such as the FFDI, and when assessing how incremental warming may shift the timing and duration of fire-weather conditions relevant to Integrated Fire Management.~~

~~FFDI was developed in Australia by (Noble et al., 1980). The Australian Bureau of Meteorology uses it operationally to issue forecasts of fire weather for fire management and response (Dowdy et al., 2009; Dowdy, 2018). It is also applied in other regions like South Africa and Spain (De Groot et al., 2010; de Groot et al., 2015). Hoffmann et al. (2003) demonstrated a strong correlation between the FFDI and satellite estimates of actual fire occurrence in the Amazon. It has also been used successfully for global studies of the impact of climate variability and changes in future fire weather (Bett et al., 2020; Burton et al., 2018; Golding and Betts, 2008; Jolly et al., 2015).~~

~~Climate change's influence over wildfire's and fire weather is beginning to emerge from natural variability in some regions, including Amazonia and the western USA (Abatzoglou et al., 2019; Abatzoglou and Williams, 2016; Jolly et al., 2015; Kelley et al., 2019; Williams et al., 2019). Even in other regions, such as Australia, where the climate change signal is more difficult to isolate from natural variability (Udy et al., 2024), attribution studies are finding that temperature rises have resulted in at least a 30% increase in severe fire weather since 1979, over the region impacted by the 2019/20 fires (van Oldenborgh et al., 2020). The recent events with the highest associated cost have tended to occur in vegetated areas at the urban/wildland interface that experience drought and/or extreme heat conditions, often associated with fire risk. The Black Summer fires of 2019/2020 in Eastern Australia, for example, were unprecedented in recorded history (Boer et al., 2020), resulting in the loss of at least 34 lives, almost 6000 buildings, hazardous air quality levels and an estimated loss of up to 1.5 billion wild animals (van Oldenborgh et al., 2020; Ward et al., 2020). This event highlights the far-reaching impacts of a wildfire season that was longer than normal, more widespread and reached into areas that do not historically burn (van Oldenborgh et al., 2020). The western USA has also seen a series of recent extreme wildfire events (Higuera and Abatzoglou, 2021), and the unprecedented fires Canada experienced in 2023 saw over 150,000 km² burned, prompting evacuations of 232,000 people and poor air quality across North America (Jain et al., 2024; Jones et al., 2024). Both events were, again,~~

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~~characterised by a shift in fire season alongside an increase in extreme fire behaviour. Much of the forested areas in South America have also seen increases in burning (Ferreira Barbosa et al., 2021; Kelley et al., 2021; Silveira et al., 2020), with widespread fires in northwestern South America in 2023/2024 including parts of Amazonia (Mataveli et al., 2024) largely driven by drier weather conditions and seasonality alongside changes in land use (Jones et al., 2024).~~

~~As fire weather worsens, understanding how changes in global warming levels affect fire risk through operational indices like the FFDI can inform proactive management strategies. Unlike models targeting physical properties such as burnt area and fire intensity — which, despite rapid improvement, still face significant disagreement and uncertainty (Burton & Lampe et al. 2024a; Hantson et al., 2020; Kloster and Lasslop, 2017) — the FFDI offers a simpler way to represent crucial aspects of fire without introducing the non-linearities inherent in physical fire models. And by extrapolating short-term responses, fire indices can be used for longer-term forest management strategies, such as enhancing resilience through planning structure, resources, and preparedness, with a particular emphasis on preparedness as advocated by (UNEP et al., 2022). Preparedness sometimes includes adapting controlled burn practices, which are key in reducing fuel loads and mitigating wildfire severity later in a fire season (Burrows and McCaw, 2013; Morgan et al., 2020; da Veiga et al., 2024; da Veiga and Nikolakis, 2022). In Australia, for example, controlled burns are widely used to manage fuel loads, with operations typically concentrated during cooler months to minimize risks to human safety and biodiversity. However, an earlier onset of high-fire weather may shift these safe operating control burn windows, potentially leaving areas more vulnerable to intense fires later in the season. In the USA, particularly in the western regions, prescribed burns and mechanical thinning are standard practices for reducing fuel loads, especially in fire-prone areas near the wildland-urban interface (WUI) (Stephens et al., 2012). These measures are often conducted during periods of low wind activity to limit fire spread. Climate change, again, may complicate fuel management efforts as well as increasing risks during the peak fire seasons. In Brazil, controlled burns are less commonly employed in natural areas, with fire management primarily focusing on suppressing agricultural and pasture fires to prevent them from spreading into protected or ecologically sensitive regions, such as the Amazon rainforest or Pantanal wetlands. While there is significant attention to preventing deforestation and illegal burning in these regions, which can exacerbate fire risk, rising temperatures and prolonged dry periods are increasing the frequency and intensity of fires in these historically less fire-prone ecosystems. Integrated Fire management policies in parts of the Cerrardo, however, are starting to incorporate fuel management and control burns in early dry seasons to prevent more intense fires later in the year (Santos et al., 2021; Schmidt et al., 2018; da Veiga and Nikolakis, 2022). The FFDI's ability to integrate multiple fire weather drivers and track seasonal changes in fire rweatherisk has the potential to provide critical insights for identifying safe operational windows under climate change. This capability already makes it a valuable tool for informing region-specific fire management practices and adapting them to changing fire weather conditions under today's climate.~~

~~The FFDI can also be calculated using components regularly output by climate models which, due to the uncertainty of how the earth's complex system will respond to increased greenhouse gas emissions, are used to explore different~~

~~futures. While a single climate model provides insight into one possible future, using multiple climate models, or variations of a single model allows, for a broader exploration of potential futures. This approach increases the likelihood of capturing the actual future within the modelled scenarios, reducing unexpected "surprises" (Booth et al., 2013; Boulton et al., 2017) . A Perturbed Physics Ensemble (PPE) comprises numerous potential future outcomes based on variations of a single climate model, offering additional information compared to multi-model ensembles like the Coupled Model Intercomparison Projects (CMIP) (Booth et al., 2013; Lambert et al., 2013). Unlike CMIP, a PPE systematically samples a spectrum of possible futures, providing a way to address uncertainty. However, it is important to note that the original climate model's decisions and biases will be present in all sampled future scenarios.~~

~~Here for the first time Wwe use a Perturbed Physics Ensemble (PPE) to explore how fire weather is projected to change globally under climate warming. Our analysis focuses on regions prone to extreme wildfires: Australia, the USA, and Brazil, and globally in non-fuel-limited ecosystems. We examine changes in the frequency and duration of Very High fire weather danger, as well as shifts in the timing of transitions from pre-fire to fire season, marking the shift from preparation to more direct firefighting and potential suppression efforts. Additionally, we investigate changes in the length of the High fire weather season length as a proxy for a safe yet effective controlled burn season, which is critical for fuel management, and assess the persistence of low-fire weather periods in regions employing seasonal firefighting strategies. These low fire weatherlow-fire-weather periods represent essential windows for recovery and planning and may narrow as fire seasons extend with warming. By analyzing these dynamics across Global Warming Levels (GWLs) of 1.5°C, 2.0°C, and 4.0°C, we provide insights into how fire weather trends may challenge current management practices. This includes evaluating the mitigation potential of meeting Paris Agreement targets and identifying adaptive strategies to manage the increasing demands of a warming climate. Understanding these shifts is vital for developing proactive fire management approaches that enhance resilience, even under limited warming scenarios.~~We use a PPE to examine projected changes in fire weather globally, focusing on wildfire-prone regions including Australia, the USA, and Brazil, as well as fuel-rich ecosystems worldwide. We assess changes in the frequency, duration, and seasonal timing of Very High, ~~and~~ High and Low-moderate fire weather~~FW~~ as indicators of shifts in fire season onset, operational windows for fuel management, and periods critical for recovery and preparedness. By analyzing these changes across Global Warming Levels of 1.5°C, 2.0°C, and 4.0°C, we evaluate how climate-driven fire weather~~FW~~ shifts may challenge current management practices, the potential benefits of meeting Paris Agreement targets, and priorities for adaptive fire management under continued warming.

2 Methods

2.1 The Forest Fire Danger Index

We calculated the McArthur Forest Fire Danger Index (FFDI) using input variables from the HadCM3C PPE~~Perturbed Physics Ensemble~~. The integration of FFDI with the HadCM framework ensures consistency with

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established methodologies and benefits from extensive evaluation and a robust body of supporting literature, enhancing the reliability of our projections (Betts et al., 2015; Burton et al., 2018a, 2020; Golding and Betts, 2008) ~~(Betts et al., 2015; Burton et al., 2018, 2020; Golding and Betts, 2008)~~. The ~~McArthur Forest Fire Danger Index~~ ~~(~~FFDI~~)~~ is a widely used fire weather index that combines temperature, relative humidity, wind speed, and prior rainfall to assess the risk of fire occurrence and spread, particularly in fuel-abundant ecosystems. Originally developed for Australian forests, the FFDI is highly sensitive to temperature and relative humidity, making it well-suited for regions where climate-induced changes in these variables significantly influence fire risk (Dowdy et al., 2009). ~~(Dowdy et al., 2009).~~ The FFDI also fulfils the balance of being simple enough to understand within our modelling framework, whilst still being used operationally, especially in Australia, alongside other fire indices such as the Canadian ~~fire weather index~~ FWI (Dowdy et al., 2009) ~~(Dowdy et al., 2009)~~. T~~As a result, t~~he FFDI has also been used in global studies of fire weather under climate variability and change, often integrated with climate model output (Betts et al., 2015; Burton et al., 2018b; Clarke and Evans, 2019b; Golding and Betts, 2008; Jolly et al., 2015) ~~(Betts et al., 2015; Burton et al., 2018; Clarke and Evans, 2019; Golding and Betts, 2008; Jolly et al., 2015)~~. One of the key strengths of the FFDI in this study is its high correlation with observed fire occurrences in tropical regions (Figure 1, Figure A1), as shown in studies such as (Hoffmann et al., 2003)~~(Hoffmann et al., 2003)~~ for the Amazon, where seasonal dryness and extreme temperatures drive fire activity. The index’s sensitivity to these meteorological factors is especially valuable ~~in studies projecting future fire weather patterns, as it aligns closely~~ for studies projecting future fire weather patterns, as it closely aligns with anticipated climate-induced shifts in temperature and humidity that will affect fire risk.

~~While the FFDI was originally developed for Australian forests, its formulation is particularly well suited for studies focused on climate-driven changes in fire weather. Unlike indices that rely on ecosystem- or fuel-specific parameters, which are poorly constrained at the scale of global climate models, the FFDI is driven entirely by meteorological inputs – temperature, relative humidity, wind speed, and antecedent rainfall – that are directly simulated by GCMs. This makes it both computationally tractable across large ensembles and highly sensitive to the climate variables most likely to shift under global warming. These features align closely with the aims of this study, which seeks to assess how climate change alters the seasonal timing and intensity of fire weather rather than fuel- or management-driven fire behaviour.~~

In comparison, the Canadian FWI, more commonly used in boreal and temperate ecosystems, has a reduced sensitivity to temperature and humidity shifts (Dowdy et al., 2010) ~~(Dowdy et al., 2010)~~. This difference makes the FFDI ~~particularly~~ well-suited to regions such as Australia, the ~~United States~~USA, and Brazil, where temperature and humidity play critical roles in fire dynamics (Forkel et al., 2017; Kelley et al., 2019). ~~(Forkel et al., 2017; Kelley et al., 2019). Although no single fire weather index is universally optimal (Yeo et al., 2015), the FFDI’s responsiveness to key meteorological drivers provides essential insights into fire~~ ~~weather~~~~risk,~~

~~especially under scenarios of climate change, which is central to understanding and managing future fire danger across a range of ecosystems.~~

While FFDI does not explicitly capture regional fuel types or suppression practices, this limitation is consistent with our emphasis on the climate signal in fire danger, and the index's responsiveness to temperature and humidity provides a robust basis for evaluating future fire weather risks across our study regions.

The FFDI ~~fire weather~~ calculation is expressed as follows:

$$FFDI = 1.25 * DF \times \exp\left[\left(\frac{T - H}{30.0}\right) + 0.0234 \times V\right]$$

where DF = drought factor, T = daily maximum temperature at 1.5 m (°C), H = daily relative humidity (%), and V = daily 10 m wind speed (km/hr~~$^{-1}$~~) (Noble et al., 1980) ~~(Noble et al., 1980)~~.

The drought factor (DF) is calculated as:

$$DF = \frac{0.191 \times (SMD + 104) \times (N + 1)^{1.5}}{(3.52 \times\times (N + 1)^{1.5} + P - 1)}$$

where N = number of days since last rain, P = precipitation (mm/day) (Noble et al., 1980) ~~(Noble et al., 1980)~~ and SMD = soil moisture deficit calculated using the models soil moisture to a soil depth of 1m compared to critical volumetric soil moisture corresponding to a soil matric water potential of~~-~~ -33 kPa (Best et al., 2011; Holgate et al., 2017a)~~.~~. This provides a climate model representation of the Keetch-Byram drought index (KBDI) as in (Burton et al., 2018a)~~.~~. ~~((Burton et al., , 2018).~~. This method of calculation can result in drier soils than the KBDI calculated from observed meteorology, leading to ~~fewer days~~less time ~~in~~at lower ~~the Low-Moderate category of the resulting~~ FFDIs (Holgate et al., 2017a)~~.~~. ~~(Holgate et al., 2017)We, t~~We therefore, focus our results on patterns of changes in FFDI, or changes in time in each FFDI category (Table 1)~~y~~ as a proxy for changes in different windows of the fire season ~~as a proxy of change~~, rather than FFDI itself. The drought factor is limited to 10, as suggested by (Sirakoff, 1985) ~~(Sirakoff, 1985)~~.

~~The standard categories for the FFDI are given in Table 1. Throughout this study, we consider days above the "Very High" threshold, corresponding to days above a threshold of 24, (i.e., days above 24) as an indicator of fire season length. The use of the FFDI ≥ 24 ("Very High") threshold as an indicator of fire season length is grounded in both operational practice and prior research [ref]. In Australia, the Bureau of Meteorology and fire management agencies use FFDI thresholds to define levels of fire danger, with the "Very High" category representing conditions where fires are likely to spread rapidly and pose a substantial risk to life and property (Noble et al., 1980; Dowdy et al., 2009, 2018). Previous studies have shown that days exceeding this threshold strongly correlate with periods of high~~

~~fire activity in fuel-abundant ecosystems and thus provide a robust proxy for the effective fire season (Jolly et al., 2015; Hoffmann et al., 2003). By focusing on this threshold, we capture the meteorological window in time when fire behaviour is most extreme and when fire management resources are typically fully mobilised, making it an operationally relevant and scientifically defensible metric for assessing season length. We also consider the "High" threshold, (FFDI 12–24) to represent conditions under which fires may still be controlled and managed, but conditions are becoming increasingly conducive to fire spread and challenging for suppression [ref] and where the FFDI is greater than 12 and less than 24, as antherefore indicator of the control burn season length. (Levine et al., 2020). Operational fire management frameworks often use similar danger thresholds to determine whether prescribed or controlled burning is permitted, with higher categories (Very High and above) typically indicating conditions too risky for routine fuel management activities [ref]. In regional contexts, studies examining future fire weather have explicitly used danger-category counts to assess the length of windowed periods suitable for prescribed burning and found that increased fire danger reduces the number of days below those operational thresholds [ref]. Therefore, the number of days within the High FFDI category offers a meaningful proxy for the approximate length of the control-burn season in many management settings, representing the practical upper bound of safe and effective burning conditions.~~

~~We also assess changes in the proportion of days classed as Low–Moderate fire danger (FFDI less than 12). These categories represent conditions under which fires are typically unlikely to ignite or spread extensively and are generally controllable with routine suppression resources. In operational terms, such periods correspond to the 'off-season' or low-risk window, during which fire agencies typically do not experience sustained wildfire activity and suppression readiness requirements are lower. Therefore, changes in the frequency of Low–Moderate fire weather provide an indication of how the relative length of the fire off-season may shorten under warming.~~
~~Changes in Low – Moderate give an indication of proportional changes in the fire off-season.~~

Table 1 FFDI categories (Holgate et al., 2017a), with the part of the season we use each category as a proxy for. ~~(Chiara M. Holgate 2017)~~

Category	**FFDI range**	**~~Proxy for~~Seasonal proxy**
Low – moderate	$0 \leq \text{FFDI} < 12$	off-season
High	$12 \leq \text{FFDI} < 24$	Preparedness/fuel management window
Very High	$24 \leq \text{FFDI} < 50$	Fire season
Severe	$50 \leq \text{FFDI} < 75$	
Extreme	$75 \leq \text{FFDI} < 100$	
Catastrophic	$100 \leq \text{FFDI}$	

~~The standard FFDI danger categories used in this study are summarised in Table 1.~~ We consider days exceeding the Very High threshold (FFDI > 24) as an indicator of fire season length and to explore the future extent of fire weather

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(Cruz et al., 2015; Hadisuwito and Hassan, 2020; Holgate et al., 2017a; Khastagir et al., 2018) ~~[ref]~~. In fuel-abundant ecosystems, days above this threshold are strongly associated with periods of elevated fire activity and extreme fire behaviour, making them a robust proxy for the effective fire season.

This threshold is widely used, ~~both~~ operationally and in previous studies, to represent conditions under which fires are likely to spread rapidly and pose substantial risks to life, property, and ecosystems (Dowdy et al., 2009; Dowdy, 2018; Hoffmann et al., 2003; Jolly et al., 2015; Noble et al., 1980) -requiring active fire suppression and a continual state of suppression readiness. ~~In fuel-abundant ecosystems, days above this threshold are strongly associated with periods of elevated fire activity and extreme fire behaviour, making them a robust proxy for the effective fire season.~~

We also analyse changes in the High FFDI category (12 ≤ FFDI < 24). The High category captures conditions under which fires may ~~still~~ be actively managed, although spread potential and suppression difficulty are increasing.~~,~~ It~~and~~ therefore provides a practical upper-bound proxy for control -burn conditions (Jones, 2019). Even where it is not formally defined as an operational burning window, the duration of High fire danger provides a consistent, management-relevant proxy for the upper bound of conditions under which fuel management and controlled burning may still be feasible (Clarke and Evans, 2019b).

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Finally, we assess changes in the proportion of days classed as Low–Moderate fire weather~~danger~~ (FFDI < 12). These conditions are associated with low ignition likelihood, limited fire spread, and fires that are generally controllable with routine suppression resources. Consequently, Low–Moderate fire weather~~danger~~ days provide an indication of the relative length of the fire off-season or low -risk period, during which fire agencies typically do not experience sustained wildfire activity, and suppression readiness requirements are lower.

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2.2 Models and data

We use a ~~Perturbed Physics Ensemble~~PPE of the Met Office Hadley Centre global climate model, HadCM3C. This ensemble includes 57 plausible variants of HadCM3C to sample uncertainties in atmospheric feedbacks, the land carbon cycle, ocean physics and aerosol sulphur cycle processes as described in (Booth et al., 2013) ~~(Booth et al., 2013)~~ and used in (Taylor et al., 2013) ~~(Taylor et al., 2013)~~. This ensemble was designed to sample a large range of future global average temperatures. U~~Importantly, u~~nlike many other ~~perturbed-parameter ensembles~~PPE, the HadCM3C model includes dynamic vegetation coupled to the atmosphere model, allowing for biophysical vegetation-climate and climate-carbon cycle feedbacks~~, as well as climate-carbon cycle feedbacks~~. HadCM3C is part of a family of models based around the HadCM3 configuration (Gordon et al., 2000) ~~(Gordon et al., 2000)~~, which showed large reductions in precipitation in the Amazon region under future climate change projections associated with particular patterns of sea surface temperature (SST) change (Good et al., 2008; Harris et al., 2008)~~(Good et al., 2008; Harris et al., 2008)~~. When dynamic vegetation is included, this leads to forest die-back in the Amazon (Cox et al., 2000) ~~(Cox et al., 2000)~~, with biophysical vegetation-climate feedback playing a key role in magnifying the circulation-induced precipitation reduction (Betts et al., 2004) ~~(Betts et al., 2004)~~. The range of future global average temperature changes broadly spans the Coupled Model Intercomparison Project Phase 5 (CMIP5) projections, except at the lower end (Booth et al., 2013)~~, (Booth et al., 2013).~~

We use two future emissions scenarios related to the Representative Concentration Pathways (RCPs), a low-emissions scenario ~~RCP2.6 and a high-emissions scenario~~, RCP2.6 and a high-emissions scenario, RCP8.5, to explore a wide range of future climate outcomes. Since the HadCM3C model includes an interactive carbon cycle, the scenarios are used here as emissions scenarios ~~instead of concentration pathways, as~~ rather than concentration pathways, as is more commonly used in climate models that do not simulate the carbon cycle, such as the CMIP5 ensemble.

We look at changes in future ~~fire weather~~fire weather~~FW~~ at three GWLs, 1.5°C, 2.0°C and 4.0°C, defined relative to 1850–1900, as used in the IPCC 6th Assessment Report (Masson-Delmotte et al., 2021) ~~(Masson-Delmotte et al., 2021)~~ and (Burton et al., 2021)~~(Burton et al., 2021)~~, for both emissions scenarios and each ensemble member. We calculated the relevant GWL for each ensemble member as twenty years surrounding the year ~~that~~ in which the member first passed the GWL threshold. This means that the time periods analysed for each GWL are not the same across the ensemble, as there are~~is~~ a range of future temperatures and periods when each model variant reaches them. We compare these changes in fire weather to a baseline period of 1986 – 2005, as used in the IPCC Special Report on Global Warming of 1.5°C. We also compare breakdowns of the length of the season in each FFDI category ~~compared~~ to the recent present (2004-2023).

All analyses are performed on the fraction of burnable land, defined using the SAGE potential vegetation database (Bett et al., 2020). Non-burnable areas, including ice-covered regions and grid cells where more than 50% of the surface is classified as bare soil, are masked out, as illustrated by the grey mask in Figure 1. This burnable land mask is applied consistently across the evaluation of modelled FFDI against Copernicus FFDI, as well as for the baseline, historical, and all future GWL~~lobal Warming Level~~s (1.5°C, 2.0°C, and 4.0°C), and across all ensemble members.

2.3 Evaluation

We evaluate the simulated ~~Fire Weather Index~~~~FWI~~FFDI from the HadCM ~~perturbed physics ensemble (~~PPE~~)~~ against FFDI constructed from reanalysis meteorology ("Copernicus FFDI"; ~~(~~CMES, 2019)~~)~~. Evaluation is performed separately for the number of days in the Low–Moderate, High, Very High, and Severe-or-higher FFDI categories over the baseline period.

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Because the PPE is an untrained ensemble designed to sample a wide range of plausible climate responses, our evaluation focuses on whether the ensemble adequately represents and contains observed fire weather characteristics, rather than on exact agreement with observations at every location (Burton et al., 2025). We therefore use two complementary evaluation approaches. First, we assess the position of the Copernicus-based FFDI within the model ensemble for each FFDI category and grid cell, following the ensemble evaluation framework described in Barbosa et al. (2025). For each location, we determine the fraction of ensemble members that simulate more or fewer days in a given FFDI category than Copernicus. If approximately half of the ensemble members lie on either side of the Copernicus value, this indicates an unbiased ensemble. A systematic tendency for most ensemble members to lie above (below) the Copernicus estimate indicates a positive (negative) bias in simulated fire weather. For untrained ensembles such as the PPE, however, the primary requirement is that the observations fall within the ensemble spread (Burton et al., 2025).

Second, we quantify model performance using the Normalised Mean Error (NME) metrics following (Burton et al., 2019; Kelley et al., 2013).~~,~~ NME is well-suited to non-normally distributed data and is widely applied in global fire model ~~evaluation .~~evaluation (Burton et al., 2024a; Hantson et al., 2020; Rabin et al., 2017) . Three NME variants are calculated:

- NME$_1$ is the area-weighted mean absolute difference between simulated and observed values and measures the overall magnitude of model error.
- NME$_2$ is calculated after removing the spatial mean from ~~both~~ model and observations, assessing differences in spatial variability about the mean.
- NME$_3$ is calculated after removing ~~both~~ the mean and the absolute mean variance, isolating differences in spatial pattern alone.

For all three metrics, lower values indicate better agreement with reanalysis-based FFDI, with a value of zero representing a perfect match to observations. To aid interpretation, NME scores are compared against three null models following Burton et al. (2018a). The median null model compares observations to a spatially uniform field equal to the median observed value, representing the best possible single-value predictor. The mean null model compares observations to their spatial mean and, by construction, yields an NME score of 1. The randomly resampled null model is generated by randomly permuting the observed data and comparing it to the observations; this is repeated 1000 times, and the 5th–95th percentile range is reported to indicate expected scores under random spatial structure. Because NME is a distance-based metric, the extent to which model scores approach zero relative to these null models indicates the degree of improvement over simple or random predictors.
NME metrics are calculated separately for each ensemble member, following Kelley et al. (2019), and results are summarized using the 5th–95th percentile range across the ensemble. This approach allows us to characterize ~~both~~ typical model performance and the spread of plausible outcomes represented by the PPE.

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2.4~~3~~ Metrics calculated

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To assess projected changes in ~~fire weather~~fire weather~~FW~~ under future global warming, we calculated a series of metrics derived from our PPE ensemble simulations of FFDI, changes in ~~fire weather~~fire weather~~FW~~ intensity during the peak fire season, and shifts in the start and end of the high-risk period while accounting for ensemble uncertainty. All analyses were conducted globally and focused regionally on Australia, Brazil, and the western USA~~United States~~.

2.4.1 Increases in Very High fire weather

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For each grid cell and ensemble member, we calculated the number of days in which the ~~McArthur Forest Fire Danger Index (~~FFDI~~)~~ exceeded the Very High threshold (FFDI > 24, Table 1). The increase in extreme fire weather~~FW~~~~fire weather~~ for each grid cell was defined as the difference between the number of days above the Very High threshold at a given ~~global warming level~~GWL relative to the baseline period (1986–2005). To visualize these results, we generated consensus maps showing the spatial distribution of changes in Very High FFDI days. The method of model consensus is used as an approach to represent and maintain the full range of information available in the ~~perturbed physics ensemble~~PPE using the method of Kaye et al. (2012)~~ of Kaye et al, 2012,~~ as implemented in Taylor et al. (2013), which quantifies the level of agreement across the 57-member PPE ensemble and highlights the fraction of ensemble members showing an increase, no change, or decrease in days at Very High FFDI. This approach maintains more of the ensemble's spatial characteristics than taking the model mean.

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We then aggregated the results spatially to determine the area-weighted mean number of days burnable land experienced Very High or greater FFDI, globally and for each region. This calculation was performed for each ensemble member that reached a given ~~global warming level~~GWL. To test for significant changes at each GWL for each RCP relative to the baseline, we compared paired ensemble values for days above Very High FFDI using a one-tailed Wilcoxon signed-rank test.

Finally, we calculated the relative change in Very High or greater FFDI days versus the baseline for each grid cell and ensemble member, expressed as a percentage of burnable land experiencing an increase, and summarised across the ensemble by reporting the 10th, 50th (median), and 90th percentiles. Because both increases in the number of days and in the spatial extent contribute, doubling either the number of days above the Very High threshold or the number of grid cells with such days results in a 100% increase.

2.4.2 Mitigation potential

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To assess the potential benefits of limiting global warming, we calculated the mitigation potential in terms of reduction in days above the Very High FFDI threshold vs 4.0°C, globally~~l~~ and for ~~eaxh~~each region. We used the same calculation for the number of days at or above Very High FFDI described in section 2.4.1~~above~~. The mitigation potential was then calculated as the difference between the number of Very High FFDI days at 4.0°C under RCP8.5 and the number of days at the lower warming levels (2.0°C or 1.5°C) for the same ensemble member. This yields a distribution of reductions across the ensemble, which captures both spatial and parametric uncertainty. Significance of the differences was assessed using a one-sided, paired Wilcoxon signed-rank test, with pairing by ensemble member. This test evaluates whether the reduction in Very High fire weather days is consistently less than zero across the ensemble for 4.0°C vs the lower GWLs.

2.4.3 Meteorological drivers of FFDI

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To assess the meteorological drivers of FFDI, we used a R~~r~~andom F~~f~~orest (RF) machine learning model to quantify variable importance. ~~Random Forest (~~RF~~)~~ models (Breiman, 2001) ~~(Breiman, 2001)~~ are often used ~~for this application as they allow us~~ to systematically assess the importance of each variable for predicting the FFDI value. We took a bootstrapping approach to assess uncertainty in RF model construction~~,~~ by performing 1000 independent samples of data points without replacement (n=300) from a population containing all grid cells with FFDI > 12 and all ensemble members for a given country and warming level (Baseline or 4°C under RCP8.5). We split each sample~~, between a randomly sampled 75% training set,~~ into a randomly selected 75% training set and a 25% testing set, using an RF classifier to predict FFDI from a set of meteorological variables ~~and a 25% testing set, using an RF model classifier to predict FFDI given a set of meteorological variables as the predictors~~.

The variable importance is estimated by repeatedly removing individual predictors~~,~~ and quantifying the resulting decrease in model skill. This provides a systematic and internally consistent way to evaluate the relative role of different drivers of fire weather~~FW~~~~fire weather~~ across climates. All RF models were trained and evaluated using the same predictor set and sampling strategy to ensure comparability between the baseline and +4.0°C experiments, with the mean and standard deviation of each sample plotted for each country and warming level. Changes in variable importance are interpreted as changes in the relative and marginal contribution of individual meteorological drivers to FFDI predictability, rather than as changes in total explained variance. A reduction in importance across variables under stronger warming reflects increased co-occurrence and reduced separability of fire-conducive conditions, rather than a weakening of fire-weather controls.

~~To assess how different meteorological drivers contribute to FFDI, we used a Random Forest (RF) machine-learning model to quantify the relative importance of it's variables. Separate RF models were trained for a baseline climate and for a +4 °C global warming level under RCP8.5. RF models are well-suited to this application because they capture non-linear responses and interactions between predictors while remaining relatively robust to multicollinearity. This allows us to explore how the influence of temperature, humidity, wind speed and fuel dryness on FFDI may change under future climate conditions without assuming a fixed functional form.~~

~~The RF approach estimates variable importance by repeatedly perturbing or withholding individual predictors and measuring the resulting decrease in model skill. Variables whose removal produces a large drop in predictive~~

~~accuracy are interpreted as exerting greater influence on FFDI. Because RFs consist of many decision trees trained on bootstrapped samples, the resulting importance measures reflect an ensemble-mean response rather than the behaviour of any single tree. This provides a systematic and internally consistent way to evaluate the relative role of different drivers of fire weather across climates. All RF models were trained and evaluated using the same predictor set and sampling strategy to ensure comparability between the baseline and +4 °C experiments.~~

~~* We use a random forest Machine learning approach to assess variable importance. Random F are often for this kinda the remove the vairbale in away that alloowes us ti symtaiclly explore the influence th have over our predictor.~~

2.4.4 Change in FFDI seasonal cycle

To examine how fire weather evolves throughout the year, we analysed daily FFDI values for each PPE ensemble member. For the regions of interest (Australia, Brazil, and the USA), FFDI values were averaged spatially using area weights across the entire region for each day of the year, producing a daily seasonal cycle for 20-year periods corresponding to the baseline (1986–2005), historic (2004-2023) and each GWL of 1.5°C, 2.0°C, 4.0°C and under both emissions scenarios. Individual ensemble members were retained in the analysis to represent parametric uncertainty, and ensemble medians, interquartile ranges, and 5th–95th percentiles were calculated for visualization. Significance testing of changes relative to the baseline was performed using a one-sided, paired Wilcoxon signed-rank test, with pairing by ensemble member, for FFDI values averaged over a 7-day running window to reduce short-term variability.

In addition to analysing changes in the magnitude of fire weather, we assessed shifts in the timing of the end of the typical fire management season in each region. Baseline end-of-season dates were chosen from regional references: 31st October for Australia (Clarke et al., 2019; Clarke and Evans, 2019a), 1st September for Brazil (Moura da Veiga et al., 2025; da Veiga and Nikolakis, 2022), and 31st May for the USA (Houghton and Lewis, 1973; Knapp et al., 2009). There is much within-country variability of these timings, with exact ~~. Exact~~ FFDIs for control burns vary among and even within a region, depending on the risk to local populations, fuel loads, and need depending on the likelihood of later extreme fires (Cirulis et al., 2020; Gill et al., 1987; Howard et al., 2020; da Veiga and Nikolakis, 2022) ~~(Cirulis et al., 2020; Gill et al., 1987; Howard et al., 2020; da Veiga and Nikolakis, 2022)~~. We use these more as an indicative proxy rather than a firm projection.~~So 'High' serves as a proxy and indication of weather-related changes only.~~

For each ensemble member, we used the –7-day running mean of the daily seasonal cycle FFDI on these end-of-season dates as our baseline-. We then identified the date in the future GWL projections (under RCP2.6 and RCP8.5) when this same FFDI value occurred. The difference in days between the baseline end-of-season date and the projected date provided the directional shift for each ensemble member. To summarise ensemble agreement, we calculated the percentage of ensemble members projecting an earlier or later transition relative to the baseline.

2.2.5 Change in Low-moderate to High FFDI

To characterise changes in the distribution of fire weather intensity throughout the year, we calculated the annual time spent in each FFDI category (Low–Moderate, High, Very High, Severe+) for each ensemble member. For each grid cell, the number of days falling into each category was summed over the course of a representative year (baseline: 1986–2005; historical: 2004–2023; future: at each Global Warming Level, GWL). This produces a per-ensemble-member, per-grid-cell annual allocation of days to each FFDI category.

We then aggregated these values spatially over each region of interest (Australia, Brazil, and the USA), weighting each grid cell by its fractional burnable land coverage to account for varying cell area. For each region and scenario, the ensemble spread was summarised by reporting the 10th, 50th (median), and 90th percentiles of annual time in each category across ensemble members.

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~~We calculate five metrics;~~

1. ~~The daily 90th percentile of the FFDI~~
2. ~~The number of days in and aboveover the Very High FFDI threshold~~
3. ~~The percent of the burnable land surface with an increase in fire weather (the land surface considered burnable after excluding non-burnable land as detailed below, rather than burned area).~~
4. ~~The shift in the date that experiences the same FFDI matching the end of the typical “fire management” season for each region: 31st Oct for Australia (Clarke et al., 2019); 1st September for Brazil (da Veiga et al., 2024; da Veiga and Nikolakis, 2022), 31st of May for USA (Houghton and Lewis, 1973; Knapp et al., 2009).~~
5. ~~The number of days in the High FFDI category (greater than 12, less than 24) as a proxy for potential control burn times – when conditions aren’t so wet as to be ineffective but preceding fire season when efforts are often diverted to more active firefighting (Prescribed burning frequently asked questions, 2024; Levine et al., 2020).~~

~~metricssWe calculated the first metric, the daily 90th percentile of the FFDI, globally and for each country of interest (Australia, Brazil and the USA) to explore the future response of the higher end of the FFDI to a warming world. This metric also allows us to explore the response of the seasonal cycle of the higher end of the FFDI. We then calculated the second metric, the number of days in the Low-Medium, High and above the Very High FFDI and above thresholds.~~

~~We calculate each metric across the globe, focusing on Brazil, Australia and the USA. These regions were chosen because of recent significant and multiple fire seasons in all three with considerable impacts, the emerging signal of climate change in these regions, and the exploration of a range of regions across the world. Each metric was calculated for the 2 emissions scenarios (RCP2.6 and RCP8.5), and the three global warming levels – baseline, 1.5°C, 2.0°C, and 4.0°C. For the mitigation scenario, RCP2.6, all 57 members of the ensemble reach 1.5°C, 50~~

~~members reach 2.0°C, and no ensemble members exceed 4.0°C. Whereas the high-end scenario, RCP8.5, shows all ensemble members reaching 4.0°C.~~

~~We identified non-burnable land by applying the SAGE potential vegetation database to the baseline period (1985–2005) for areas with either ice or where greater than 50% of the model grid square was bare soil as used in Bett et al. (2020). This non-burnable land was masked out in the calculation of these metrics.~~

~~Visualising the ensemble data~~

~~The method of model consensus is used as an approach to represent and maintain the full range of information available in the perturbed physics ensemble using the method of Kaye et al, 2012. This method calculates the level of model agreement for each grid square and thus highlights areas with higher or lower agreement which can be interpreted as higher or lower confidence in the strength of the projected change. This approach maintains more of the ensemble's spatial characteristics than taking the model mean~~

3 Results

3.1 Evaluation of the modelled FFDI vs reanalysis

We begin by evaluating fire weather derived from the PPE model simulations against FFDI constructed from reanalysis. Figure 1 compares the time spent in Low–Moderate, High, Very High, and Severe+ FFDI categories during the baseline period (1986–2005) from the PPE ensemble with FFDI calculated from Copernicus reanalysis data. Overall, the model reproduces the large-scale spatial patterns of fire weather across FFDI categories well. Both the Copernicus reanalysis and the PPE ensemble show High and Very High FFDI emerging in known fire-prone regions, including the western USA~~United States~~, the Cerrado and central Argentina, the interior of Australia, the Mediterranean Basin, western India, the Eurasian Steppe, and southern African grasslands. In these regions, the ensemble spread is generally small, indicating strong agreement across ensemble members.

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At high northern latitudes, both the Copernicus reanalysis and the HadCM3C~~model~~ ensemble indicate that fire weather remains predominantly within the Low–Moderate FFDI category throughout the year. A similar dominance of Low–Moderate FFDI is found in densely forested tropical regions, including much of the Amazon Basin, the Congo Basin, and the Maritime Southeast Asian region (including the Indonesian archipelago), reflecting persistently humid conditions. Northern boreal regions of North America show limited representation of High or Very High FFDI in both observations and model output, consistent with the FFDI's design for warmer, fuel-abundant environments.

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In arid and semi-arid regions, including the Sahara and Sahel, both Copernicus and the PPE ~~ensemble~~ show extended periods of elevated fire weather, with approximately 2–4 months in the High FFDI category, 6–8 months in Very High FFDI, and in some areas 1–2 months reaching Severe+ FFDI. Similar seasonal lengths are evident in northern India and central Australia, although there is no strong signal of Severe+ conditions in these locations.

Across most regions, the Copernicus-derived FFDI falls within the spread of the PPE ensemble. Where systematic biases appear, these are typically modest and regionally specific. In parts of the Sahel, the ensemble tends to overestimate time spent in the Low–Moderate category, with around 95 % of ensemble members exceeding the Copernicus estimate, and correspondingly underestimate time spent at High and above FFDI. A similar bias is evident in central Australia. In the Cerredo region of Brazil, this bias is present but weaker, with approximately 90 % of ensemble members indicating slightly longer Low–Moderate periods than observed.

The model also captures the presence of the Eurasian Steppe fire region, although its spatial extent appears slightly displaced northward. In the southern part of this region, the ensemble tends to overestimate Low–Moderate FFDI and underestimate High or greater FFDI. In contrast, the opposite bias is apparent toward the northern margins. Across India, the ensemble tends to underestimate time spent in the Low–Moderate category (with more than 95% of ensemble members below the Copernicus estimate) and overestimate time spent in Very High FFDI. Parts of the western ~~United States~~USA, show a tendency toward longer Low–Moderate periods (80–95 % of ensemble members above Copernicus) and correspondingly less time in the High category.

Despite these regional biases, the PPE ensemble consistently reproduces the observed spatial patterns of fire weather categories. Importantly, even in regions where the ensemble mean shows a bias, the ensemble distribution still encompasses the observational Copernicus-derived FFDI. This supports the use of PPE to assess changes in fire-weather characteristics, including the timing and duration of Low, transitional, and peak fire-weather periods, in the regions examined in this study—Australia, the USA, and Brazil.~~We beginstart bywith evaluating FFDI from model simulations against FFDI constructed from observations. Figure 1 shows the number of days above the Very High FFDI threshold ("fire weather days") for the PPE model baseline period, 1986–2005 (1a), compared to the same FFDI metric and time period calculated from Copernicus reanalysis data. The modelled fire weather broadly matches that from the reanalysis. Modelled FFDI in Figure 1 is presented as consensus plots of the 57-member ensemble and is being compared to one realisation of the reanalysis results from Copernicus, so we would not expect them to align directly because the PPE was designed to sample a wide range of climate variability. However, simulated fire weather does occur in regions of observed FFDI except over northern American boreal regions (Figure 1). These boreal regions are not typically represented as having High fire risk due to their low average temperature, especially in fire indices designed for sub-tropic regions such as the FFDI. There is also a high occurrence of peat fires in this area which are difficult to represent in both fire indices and fire-land surface models, as these long-lasting smoldering fires behave very differently from forest and grass fires (Blackford et al., 2024). We, therefore, do not include a high-latitude region in our regional analysis.~~

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Table 2: Normalized Mean Error (NME) scores for the PPE ensemble compared to Copernicus-derived FFDI for the baseline period (1986–2005). Scores are shown for each FFDI category (Low–Moderate, High, Very High, Severe+), with NME_1 representing absolute differences, NME_2 differences after mean removal, and NME_3 differences after removal of both mean and variance to assess spatial patterns. Lower NME scores indicate better model performance. For comparison, three null models are included: the median and mean null models, which represent the best single-value predictions across the domain, and a randomly resampled null model (1000 iterations, 5–95th percentile range), which provides an expected range for a model with no skill.

	Metric	**Low-Moderate**		**High**		**Very High**		**Severe+**	
Null Model	**Median**	0.69		0.70		0.60		0.52	
	Mean	1.00		1.00		1.00		1.00	
		5%	95%	5%	95%	5%	95%	5%	95%
	Randomly resampled	1.08	1.16	1.1	1.14	1.05	1.11	1.00	1.04
Simulated	**NME_1**	***0.26***	***0.33***	***0.4***	***0.52***	***0.30***	***0.40***	*0.64*	1.52
	NME_2	***0.27***	***0.37***	***0.42***	***0.53***	***0.31***	***0.46***	*0.79*	2.67
	NME_3	***0.29***	***0.38***	***0.42***	***0.59***	***0.32***	***0.44***	*0.62*	*0.83*

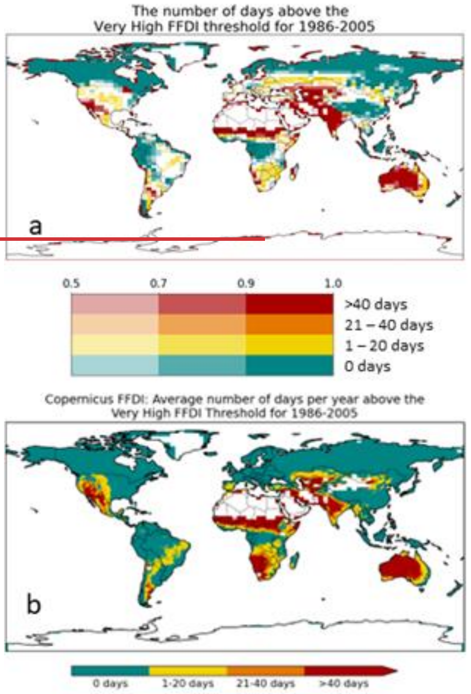
The spatial performance of the PPE in different FFDI categories compared to reanalysis FFDI is reflected in the Normalized Mean Error (NME) scores (Table 2). For annual average time in the Low–Moderate category, NME_1 scores across the ensemble range from 0.26–0.33, indicating that the model ensemble is on average 52–62% closer to the Copernicus FFDI than the median null model score of 0.69. When focusing on spatial patterns using NME_3, Low–Moderate scores are 0.29–0.38, indicating that the model reliably reproduces the distribution of low fire-weather days across regions. Performance is slightly lower for higher FFDI categories, reflecting the increased stochasticity of extreme fire weather. For High fire weather days, NME_1 ranges from 0.40–0.52, while NME_3 ranges from 0.42–0.59, indicating reasonable skill in both magnitude and spatial distribution. At Very High FFDI, the ensemble still performs well, with NME_1 of 0.30–0.40 versus a median null of 0.60, and NME_3 of 0.32–0.44. Model skill declines for the Severe+ category, with NME_1 ranging 0.64–1.52, exceeding the median null model (0.52) in most ensemble members. Randomly resampled null models give a 5–95th percentile range of 1.00–1.04, illustrating that some ensemble members perform worse than a random expectation due to the very limited occurrence of extreme FFDI days in both the simulation and observations. Nonetheless, NME_3 scores of 0.62–0.83 show that the ensemble still captures broad spatial patterns of more extreme FFDIs, albeit with increased uncertainty.

Overall, these results indicate that the PPE ensemble provides a robust representation of fire weather across Low–Moderate, High, and Very High categories, capturing both spatial and temporal patterns observed in reanalysis data.

Severe+ fire weather is less well represented due to its rarity, and therefore the rest of our global and country-level analyses focus primarily on the Low–Moderate to Very High range.

We also illustrate in Figure A1 that the time spent in Low–Moderate, High, and Very High FFDI categories throughout the year serves as an indicator of likely annual burned area. For example, regions that remain in the Low–Moderate category for almost the entire year show negligible burned area. Intermediate burned area (around 1%) is associated with a reduction in Low–Moderate FFDI to approximately 335 days and an increase in High FFDI to roughly one month. The most extreme burned areas occur where Low–Moderate FFDI drops to around 250 days, accompanied by increases in both High and, importantly, Very High FFDI. This demonstrates that the FFDI categories provide a physically meaningful proxy for fire activity over the course of a year.

~~We use the approach from Taylor et al, 2013, based on Kaye et al, 2012 to summarise the information over the whole ensemble using a consensus mapping method. We calculated and visualised the number of days per year above the Very High FFDI threshold for each ensemble member and each grid cell. We then created 4 categories (or bins) of this number of days to classify each model response in to: 0 days, 1-20 days, 21-40 days, and >40 days. For each grid cell we count how many ensemble members have a value in each category to give the model consensus. The higher the consensus (or model agreement) the darker the colour. For figure 1 there is a high level of model consensus for the majority of grid cells, so the full range of colours are not visible on the plot.~~


The number of days above the
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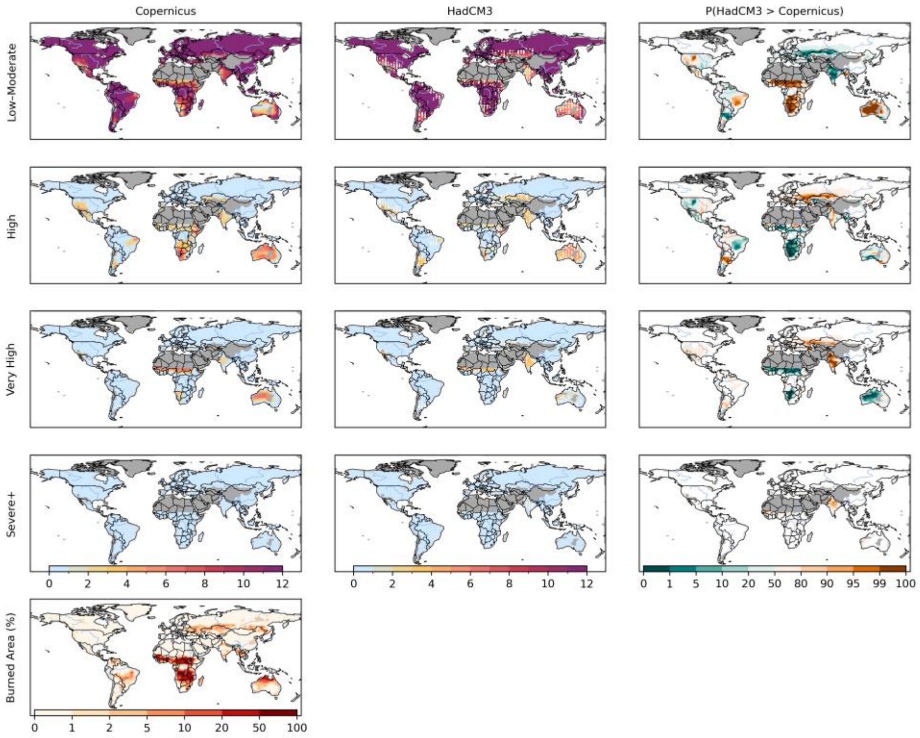
Copernicus FFDI: Average number of days per year above the
Very High FFDI Threshold for 1986-2005
b
0 days
1-20 days
21-40 days
>40 days



~~Figure 1 Comparison of the average number of days per year above the Very High FFDI threshold in 1986-2005 for (a) HadCM3C PPE historical and (b) with the Copernicus FFDI for the same metric and time period (CMES, 2019). The model ensemble data shows the model agreement (consensus) across the PPE shown by the colour bar in the lower left corner (for panel a but not panel b)~~Figure 1. Comparison of the average number of days per year within the (top to bottom) Low-moderate, High, Very High, and Severe or greater FFDI categories for 1986 - 2005, defined in Table 1. The first column shows data from Copernicus FFDI (CMES, 2019)~~.~~, while the second column displays HadCM3C PPE historical data (1986 - 2005). The model ensemble data indicate the model agreement (consensus) across the PPE, with large white dots highlighting where more than 10% of ensemble members exhibit over one month's variation in time within that category. The third column presents the percentage of members with more time in each category compared to Copernicus, following the ensemble-based evaluation described in Barbosa et al. (2025). A value of 50% indicates that Copernicus falls in the middle of the ensemble, suggesting an unbiased estimate, 0 or 100 indicates a biased ensemble that over- or underestimates the amount of time, respectively.~~.~~ We show mean annual burned area from ESA Fire CCI version 5.1 (Chuvieco et al., 2019) in the lowest panel for qualitative comparison with global patterns of fire weather derived from FFDI. Burned area is included as an observable indicator of fire activity rather than a direct measure of fire danger, and should therefore be interpreted only as contextual information rather than a target or metric of FFDI effectiveness. ~~The numbers on the colour bar refer to the percent of models that agree with the band of number of days. White regions indicate low model agreement and the non-burnable land surface~~

~~We also illustrate in Figure A1 that the time spent in Low–Moderate, High, and Very High FFDI categories throughout the year serves as an indicator of likely annual burned area. For example, regions that remain in the Low–Moderate category for almost the entire year show negligible burned area. Intermediate burned area (around 1%) is associated with a reduction in Low–Moderate FFDI to approximately 335 days and an increase in High FFDI to roughly one month. The most extreme burned areas occur where Low–Moderate FFDI drops to around 250 days, accompanied by increases in both High and, importantly, Very High FFDI. This demonstrates that the FFDI categories provide a physically meaningful proxy for fire activity over the course of a year.~~

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3.2 FFDI fire season changes

3.2.1 Increases in Very High fire weather.

We use Very High fire weather (>24, Table 1) to determine changes in the fire season length. Table ~~2~~3 gives the percent of the burnable land with an increase in the number of days above the Very High FFDI threshold globally, as well as for Australia, Brazil, and the USA, for the three GWLs and both emissions scenarios. Globally, we project between 30% (central estimate, 25-37~~34~~% across the ensemble) at 1.5°C to 50% (41-58%) at 4.0°C of burnable land with increased fire weather days under higher emissions (RCP8.5). Limiting warming to 2.0°C with the mitigation scenario (RCP2.6) ~~gives 35~~gives 35% (31-42%) and 31% (25-36%) if we limit to 1.5°C~~-~~.

Table 3~~2~~ The percent of the burnable land with an increase in the number of days above the Very High FFDI threshold (compared to 1986 – 2005) showing the 50th percentile (central estimate) of the PPE ensemble and the 10th and 90th percentiles in brackets below, for the three GWLs (1.5°C, 2.0°C and 4.0°C).

Region	**Scenario**	**Global Warming Level**		
		1.5°C	**2.0°C**	**4.0°C**
Global	**RCP2.6**	31% (25 – 36)	35% (31 – 42)	-
	RCP8.5	30% (25 – 37)	36% (31 – 44)	50% (41 – 58)
Australia	**RCP2.6**	82% (46 – 94)	87% (46 – 97)	-
	RCP8.5	73% (37 – 95)	87% (55 – 97)	95% (88 – 100)
Brazil	**RCP2.6**	30%	45%	-

		(12 – 48)	(26 – 57)	
	RCP8.5	30% (17 – 48)	41% (24 – 58)	70% (52 – 83)
USA.	**RCP2.6**	33% (14 – 51)	42% (20 – 60)	-
	RCP8.5	34% (17 – 57)	44% (18 – 65)	65% (40 – 79)

Australia has the largest amount of its burnable land surface ~~with an~~ increase in Very High fire weather at all future GWLs, ranging from 73% (37-95%) at 1.5°C to 95~~6~~% (88-100%) at 4.0°C under higher emissions. For the mitigation scenario, 87% (46-97%) at 2.0°C and 82% (46-94%) at 1.5°C of the land show an increase in fire weather days. Most of Australia is fuel-limited (Kelley et al., 2019)~~(Kelley et al., 2019)~~ and vegetation productivity changes will likely have a strong influence on the resultant burnt area and fire intensity in the future (Haas et al., 2024) ~~(Haas et al., 2024)~~. However, we show the same pattern in the more populated and moisture-limited southern Eastern Australia (Figure 2), though with slightly less agreement in ~~this~~ these fuel-abundant regions ~~region~~ at 1.5°C. Across Brazil, 30% (17-48% at 1.5°C) to 70% (52-83~~2~~% at 4.0°C) of the burnable land has an increase in Very High fire weather days. There is a considerable increase between 1.5°C and 2.0° for both emissions scenarios, with 45% (26% ~~to~~ - 57%) of the burnable land experiencing an increase in fire weather days at 2.0°C for RCP2.6. For the USA, our simulations indicate between 34% (17-57% at 1.5°C) and 65% (40-79% at 4.0°C) of the burnable land experiencing an increase in fire weather days in RCP8.5 with the mitigation scenario limiting it to 44% (18-65%) at 2.0°C for RCP2.6.

There is strong consensus for increases in Very High fire weather days across the eastern USA, Brazil, southern South America, southern Africa, northern Africa, southern Europe, central Asia and Australia (Figure 2). Both 1.5°C and 2.0°C look broadly similar for both emissions scenarios; however, there are spatial differences in the extent of increases and the amount of consensus. The number of ~~fire weather days and the level of consensus increases with warming levels across all regions wherever there is a rise in fire weather~~fire -weather days and the level of consensus increase with warming across all regions, wherever fire -weather conditions rise. There are also consistent areas showing decreases across the tropics in India and Africa, which continue to 4.0°C, though over a reduced spatial area. Western USA and Eastern Amazon show a reasonable consensus (normally > 70%) for an increase in Very High FFDI at 1.5°C. However, areas affected by the Black Summer fires along Southeast Australia show less consensus, often < 50%, at 1.5°C. Consensus increases in all these regions at 2.0°C and approaches 100% by 4.0°C.

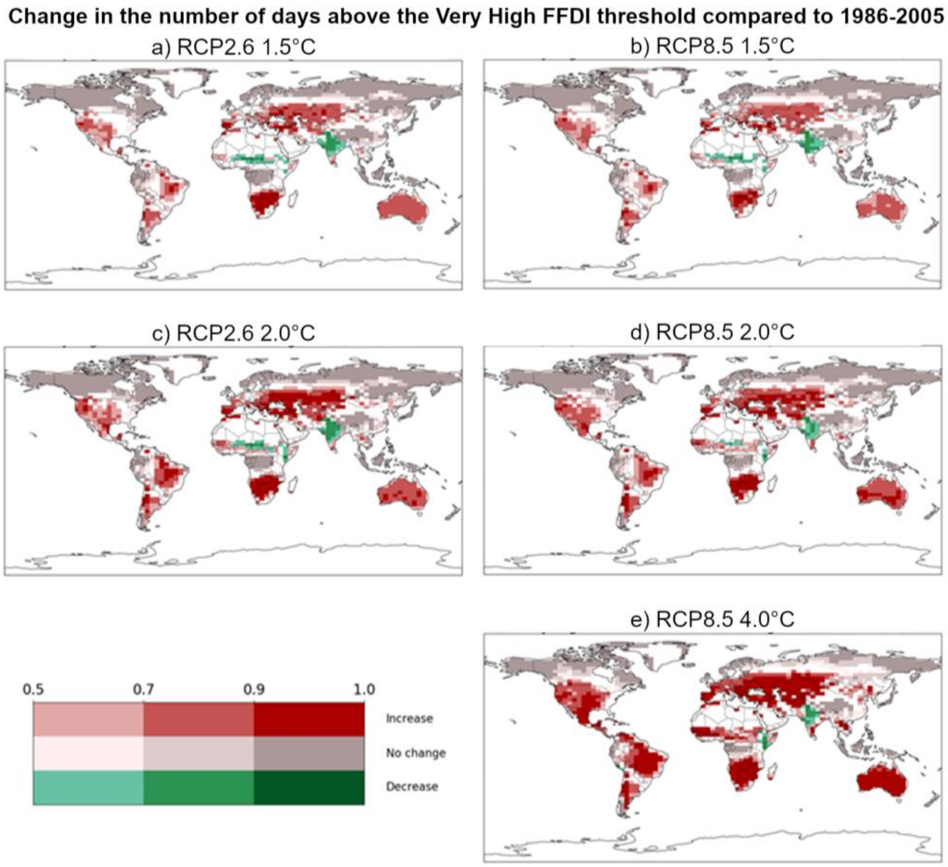

Figure 2 ~~The change in the number of days above~~Agreement in the change of number of days at or above the Very High FFDI threshold presented as consensus plots showing model agreement across the 57-member PPE using the method of Kaye et al. (2012) as implemented in Taylor et al. (2013)~~Taylor et al. (2013)~~ to show areas of ensemble member agreement, or "consensus". Red indicates areas with an increase in the number of days, compared to the baseline period (1986 – 2005). Grey is no change and green indicates a decrease. The darker the colour, the more models agree with that change. White areas indicate no clear consensus. Non-burnable land has been excluded and appears white. For RCP2.6 (panels a and c) and RCP8.5 (panels b, d, f) and three GWLs, 1.5°C (panels a and b), 2.0°C (c,d) and 4.0°C (panel e)

Figure 3 shows the distribution of the annual number of days at or above the Very High FFDI threshold across the ensemble, while Table 4 summarises the corresponding mean change relative to the baseline period for each Global Warming Level (GWL). Globally, there is a clear shift towards longer fire seasons as warming increases (Figure 3). Even at 1.5°C, the distribution moves towards higher values, with an increase of around one additional Very High

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fire weather day per year on average (Table 4, 0.95 days, 10–90th percentile range 0.59–1.26 under RCP2.6; 0.88, 0.56–1.40 under RCP8.5). While these global mean changes are modest, they reflect consistent shifts across regions and mask much larger regional responses.

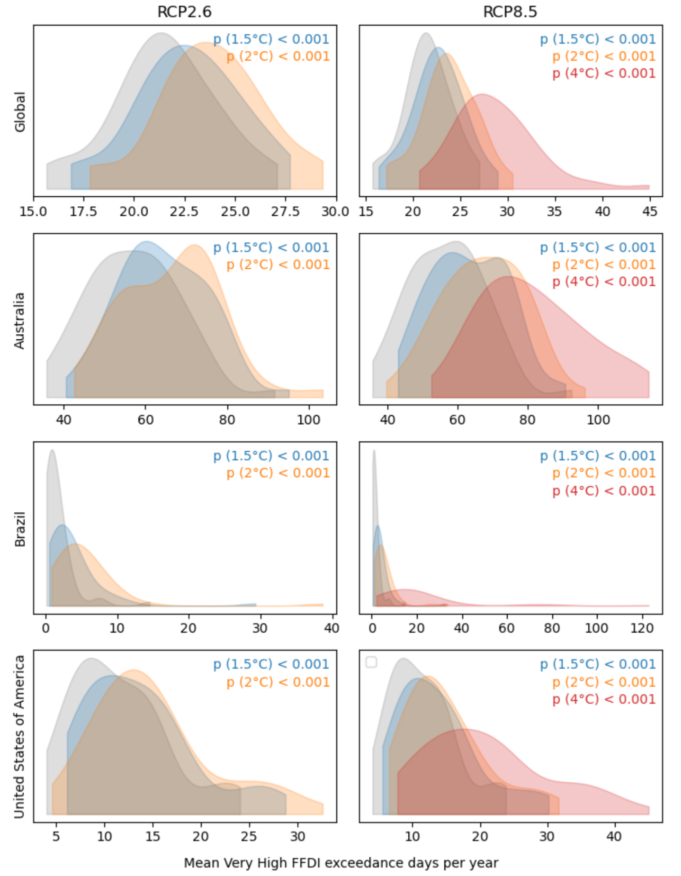

Figure 3 The annual average number of days above the Very High FFDI threshold for 3 future Global Warming Levels, 1.5°C, 2.0°C and 4.0°C and the baseline of 1986 – 2005, for 2 emissions scenarios, RCP 2.6 (a mitigation scenario, left column) and RCP 8.5 (a high-end scenario, right column), and for (top to bottom) globally , and for Australia, Brazil and the USA. P-values indicate the significance of differences between future GWLs and the baseline, assessed using a one-sided paired Wilcoxon signed-rank test, with pairing by ensemble member.

Australia, for example, exhibits the strongest and most robust signal out of our three countries analysed. In absolute terms, the minimum number of Very High FFDI days across the ensemble increases from 36 days per year in the baseline period (1986–2005) to 40–43 days at 1.5°C and 2.0°C, reaching 53 days at 4.0°C under RCP8.5 (Figure 3). These shifts correspond to large increases relative to baseline (Table 4), particularly at higher warming levels: +9.82 days (1.08–17.08) at 2.0°C under RCP2.6, +10.64 days (3.14–18.45) at 2.0°C under RCP8.5, and +21.07 days (13.19–34.89) at 4.0°C. All ensemble percentiles show positive changes, indicating a substantial and unavoidable lengthening of the core fire season with warming.

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Brazil shows greater variability but increasingly pronounced changes at higher warming levels. In absolute terms, some ensemble members retain fewer than one Very High FFDI day per year even at 4.0°C, reflecting continued interannual variability (Figure 3). However, the upper tail of the distribution expands dramatically, with peak years increasing from a baseline maximum of around 15 days to 33 days at 1.5°C, 34 days at 2.0°C, and as many as 123 days at 4.0°C. These distributional shifts are reflected in the mean changes (Table 4), which remain small under strong mitigation (+0.98 days, 0.27–3.05 at 1.5°C under RCP2.6) but increase sharply at higher warming levels (+10.83 days, 4.59–19.71 at 4.0°C under RCP8.5). This indicates a growing risk of exceptionally long fire seasons emerging from the upper tail of the climate distribution.

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The USA shows smaller mean changes and greater uncertainty across the PPE. Absolute distributions indicate that some ensemble members still produce fewer than five Very High FFDI days per year even at 4.0°C (Figure 3), highlighting persistent variability. Correspondingly, mean changes at 1.5°C remain uncertain, with ranges spanning zero (+2.19 days, −0.03–4.91 under RCP2.6; +2.07 days, −0.23–4.83 under RCP8.5; Table 4). However, by 4.0°C, all ensemble members indicate an increase (+9.26 days, 3.97–15.40 under RCP8.5), and the upper tail of the distribution shifts from around 24 days in the baseline to up to 45 days per year, signalling a heightened likelihood of unusually long and severe fire seasons.

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Across all regions, these results demonstrate that warming drives both systematic increases in the average length of the Very High fire weather season and disproportionate changes in the extreme tails of the distribution, particularly under higher warming levels. While mitigation limits the magnitude of change, even 1.5°C warming is associated with meaningful lengthening of the fire season in some regions, underscoring the need for adaptation alongside mitigation.

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~~We also calculate the number of days above the Very High FFDI threshold, averaged across the twenty-year GWL period, to give an annual average of threshold exceedance for each GWL (Figure 2, Table 3). Globally, the average number of days exceeding the Very High FFDI threshold increases even at 1.5°C of warming (0.95 central estimates, or 0.59-1.26 for 10-90th percentile for RCP2.6, and 0.88, 0.56-1.4 for RCP8.5), with more substantial increases at higher GWLs (Table 3). While the changes are small in terms of global averages, the patterns are consistent across regions, with only slight differences between RCP2.6 and RCP8.5 at 1.5°C and 2.0°C.~~

~~However, RCP2.6 does avoid the substantial regional increase in Very High fire weather days, which are projected at 4.0°C in RCP8.5. Regionally, Australia experiences the largest and most consistent increases in fire weather days, with all percentiles and emissions scenarios indicating positive changes, particularly at 2.0°C (9.82, 1.08-17.08 for RCP2.6 and 10.64, 3.14-18.45 for RCP8.5) and 4.0°C (21.07, 13.19-34.89 for RCP8.5). Brazil also shows notable though less pronounced increases by 4.0°C (10.83, 4.59-19.71, RCP8.5) and with much smaller increases under mitigation (i.e. 0.98, 0.27-3.05 at 1.5°C in RCP2.6). The USA increases shows more uncertainty across the perturbed physics ensemble (PPE). By 4.0°C (9.26, 3.97-15.40 for RCP8.5), though much less of an increase, with even uncertainty that there will be increase, at lower warming levels (2.19, -0.03-4.91 for RCP2.6 and 2.07, -0.23-4.83 for RCP8.5 at 1.5°C). By 4.0°C, all regions exhibit clear and considerable increases in fire weather days, emphasizing the growing fire weatherrisk with warming.~~

Table 4. ~~3~~The average (over land and excluding non-burnable land) change in the number of days above the Very High FFDI threshold (compared to 1986 – 2005) for the two scenarios, RCP2.6 and RCP8.5, the three Global Warming Levels, 1.5°C, 2.0°C and 4.0°C, showing the 50th percentile (central estimate) of the PPE ensemble and the 10th and 90th percentiles in brackets below.

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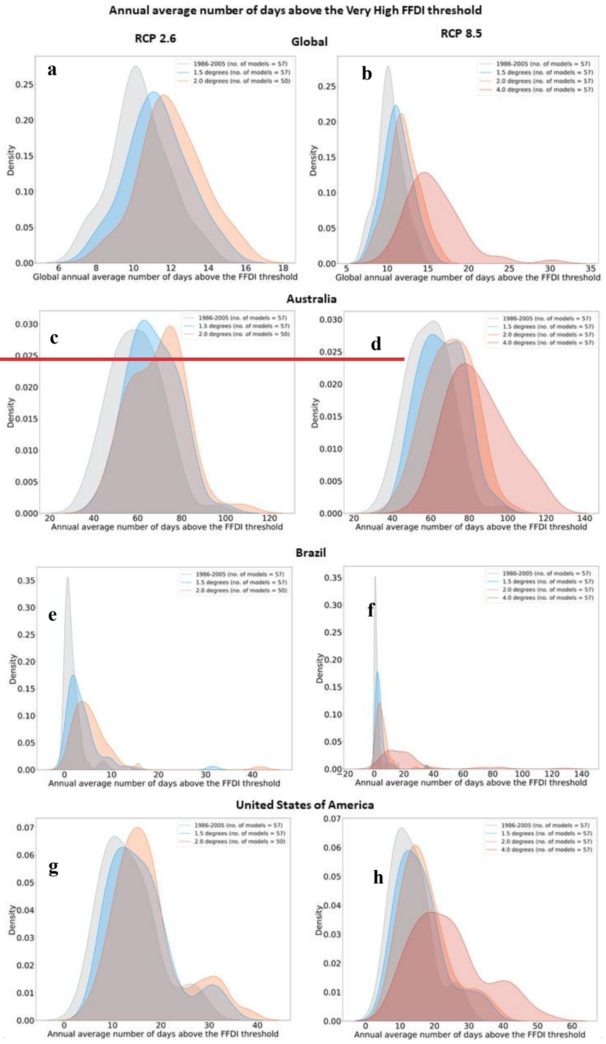
Region	Scenario	Global Warming Level		
		1.5°C	2.0°C	4.0°C
Global	RCP2.6	0.95 (0.59 – 1.26)	1.49 (1.0 – 2.08)	
	RCP8.5	0.88 (0.56 – 1.4)	1.5 (1.13 – 2.37)	4.87 (3.32 – 8.04)
Australia	RCP2.6	6.38 (0.24 – 14.61)	9.82 (1.08 – 17.08)	
	RCP8.5	6.82 (-1.56 – 13.71)	10.64 (3.14 – 18.45)	21.07 (13.19 – 34.89)
Brazil	RCP2.6	0.98 (0.27 – 3.05)	2.52 (1.01 – 4.71)	
	RCP8.5	0.99 (0.3 – 2.62)	1.95 (0.76 – 4.47)	10.83 (4.59– 19.71)
USA.	RCP2.6	2.19 (-0.03 – 4.91)	2.77 (0.21 – 6.42)	
	RCP8.5	2.07 (-0.23 – 4.83)	3.35 (0.26 – 6.54)	9.26 (3.97 – 15.40)



~~Figure 3 The annual average number of days above the Very High FFDI threshold for 3 future Global Warming Levels, 1.5°C, 2.0°C and 4.0°C and the baseline of 1986 – 2005, for 2 emissions scenarios, RCP 2.6 (a mitigation scenario, panels a,c,e,g) and RCP 8.5 (a high-end scenario, panels b,d,f,h), globally (panels a and b), and for Australia (c, d), Brazil (e, f) and the USA (g, h).~~

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~~There is a clear shift in the distribution of the number of days per year with Very High FFDI and above, indicating a lengthening fire season as temperatures rise (Figure 3). Globally and for Australia, the minimum number of days meeting the Very High threshold increases substantially. For example, in Australia, the minimum number of days with Very High FFDI is 20 during the baseline period (1986–2005), rising to 37 at 1.5°C and 2°C under both RCP2.6 and RCP8.5, and reaching 40 at 4°C under RCP8.5. For Brazil and the USA, the distribution retains some years with no Very High FFDI days even at 4°C, reflecting ongoing variability in fire weather extremes. However, the median and upper-end estimates shift significantly toward longer fire seasons. The most concerning changes occur in the extreme tails of the distribution, particularly for Brazil and the USA. In Brazil, there is a small likelihood during the baseline period of a peak around 15 days per year meeting the Very High FFDI threshold. This increases sharply to 32 days at 1.5°C, 42 days at 2°C, and as many as 90–140 days at 4°C. For the USA, the increase in the extreme tail is smaller in magnitude but still substantial, with the likelihood of very long fire seasons increasing, from around 30 days at the baseline to up to 60 days at 4°C.~~

3.2.2~~3~~ Mitigation potential

Figure 4 illustrates the influence of mitigation on the number of days exceeding the Very High FFDI threshold, expressed as the difference between a 4.0 °C warming level and lower warming levels of 2.0 °C and 1.5 °C. Under RCP8.5, all PPE members globally show reductions in Very High fire weather days when warming is limited, with decreases ranging from 2–17 days at 2.0 °C and -2–20 days at 1.5 °C relative to 4.0 °C ($p < 0.001$ for all results). Regionally, similar patterns emerge, though with greater spread reflecting regional climate responses. In Australia, reductions under RCP8.5 range from 1–33 days at 2.0 °C and- 7–40 days at 1.5 °C, while in Brazil the corresponding reductions are substantially larger, spanning a 1–97 days at 2.0 °C and 2-111 days at 1.5 °C. In the USA, most ensemble members project reductions of up to 23 days at 2.0 °C and 26 days at 1.5 °C, although a small number of members show near-zero or slight increases, indicating lower confidence in the magnitude of change. Overall, the difference between the 1.5 °C and 2.0 °C pathways is comparatively modest across regions, whereas the contrast with a 4.0 °C world is pronounced. Though 1.5°C -does tend to show are larger reduction vs 4.0 °C -than 2.0 °C.

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~~Figure 4 illustrates the influence of mitigation scenariosmitigation anomaly on the number of days above the Very High FFDI threshold, representing the difference in Very High fire weather days between a GWL of 4.0°C and the lower warming levels of 2.0°C and 1.5°C. Globally, all ensemble members indicate fewer Very High fire weather days when warming is limited, with the entire PPE ensemble showing values above zero. This consistent reduction highlights the clear benefits of mitigation in reducing fire weather days. Similar trends are observed across the three regions, where most ensemble members project reductions, though a few members show a low likelihood of slight increases. Notably, the difference between 1.5°C and 2.0°C is relatively small, underscoring the value of staying well below 4.0°C to minimize fire risk.~~

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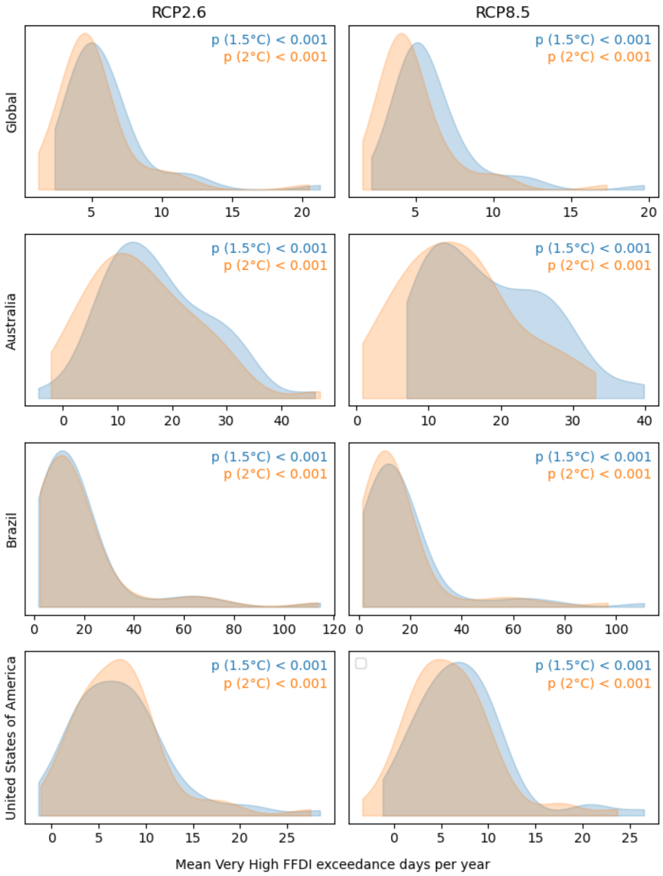
~~There is strong consensus for increases in fire weather days across the eastern USA, Brazil, southern South America, southern Africa, northern Africa, southern Europe, central Asia and Australia (Figure 2). Both 1.5°C and 2.0°C look~~

~~broadly similar for both emissions scenarios; however, there are spatial differences in the extent of increases and the amount of consensus. The number of fire weather days and the level of consensus increases with warming levels across all regions wherever there is a rise in fire weather. There are also consistent areas showing decreases across the tropics in India and Africa, which continue to 4.0°C, though over a reduced spatial area. Western USA and Eastern Amazon show a reasonable consensus (normally > 70%) for an increase in Very High FFDI at 1.5°C. However, areas affected by the Black Summer fires along Southeast Australia show less consensus, often < 50%, at 1.5°C. Consensus increases in all these regions at 2°C and approaches 100% by 4°C.~~



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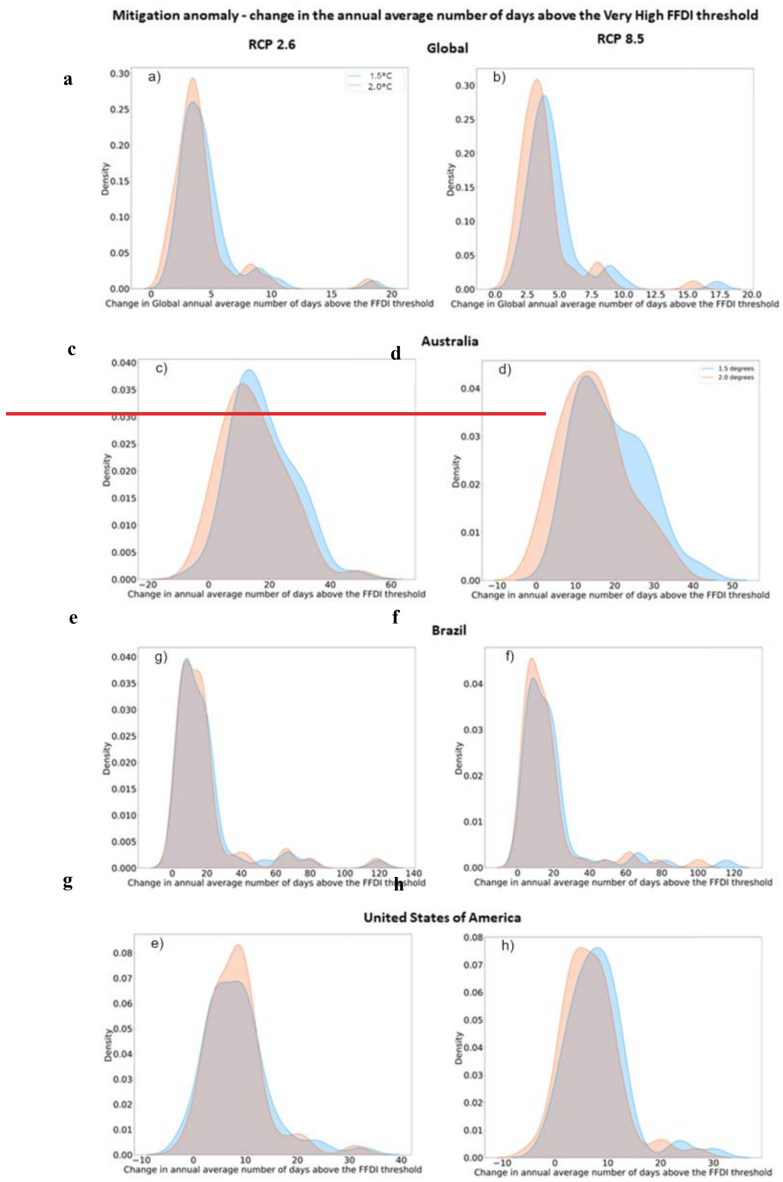

Figure 4 The influence of mitigation scenarios ~~The mitigation anomaly~~ on~~f~~ the change in annual average number of days above the Very High FFDI threshold, calculated as the difference between 4.0°C GWL (RCP8.5) and 1.5°C (blue) and

2.0°C (orange) respectively, for both emission scenarios. RCP2.6 (left column~~, panels a, c, e, g~~) and RCP8.5 (right column, ~~panels b, d, f, h~~), and for (top to bottom) Globally, ~~(panels a and b) and for~~ Australia ~~(c,d)~~, Brazil ~~(e,f)~~ and the USA. ~~(g,h),~~ P-values indicate the significance of differences between future GWLs and RCP8.5 4.0°C GW , assessed using a one-sided paired Wilcoxon signed-rank test, with pairing by ensemble member.

3.2.34 Meteorological drivers of FFDI

Figure 5 shows the relative importance of meteorological drivers contributing to FFDI variability for Australia, Brazil, and the ~~United States~~USA, estimated using RF~~random forest~~ models for baseline conditions and for a ~~Global Warming Level (~~GWL~~)~~ of 4.0°C. Across all regions, relative humidity ~~(RH)~~, air temperature, and wind speed dominate the importance rankings under baseline conditions, while precipitation and soil moisture contribute comparatively little to short-term FFDI variability.

Under a GWL of 4.0°C, all regions exhibit a consistent reduction in the relative importance of ~~RH~~ relative humidity, temperature, and wind, accompanied by modest increases in the importance of soil moisture and, to a lesser extent, precipitation. In Australia, mean importance values for ~~RH~~ relative humidity, temperature, and wind decrease from 0.17, 0.13, and 0.10 at baseline to 0.12, 0.09, and 0.07 at GWL4, respectively, while soil moisture remains low but slightly increases in relative contribution. Brazil shows the strongest shifts, with ~~RH~~ relative humidity, temperature, and wind importance declining substantially (~~RH~~ relative humidity from 0.50 to 0.33; temperature from 0.37 to 0.24; wind from 0.39 to 0.24), alongside a near-doubling of soil-moisture importance. In the ~~United States~~USA, similar but more moderate changes are observed, with decreasing importance of atmospheric drivers and increasing contributions from soil moisture and precipitation.

The reduction in the relative importance of individual atmospheric variables under strong warming is accompanied by increased similarity in their contributions, suggesting a reduced separability of meteorological drivers in explaining FFDI variability at higher warming levels. Standard deviations across bootstrap samples remain small in all regions and warming levels, indicating robust and internally consistent estimates of relative importance. Differences in importance between variables is ~~signifcant~~significant (t-test <0.001) for all regions and for the baseline and ~~4 degree~~4.0°C of warming.

~~Next, we examine the meteorological factors influencing changes in fire weather days to help understand the aspects of climate that change future fire risk. We sampled grid cells with High (12) FFDI or greater within the 20-year baseline period and within the 20-year 4°C global warming period for each model, Australia, the USA, and Brazil (Figure 5). Brazil generally has lower FFDI extremes than Australia in the 4°C world. USA high FFDIs are more sensitive to small changes in relative humidity (RH) rather than temperature, which is also found in other independent studies (Volpato et al., 2023). Also, the steeper curve for RH in Brazil shows that RH has more influence on lower FFDI values than in the other countries, though temperature becomes important at higher FFDIs,~~

~~especially at 4°C. Whereas in Australia and the USA, relatively small reductions in RH values below 20% have a larger influence on FFDI values above 40. At 4°C global warming, Brazil is also projected to see the biggest changes in FFDI, with more days at more extreme FFDI values due to higher temperatures and lower RH.~~

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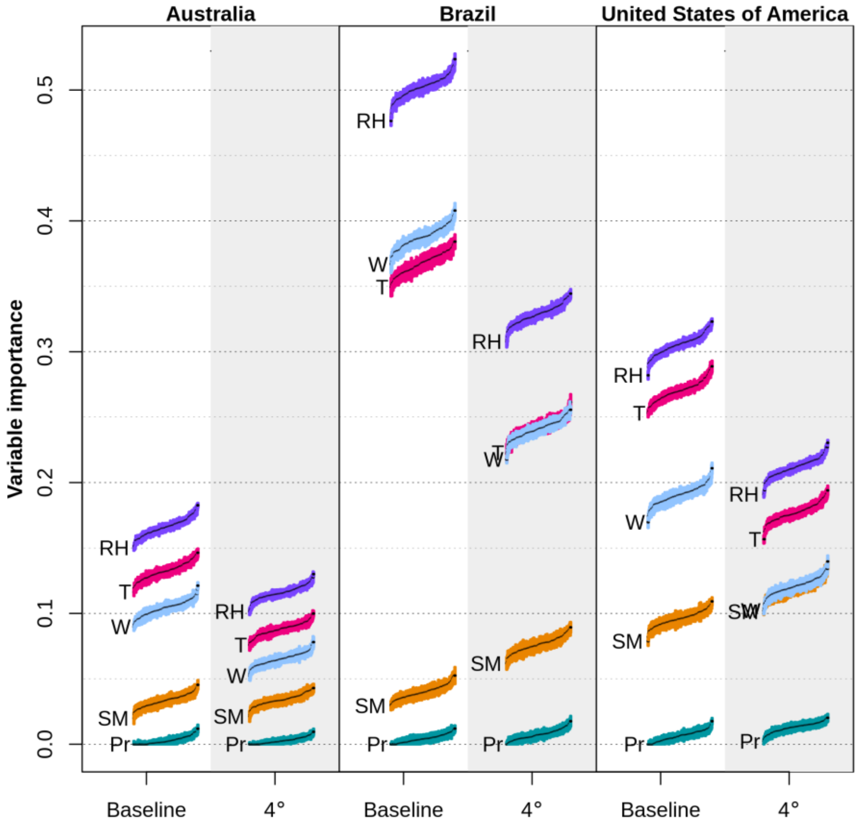

~~Figure 5~~

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Figure 5: Relative variable importance of meteorological drivers contributing to the Fire Forest Danger Index (FFDI), derived from random forest models, shown for (left to right) Australia, Brazil, and the ~~United States~~ USA~~of America~~. For each region, results are presented for baseline conditions (1986–2005; left column within each panel) and for a Global Warming Level (GWL) of 4.0~~-~~°C (right column). The variables are Relative Humidity (RH),

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Temperature (T), Wind speed (W), Soil Moisture (SM) and Precipitation (P). Variable importance values are based on 1000 bootstrapped random forest models; black bars show the mean importance across bootstrap samples, with shaded regions indicating ±1 standard deviation, illustrating variability in~~ both~~ the estimated means and their spread.~~Alternative plots to figure 5.~~

~~This is based on a random forest model, trained on a sample of the daily gridded data (all ensemble members, all days, all grid cells). The model was built using the meteorological variables that go into the FFDI calculation as the predictor variables for FFDI. Variable importance was calculated by bootstrapping removal of variables and quantifying the accuracy decrease in model accuracy related to each variable.~~

~~**Figure 5 A sample of grid cells and ensemble members showing the FFDI (x-axis) vs each variable (rows) used for its calculation (temperature, relative humidity, precipitation, soil moisture and wind speed), for the three countries (Australia, Brazil and the USA). The blue dots and line are for the baseline time-period and the orange dots and line are for the 4°C GWL. Trendlines have been applied using Loess fit.**~~

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~~Figure 5 shows the relative importance of meteorological drivers contributing to FFDI variability for Australia, Brazil, and the United States, estimated using random forest models for baseline conditions and for a Global Warming Level (GWL) of 4 °C. Across all regions, relative humidity (RH), air temperature, and wind speed dominate the importance rankings under baseline conditions, while precipitation and soil moisture contribute comparatively little to short-term FFDI variability.~~

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~~Under GWL4, all regions exhibit a consistent reduction in the relative importance of RH, temperature, and wind, accompanied by modest increases in the importance of soil moisture and, to a lesser extent, precipitation. In Australia, mean importance values for RH, temperature, and wind decrease from 0.17, 0.13, and 0.10 at baseline to 0.12, 0.09, and 0.07 at GWL4, respectively, while soil moisture remains low but slightly increases in relative contribution. Brazil shows the strongest shifts, with RH, temperature, and wind importance declining substantially (RH from 0.50 to 0.33; temperature from 0.37 to 0.24; wind from 0.39 to 0.24), alongside a near-doubling of soil-moisture importance. In the United States, similar but more moderate changes are observed, with decreasing importance of atmospheric drivers and increasing contributions from soil moisture and precipitation.~~

~~The reduction in the relative importance of individual atmospheric variables under strong warming is accompanied by increased similarity in their contributions, suggesting a reduced separability of meteorological drivers in explaining FFDI variability at higher warming levels. Standard deviations across bootstrap samples remain small in all regions and warming levels, indicating robust and internally consistent estimates of relative importance. Differences in importance between variables is signifcant (t-test <0.001) for all regions and for baseline and 4 degree.~~

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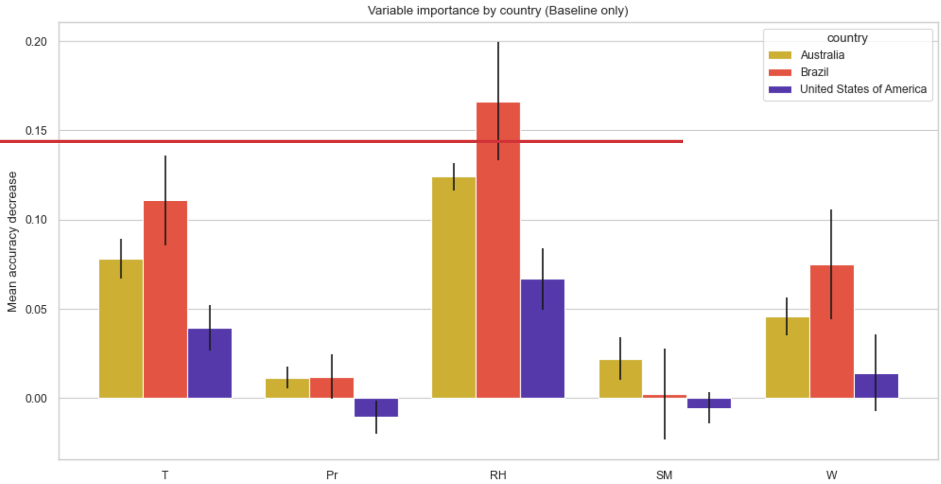

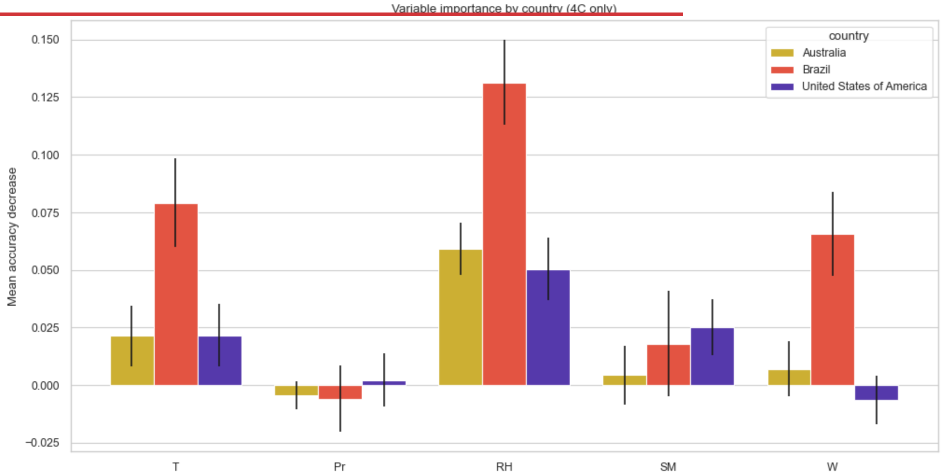

~~Bottom plot is 4 degrees, top one is baseline, for a random sample of grid squares – currently the top and bottom are not the same grid squares so not directly comparable~~

3.2.~~3~~4 Change in FFDI seasonal cycle

Figure 6 examines how changes in fire weather evolve across the full annual cycle by analysing the daily 90th percentile of FFDI for each model grid cell, averaged over 20-year periods at each Global Warming Level (GWL).

For the baseline period (1986–2005), Australia, Brazil, and the USA each exhibit a clear seasonal cycle, with elevated fire weather during spring and summer and lower FFDI values during winter. This cycle is retained across all warming levels and emissions scenarios, indicating no fundamental change in the overall shape of the fire season. However, substantial amplification occurs across all phases of the season as warming increases.

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During the baseline period, the PPE ensemble shows considerable spread in FFDI during elevated fire weather across all three regions. Even at 1.5°C of global warming, fire weather increases across much of the fire season in all regions, with larger increases at higher GWLs. As warming intensifies, peak FFDI values rise further, and ensemble spread increases, while minimum FFDI values remain comparatively stable, indicating a widening of fire-weather extremes rather than a uniform upward shift.

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In Australia, the largest changes in FFDI occur during the core fire season. Baseline peak FFDI values of 25–37 (5th–95th percentile across ensemble members) in October–November increase to 28–40 in the historical period and at 1.5°C, rising further to 30–41 at 2.0°C under RCP2.6 and 28–42 under RCP8.5. At 4.0°C under RCP8.5, peak values increase substantially to 30–49. These fire-season changes are significantly different across GWLs and emissions scenarios. In contrast, out-of-season increases in FFDI emerge later under RCP8.5, becoming statistically significant only at 4.0°C, though they are already detectable by 1.5°C under RCP2.6.

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Brazil exhibits the largest relative changes across the annual cycle of the three regions. Baseline peak FFDI values in September of 8–18 increase to 9–21 in the historical period, 10–21 at 1.5°C under RCP2.6, and 11–22 under RCP8.5. At 2.0°C, peak values reach 12–22 (RCP2.6) and 11–21 (RCP8.5), before rising sharply to 18–29 at 4.0°C under RCP8.5. Unlike Australia, statistically significant increases in out-of-season FFDI emerge early, becoming nearly continuous across the year by 1.5°C in both emissions scenarios. While the baseline period shows a modest elevation in FFDI after the fire season (3–8 through March), by 2.0°C under RCP8.5 March begins to form a secondary peak, with 95th percentile values around 12, increasing to approximately 18 by 4.0°C. These values fall within the range of the baseline September peak, suggesting a prolonged period of elevated fire risk extending several months beyond the historical fire season.

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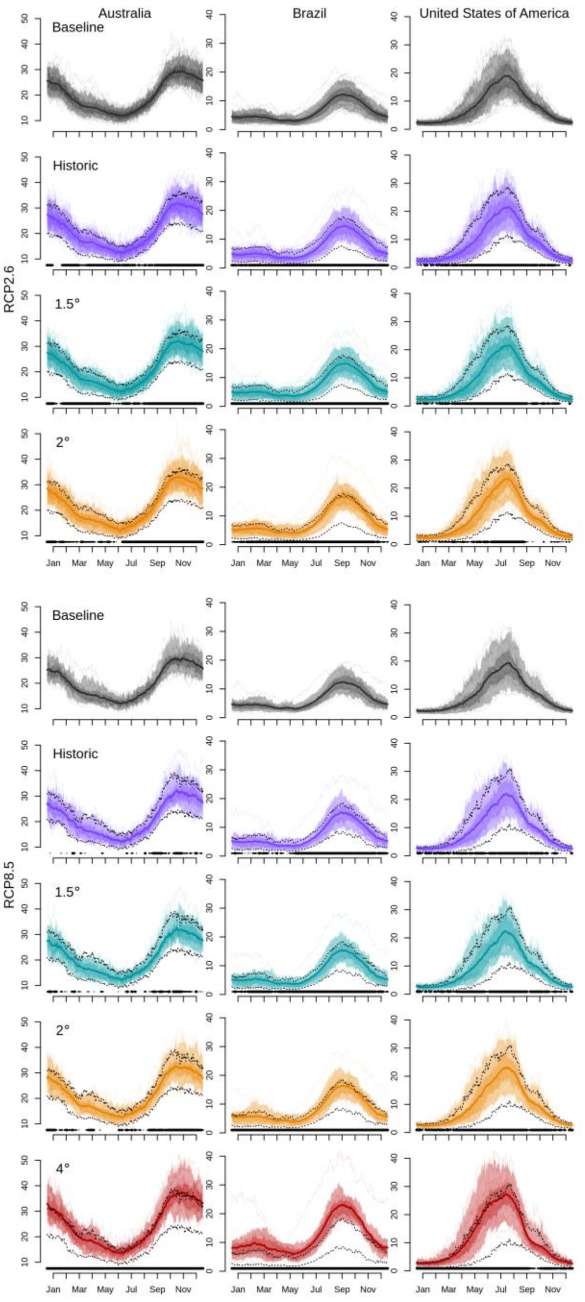
The USA shows the most pronounced increase in FFDI across the entire year, not solely during the peak fire season. Baseline peak FFDI values of 11–28 in July–August increase to 12–30 in the historical period, 13–31 at 1.5°C under RCP2.6, and 13–32 under RCP8.5. At 2.0°C, peak values reach 14–32 (RCP2.6) and 13–33 (RCP8.5), before rising sharply to 19–39 at 4.0°C under RCP8.5. Importantly, even the lowest out-of-season FFDI values increase by 1–2 units across all GWLs, with statistically significant departures from the baseline already evident in the historical period. This indicates a systematic elevation of background fire weather risk throughout the year.

Across all three regions, warming leads to higher FFDI values during the peak fire season, earlier transitions into elevated fire weather, later transitions out, and a shortening of historically low-risk periods. While the overall seasonal shape is largely preserved—aside from the emergence of a secondary late-season peak in Brazil—the fire season effectively lengthens as conditions characteristic of today's fire season expand into transitional and off-season periods. By 4.0°C, increases in FFDI are significant across all phases of the year in all regions, consistent with a future characterized by longer fire seasons, more extreme peak conditions, and reduced windows of low fire risk.~~In this section, we focus on the implications of changes in FFDI values over the full fire season, to inform seasonal fire management practices across different regions. For this, we calculated the daily 90th percentile for each model grid cell, averaged across every 20-year period at each GWL (Figure 6). All three countries show a distinct seasonal cycle of increased fire weather in the spring/summer and lower FFDI in the winter for the baseline – a cycle still maintained for all levels of warming. Brazil and the USA both have very low FFDI values in the winter, whilst Australia has a higher wetter season FFDI. For 1986 – 2005, the PPE ensemble shows considerable spread across all three countries during periods of higher fire weather. There are increases in fire weather throughout most of the fire season, even at 1.5°C, with larger increases at higher warming levels. At higher warming levels, the peak FFDI values also increase, and the range of values across the ensemble increases even whilst the minimums stay largely the same.~~



Australia
Brazil
United States of America
RCP2.6
RCP8.5
Baseline
Historic
1.5°
2°
4°
10
20
30
40
50
0
Jan
Mar
May
Jul
Sep
Nov

Figure 6~~5~~. Daily 90th percentile of future fire weather as represented by the FFDI for the baseline (1986 - 2005), historic (2004-2023), and three future Global Warming Levels—1.5°C, 2.0°C, and 4.0°C—for two emissions scenarios: (top) RCP2.6 and (bottom) RCP8.5; and (left to right) Australia, Brazil, and the USA. Thin lines depict individual ensemble members, with lighter shared areas indicating the 5-95th percentile range, darker areas showing the interquartile range, and solid coloured lines representing the median across ensemble members. The black dotted region displays the 5-95th percentile from the baseline. The lines at the bottom of each plot show the significance level versus the difference from the baseline for a one-week running average of FFDIs, where no line indicates a p-value > 0.1, a thin line indicates 0.01 > p-value > 0.01, and a thick line indicates p-value < 0.01. P-values are assessed using a one-sided paired Wilcoxon signed-rank test, with pairing by ensemble member.

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Australia exhibits substantial changes in burn season timing, with a consistent tendency towards earlier end-of-season thresholds across warming levels (Table 5). Under RCP2.6 at 1.5°C, the end-of-burn threshold occurs between 4 days later and 36 days earlier than the baseline, with 88% of ensemble members indicating an earlier season end. At 2.0°C, this range shifts further earlier (10–42 days), with a 93% likelihood of advancement. Under RCP8.5, the signal strengthens with warming: by 4.0°C, the season end occurs 5–44 days earlier in 96% of ensemble members. These results indicate a robust and increasingly compressed non-fire season in Australia, particularly under higher warming.

In Brazil, projected shifts are smaller at lower warming levels but become both larger and more certain with increased warming. Under RCP2.6 at 1.5°C, the end-of-season threshold advances by 9–26 days in 99% of ensemble members, increasing to 9–51 days at 2.0°C with complete ensemble agreement. Under RCP8.5, the signal becomes especially pronounced at higher warming, with the end-of-season advancing by 33–59 days at 4.0°C in 100% of ensemble members. This substantial and highly consistent advancement suggests a marked contraction of the traditional low-fire window in Brazil under strong warming.

In the USA, projected changes show greater ensemble spread at lower warming levels but converge towards earlier season ends with increased warming. Under RCP2.6 at 1.5°C, the end-of-season threshold ranges from 6 days later to 28 days earlier, with 70% of ensemble members indicating advancement. By 2.0°C, this shifts to 22–70 days earlier in 68% of members. Under RCP8.5, the likelihood and magnitude of earlier season end increase steadily, reaching 21–48 days earlier by 4.0°C in 96% of ensemble members. While the USA exhibits more variability than Australia or Brazil, the dominant signal remains one of shortening preparatory periods.

Across all three regions, distinct periods of low fire weather persist even at higher warming levels, indicating that opportunities for fuel management, recovery, and planning remain. However, the high likelihood of earlier season termination—combined with the increasing magnitude of these shifts—points to a systematic compression of the non-fire season. This compression has direct implications for fire management strategies that rely on predictable seasonal boundaries, reinforcing the need to adapt the timing of preparedness and fuel reduction activities under climate change.

~~Table 4: Projected shift in the end-of-season date for controlled burns in Australia, Brazil, and the United States at each global warming level (GWL). Calculated as the number of days earlier in the year that the FFDI reaches the baseline threshold typically marking the end of the burn season: 31st October for Australia, 1st September for Brazil, and 31st May for the USA. Values show the 10th and 90th percentiles across ensemble members, indicating the range of projected changes.~~

~~Later or no change~~	~~Less than a week earlier~~	~~1-2weeks earlier~~	~~2 weeks to one month~~	~~More than a month earlier~~

			~~Australia~~	~~Brazil~~	~~USA~~
	~~GWL~~		~~End of October~~	~~Early September~~	~~Late May~~
~~RCP2.6~~	~~1.5°C~~	~~10th~~	~~5~~	~~9~~	~~17~~
		~~90th~~	~~12~~	~~13~~	~~18~~
	~~2°C~~	~~10th~~	~~22~~	~~16~~	~~11~~
		~~90th~~	~~22~~	~~16~~	~~19~~
~~RCP8.5~~	~~1.5°C~~	~~10th~~	~~5~~	~~11~~	~~24~~
		~~90th~~	~~21~~	~~26~~	~~24~~
	~~2°C~~	~~10th~~	~~9~~	~~22~~	~~8~~
		~~90th~~	~~17~~	~~22~~	~~24~~
	~~4°C~~	~~10th~~	~~25~~	~~34~~	~~28~~
		~~90th~~	~~33~~	~~50~~	~~40~~

		~~Australia~~	~~Brazil~~	~~USA~~
~~Historic~~	~~10%~~	~~0~~	~~7~~	~~-7~~
	~~90%~~	~~35~~	~~25~~	~~30~~
	~~Likelihood~~	~~89~~	~~96~~	~~72~~
~~1.5~~	~~10%~~	~~-4~~	~~9~~	~~-6~~
	~~90%~~	~~36~~	~~26~~	~~28~~

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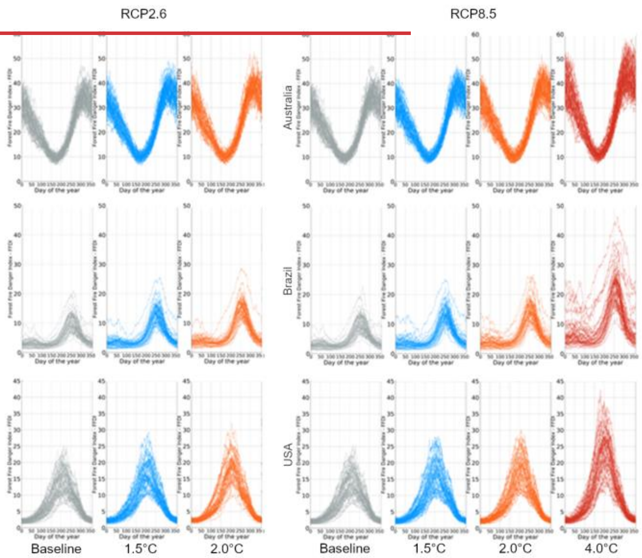
	~~Likelihood~~	~~88~~	~~100~~	~~70~~
~~2~~	~~10%~~	~~10~~	~~3~~	~~-22~~
	~~90%~~	~~42~~	~~51~~	~~70~~
	~~Likelihood~~	~~93~~	~~90~~	~~68~~
~~Historic~~	~~10%~~	~~-3~~	~~0~~	~~-3~~
	~~90%~~	~~32~~	~~28~~	~~36~~
	~~Likelihood~~	~~78~~	~~88~~	~~79~~
~~1.5~~	~~10%~~	~~5~~	~~11~~	~~-3~~
	~~90%~~	~~30~~	~~27~~	~~38~~
	~~Likelihood~~	~~92~~	~~96~~	~~83~~
~~2~~	~~10%~~	~~7~~	~~12~~	~~5~~
	~~90%~~	~~36~~	~~32~~	~~36~~
	~~Likelihood~~	~~96~~	~~100~~	~~92~~
~~4~~	~~10%~~	~~5~~	~~33~~	~~21~~
	~~90%~~	~~44~~	~~59~~	~~48~~
	~~Likelihood~~	~~96~~	~~100~~	~~96~~



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~~Figure 6 Daily 90th percentile of future fire weather as represented by the FFDI for the baseline (1986-2005), and 3 future Global Warming Levels, 1.5°C, 2.0°C and 4.0°C for two emissions scenarios, RCP2.6 in panels a, c, e and RCP8.5 in panels b, d, f, for Australia (panels a and b), Brazil (panels c and d) and the USA (panels e and f)~~

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~~As is expected, each country has a different range of FFDI values for the baseline and future GWLs, reflecting the respective climates of those regions. Australia exhibits significant changes in its burn season timing, with the end-of-season threshold occurring approximately 5–22 days earlier under RCP2.6 at 1.5°C and roughly 22 days earlier at 2°C, depending on ensemble member spread (**Table 4**). Under RCP8.5, end-of-season shifts could be up to 24 days earlier. In Brazil, the seasonal shift is less pronounced but still notable, with the end-of-burn season threshold advancing by approximately 9–13 days under RCP2.6 at 1.5°C and reaching up to 16 days at 2°C. Under high-end warming (RCP8.5), the threshold moves up to 11 days earlier. In the USA, end-of-burn season thresholds advance by approximately 17–24 days under RCP2.6 at 1.5°C and up to 24 days earlier under RCP8.5 at 1.5°C. While the USA's fire season shifts less dramatically than Australia's, this change marks a significant adjustment, likely affecting spring/summer management. The consistency of these patterns across regions reinforces the importance of adapting the timing of pre-season fire management practices to changing conditions. Across all three regions, even at the highest warming levels, distinct periods of low fire weather in winter remain. These retained low-fire periods provide strategic windows for fire season preparation, fuel reduction and control burning, resource planning and as an off season for seasonal firefighting. However, the consistent advancement of season-end dates underscores an increasingly compressed non-fire season.~~

Table 5 Projected shift in the end-of-season date for controlled burns in Australia, Brazil, and the ~~United States~~USA at each global warming level (GWL). Calculated as the number of days earlier in the year that the FFDI reaches the baseline threshold, typically marking the end of the burn season: 31st October for Australia, 1st September for Brazil, and 31st May for the USA. Values show the 10th and 90th percentiles across ensemble members, indicating the range of projected changes. Likelihood is based on the % of ensemble members that show an early end of burn season.

		Australia			**Brazil**			**USA**		
RCP2.6		**10%**	**90%**	Likelihood	**10%**	**90%**	Likelihood	**10%**	**90%**	Likelihood
	Historic	0	35	89	**7**	25	**96**	-7	30	72
	1.5°	-4	36	88	9	26	**99**	-6	28	70
	2°	**10**	**42**	**93**	9	**51**	**100**	-22	70	68
RCP8.5	Historic	-3	32	78	0	26	88	-3	36	79
	1.5°	**5**	30	**92**	**11**	27	**96**	-3	38	83
	2°	**7**	**36**	**96**	**12**	**32**	**100**	**5**	**36**	**92**
	4°	**5**	**44**	**96**	**33**	**59**	**100**	21	**48**	**96**

Later or no change | Less than a week earlier | 1-2weeks earlier | 2 weeks to one month | More than a month earlier

3.2.5~~5~~ Change in Low to High FFDI

Figure 7 ~~We also~~ evaluates projected increases in Low-moderate, High fire weather~~danger~~ days across Australia, Brazil, and the ~~United States~~ USA under historical, current, and future GWLs ~~(Figure 7), which is a proxy for changes in the amount of time control burns that might be conducted – i.e, not so wet for fire control burns to be ineffective, but without so higher fire weather as to risk fire's becoming out of control. Exact FFDIs for control burns vary among and even within a region, depending on the risk to local populations, fuel loads, and need depending on the likelihood of later extreme fires (Cirulis et al., 2020; Gill et al., 1987; Howard et al., 2020; da Veiga and Nikolakis, 2022). So 'High' serves as a proxy and indication of weather-related changes only.~~

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Across all three regions, increases in High, as well as Very High, fire weather~~danger~~ days are projected, especially under scenarios exceeding 1.5°C, though 1.5°C still shows substantial increases. Australia exhibits the highest

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baseline levels of fire weather~~danger~~ among the regions analysed, with 132.61 days per year at or above High fire weather~~danger~~ between 1986 and 2005. In the present day (2004–2023), our model indicates that this may have increased by an additional 7 days annually. At 1.5°C warming, High fire weather~~danger~~ days will increase by approximately 9.53 days under the RCP2.6 scenario and 8.37 days under RCP8.5, with even more significant increases at 2.0°C and higher GWLs. Brazil historically had much lower annual High fire weather~~danger~~ days than Australia, with an average of 16.99 days per year from 1986 to 2005. Since then, there has been an increase of 5 days, bringing the present-day average to approximately 21.99 days annually. At 1.5°C, Brazil's High fire weather~~danger~~ days are projected to increase by 7.12 days under RCP2.6 and 6.92 days under RCP8.5, indicating a notable shift towards higher fire potential even at this lower warming level. The USA~~nited States~~ had an average of 29.31 High fire weather~~danger~~ days annually from 1986 to 2005, with an increase of 3.51 days observed by the present day, making current annual totals approximately 32.82 days. Projections at 1.5°C warming indicate additional increases of around 3.82 days under RCP2.6 and 3.76 days under RCP8.5. Though the USA's increases are smaller than Australia's, the cumulative effects of additional High AND Very High fire weather~~danger~~ days will still likely strain current, often seasonal fire management resources and underscore the need for adaptive strategies, especially in high-risk regions like the western USA~~United States~~.

We also evaluate projected changes in the spatial distribution of time spent in different FFDI categories across Australia, Brazil, and the USA~~nited States~~ (Figures B1–B6). Rather than focusing solely on country-mean changes, these maps highlight how climate-driven shifts in fire weather are unevenly distributed within countries, with implications for where and when fire management actions—such as fuel treatment, prescribed burning, and preparedness—may remain feasible or become increasingly constrained. As in the aggregated analysis, time spent in the *High* FFDI category is used as a proxy for conditions that may permit controlled burning, recognising that operational thresholds vary locally depending on fuel type, risk tolerance, population exposure, and ecological objectives (Cirulis et al., 2020; Gill et al., 1987; Howard et al., 2020; da Veiga and Nikolakis, 2022). The maps therefore isolate weather-driven changes only, rather than prescribing management actions directly.

Across Australia, projected changes show a general shift away from Low–Moderate fire weather towards increased time spent in High and Very High FFDI categories, though the precise spatial pattern of change is more uncertain under RCP2.6, particularly at 1.5°C (Figure B1). Despite this uncertainty, a consistent signal emerges by 2.0°C, with large parts of the continental interior experiencing substantial increases in Very High FFDI—locally reaching increases of up to ~50–60 days per year in the upper ensemble range. Importantly, regions that historically experience lower fire danger, including parts of the south-eastern and southern coastal zones, show more confident increases in time spent in the High FFDI category (typically between 0 and ~50 additional days), areas that also coincide with higher population density and more continuous vegetation cover. There is also early evidence of the emergence of Severe-or-higher FFDI in parts of western Australia, although this remains spatially limited and ensemble-dependent at these warming levels.

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Under RCP8.5 (Figure B2), spatial patterns are broadly similar at lower warming levels, though uncertainty remains high up to 2.0°C. By 4.0°C, however, changes intensify markedly across much of the continent, with increases in Very High FFDI exceeding ~70 days in some interior regions and widespread increases of 5–30 days in High FFDI along the populated south-eastern coast. Several regions, including parts of western Australia, also show increases of up to a week or more in Severe-or-higher fire weather, indicating a qualitative shift in fire risk beyond historical experience.

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Brazil exhibits some of the strongest and most spatially coherent changes among the three regions (Figures B3 and B4). Under RCP2.6, increases in High FFDI are already evident by 1.5°C, accompanied by compensating decreases in Low–Moderate conditions across much of the eastern Amazon basin and extending towards the coastal Caatinga. In many areas, these changes range from a few days to as much as ~50 additional High FFDI days per year. The southern Amazon–Cerrado transition zone shows the most consistent and confident signal, with nearly all ensemble members indicating increases, typically exceeding one week and locally approaching several weeks. These patterns strengthen and expand at 2.0°C.

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There are also early indications, even at 1.5–2.0°C, of emergent Very High FFDI in forested regions, including near the Amazon river mouth and areas already associated with deforestation and land-use change. Under RCP8.5, these spatial patterns remain similar but intensify, particularly at higher warming levels (Figure B4). At 4.0°C, large parts of eastern Amazonia experience increases in High FFDI of several weeks to up to three months, with parts of the region showing increases in Very High FFDI approaching or exceeding one month per year. These changes suggest a substantial extension of fire-prone conditions into regions that have historically experienced only limited seasonal fire weather.

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In the USA~~United States~~, the most pronounced spatial changes occur in the western and south-western regions, including California (particularly southern California), Nevada, Arizona, New Mexico, Texas, and extending eastward into Louisiana (Figures B5 and B6). Under RCP2.6, increases in High and Very High FFDI are already evident by 1.5°C, typically ranging from 0 to ~40 additional High FFDI days per year, with the largest changes concentrated in the south-west. By 2.0°C, these increases become more spatially extensive, particularly along the US–Mexico border. Parts of southern California also show the emergence of Severe-or-higher fire weather, locally approaching about a week per year.

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Under RCP8.5, changes in High FFDI remain spatially heterogeneous and more ~~uncertain, but~~uncertain but increases in Very High FFDI are more pronounced and robust across ensemble members (Figure B6). At 1.5°C, southern California already shows increases ranging from weeks to nearly two months, expanding eastward at 2.0°C. By 4.0°C, Very High FFDI increases become widespread across border states, with local increases of up to ~2–2.5 months, while Severe-or-higher conditions become more common, in some areas increasing by a week or more across large parts of the southern USA~~United States~~.

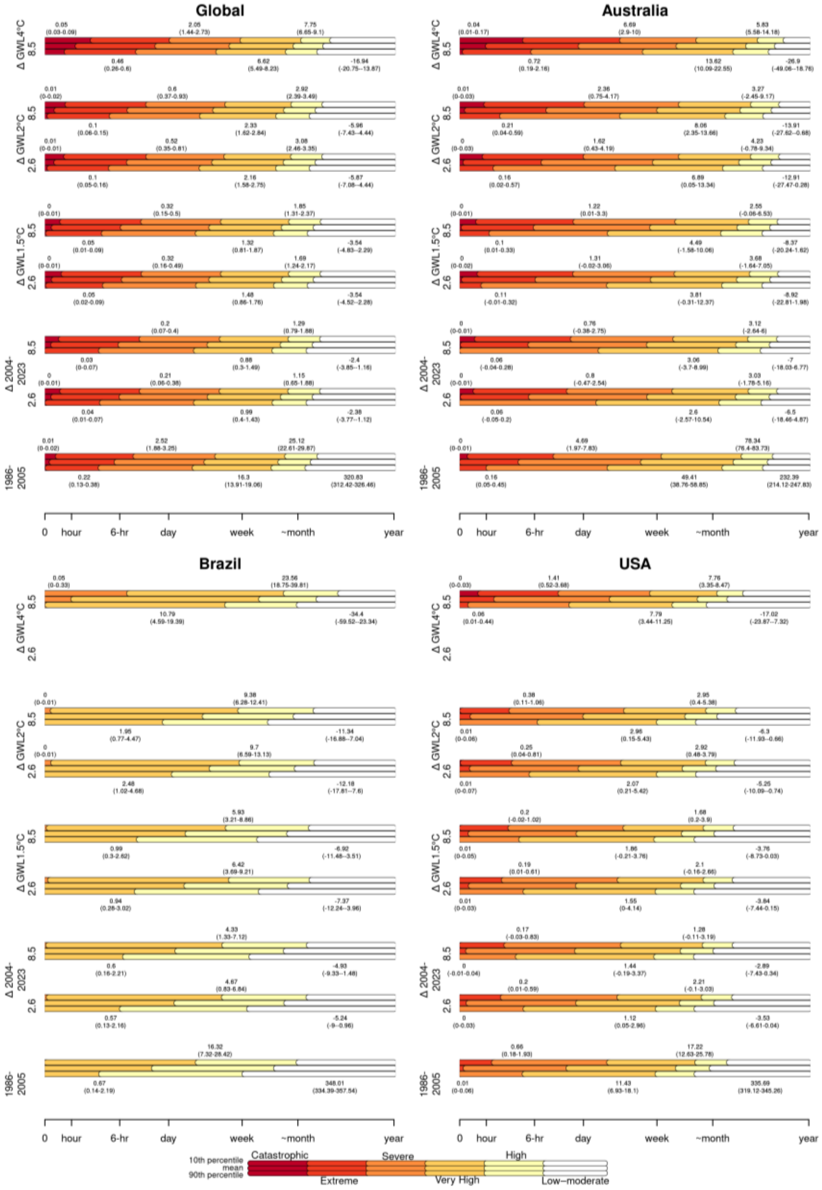

Figure 7: Projected changes in annual time spent in different fire weather categories across Australia, Brazil, and the USA~~nited States~~ under various Representative Concentration Pathways (RCPs) and Global Warming

Levels (GWLs). The bottom row for each region shows historical averages (1986–2005) of annual time spent in each Fire Danger Index category, from Low-~~Medium~~ Moderate (white) to High through Catastrophic (yellow to deep red), as defined in Table 1. Rows above (from bottom to top) display changes under present-day conditions (2004–2023) and future projections at 1.5°C, 2°C, and 4°C global warming levels.

Globally, the Low–moderate FFDI category decreases by approximately 2.4 days at 1.5°C and by nearly 17 days at 4.0°C under RCP8.5. These reductions suggest significant global shifts in the duration of periods typically associated with low fire weather~~risk~~. Across all regions, there is a clear trend towards a reduction in the time spent in the Low–moderate FFDI category, accompanied by an increase in the time spent in the higher FFDI categories. This reflects a contraction of the low fire-risk period and a corresponding extension of fire-prone conditions. Australia exhibits the most pronounced changes, with a decrease in the Low–moderate category of approximately 7 days at 1.5°C, extending to over 26 days by 4.0°C under RCP8.5. In the USA, the decrease in the Low–moderate category is less pronounced, with reductions of approximately 1 week at 1.5°C and up to 10 days at 4.0°C under RCP8.5. Brazil also demonstrates a marked decline in time spent in the Low–moderate category - up to 12 days at 2.0°C and over 26 days at 4.0°C.

The increases in the more extreme FFDI categories (Severe, Extreme, Catastrophic) provide a useful proxy for understanding changes in fire behaviour under climate change. Globally, time spent in the Extreme category shows a modest increase of ~0.1 days at 1.5°C, reaching ~0.5 days at 4.0°C under RCP8.5. The most dramatic changes occur in the Severe category, which increases by ~0.6 days at 1.5°C and ~2 days at 4.0°C. Time spent in the Extreme category in Australia increases significantly, particularly under higher warming levels, reaching an additional ~0.7 days by 4.0°C under RCP8.5. Similarly, the Severe category grows by over 6 days by 4.0°C, suggesting heightened risk of extreme fire weather events. Although changes are smaller in USA, there are notable increases in the Severe category, reaching 2–3 days at higher warming levels. Brazil shows smaller increases in extreme categories, with the Very High category dominating changes.

4. Discussion

Our model projections~~, supported by evidence from previous studies (e.g. Jones et al (2022), Peng et al (2023)),~~ show that the more global warming we experience in the future, the higher the increase in peak fire ~~risk~~danger, and the longer Very High ~~fire weather~~fire weather~~FW~~ seasons will become, extending over much more land area, especially at 4.0°C of ~~global~~ warming. This supports evidence from previous studies (e.g. Jones et al., 2022; Peng et al., 2023). O~~Though o~~ur analysis provides~~ing~~ a complementary line of evidence through a structured assessment of uncertainty across warming levels, emissions scenarios, and model parameterisations, thereby strengthening confidence in the robustness of conclusions from these previous studies. ~~WHowever, we take a novel approach by also quantifying the uncertainty in future projections with a combination of a PPEperturbed physics ensemble, three global warming levels and two emissions scenarios. UAdditionally, unlike~~Additionally, unlike previous studies, ~~that~~which ~~have mainly~~mostly quantify~~ied~~ the magnitude of these increases, our analysis focuses on what these

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changes mean for fire management, particularly the seasonal timing of preparation windows, controlled burns, and low-fire periods~~,~~ that remain critical for adaptation. This management-oriented framing inverts the usual problem: instead of only asking "how much worse will fire weather get~~,~~" (Section 4.1), we also ask, "how and when can societies still act within an increasingly altered seasonal cycle?" (Section 4.2).~~"~~

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4.1 Projections and the scale of the adaptation challenge

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~~Our model projections show that the more global warming we experience in the future, the higher the fire risk, and the longer Very High fire weather seasons will become, extending over much more land area, with the strongest changes occurring under 4 °C of global warming., especially at 4°C global warming.~~ ~~However, e~~Even under strong mitigation consistent with the Paris ~~Agreement temperature goals of 1.5 °C or 2 °C~~Agreement's 1.5-°C or 2.0-°C temperature goals, we project increases in the duration of Very High ~~fire -weather~~FFDI~~FW~~ seasons across most regions globally, including all three of our study regions. This indicates that some degree of adaptation to longer and more persistent ~~fire-weatherFW~~fire weather -seasons will be required even under the most optimistic warming trajectories.

~~However, we take a novel approach by also quantifying the uncertainty in future projections with a combination of the Perturbed Physics Ensemble, three Global Warming Levels and two emissions scenarios. Additionally,However, unlike previous studies that have mainly quantified the magnitude of these increases, our analysis focuses on what these changes mean for fire management, particularly the seasonal timing of preparation windows, controlled burns, and low-fire periods that remain critical for adaptation. This management-oriented framing inverts the usual problem: instead of only asking "how much worse will fire weather get," we ask "how and when can societies still act within a shifting seasonal cycle? Our subsequent analysis, therefore, focuses on what these shifts imply for fire management, particularly the seasonal timing of preparation windows, opportunities for controlled burning, and the contraction of low-fire periods that remain critical for adaptation. This framing inverts the usual question: rather than asking only how much worse fire weather may become, we ask how and when societies may still be able to act within an increasingly altered seasonal cycle.~~

We show significant sensitivity of fire weather ~~FWfire weather~~ to GWL~~global warming level~~s, with increases in Very High ~~fire weather~~fire weather ~~FW~~ days (FFDI > 24) projected globally and regionally at all temperature thresholds. At 4.0°C, we project an increase in Very High ~~fire weather~~ fire weather ~~FW~~ days over 50% of affected burnable land worldwide, compared to 30% at 1.5°C ~~global~~ warming. These results align with previous studies showing measurable increases in fire weather severity and longer fire seasons even between 1.5°C and 2.0°C of warming, with particularly strong regional responses (Jones et al., 2022; Son et al., 2021; Sun et al., 2019; Tian et al., 2023). ~~These results align with previous studies such as xxx who project xyz under the abc scenario~~ This highlights the disproportionate impact of higher warming levels and the urgent need for mitigation to limit global temperatures.

Regionally, Australia emerges as particularly vulnerable, with 82% of its burnable land ~~impacted~~ affected by an increase in Very High (or greater) fire weather days at 1.5°C, rising to 87% at 2.0°C and 96% at 4.0°C (RCP8.5 central estimate, Table ~~2~~3), with increases seen even in the fuel-abundant southeast coast. While the increases between the 1.5°C, ~~/~~2.0°C and 4.0°C warming levels highlight the benefits of limiting warming, the high proportion of affected land, even at lower thresholds, emphasises that adaptation will also be necessary if significant impacts are to be avoided. In Brazil, fire weather also shows a marked escalation, with 30% of burnable land affected at 1.5°C, increasing steeply to 41~~5~~% at 2.0°C and 70% at 4.0°C warming levels (RCP8.5 central estimate, Table 3). This jump ~~-~~reflects the acute sensitivity of Brazil's ecosystems, already under pressure from deforestation and land-use change (Ferreira et al., 2023; Kelley et al., 2021; Mataveli et al., 2022)~~(Ferreira et al., 2023; Kelley et al., 2021; Mataveli et al., 2022)~~.~~.~~ In the USA, ~~fire weather~~ fire weather ~~FW~~ increases more steadily, but still markedly, with 34~~3~~% of burnable land affected at 1.5°C~~ and~~, 44~~2~~% at 2.0°C and 65% at 4.0°C warming levels (RCP8.5 central estimate, Table 3). Together, these results illustrate that there will likely be regional variation in how ~~fire weather~~~~risk~~ fire weather ~~FW may~~ responds ~~differently~~ to warming in diverse landscapes, but they also highlight the need for adaptation even at the lowest warming level we assess.~~. However, all regions still show an increase even at 1.5°C.~~

While RCP2.6 (a mitigation scenario) limits global warming to much lower temperatures in comparison to RCP8.5, at the lower warming levels there is relatively little variation between emissions scenarios, similar to (Peng et al., 2023).~~ — evidence of the critical role of achieving and maintaining Paris Agreement targets.~~ These results clearly show that mitigation to limit warming to well below 2.0°C presents a substantial opportunity to reduce the area affected by worsening fire weather, but even at 1.5°C, our results suggest that increases in Very High fire weather~~danger~~ days are unavoidable. Any policy response to this projected increase in future fire weather ideally needs to address these two elements that should complement and support each other. Firstly, an effective global mitigation policy is needed to limit future climate change and ~~hence limit the increase in future~~ , in turn, the increase in fire weather days. Secondly, enhanced fire management policies are needed to ~~respond to the unavoidable increases in fire weather days that are projected for all global warming levels~~address the unavoidable increase in fire weather days projected across all levels of global warming.

Using the~~a~~ PPE in this study has helped to isolate climate sensitivities and meteorological drivers relevant to fire weather, under-pinned by a well-established framework for assessing uncertainty in GCMs (Murphy et al., 2007) ~~(Murphy et al., 2007).~~ Although the PPE captures considerable uncertainty in future fire weather projections by systematically perturbing key model parameters, it does not encompass the full range of plausible or possible outcomes across structurally different climate models. However, the structured nature of the PPE provides key advantages: it ~~allows for a more systematic exploration of parameter-driven uncertainties and offers a more straightforward coupling between model outputs and fire weather indices like~~enables a more systematic exploration of parameter-driven uncertainties and provides a more straightforward coupling between model outputs and fire weather indices such as the FFDI. Unlike the CMIP multi-model ensemble, which relies on a smaller selection of available models with varying levels of evaluation for fire weather projections, the PPE is based on a single, extensively evaluated climate model.

4.2 Opportunities for adaptation actions

The magnitude of FFDI increases vary across our study regions, alongside shifts in fire season timing and duration and differences in regional sensitivity to key climate drivers. This indicates that each region's fire season responds differently to climate change, requiring tailored adaptation strategies as highlighted by Pandey et al. (2023)~~Pandey et al. (2023)~~. Despite this diversity in response, some consistent patterns emerge across all regions. Under strong warming (4.0ºC warming level), the relative influence of individual meteorological drivers on fire weather declines, reflecting an increasing role for compound ~~fire weather conditions rather than dominance by~~fire -weather conditions rather than the dominance of any single variable (Figure 5).

Brazil, for example, generally experiences lower FFDI values compared to Australia and the USA, and we find that relative humidity is a dominant contributor to fire weather~~danger~~ variability under baseline conditions, but its relative importance declines under strong warming as fire-conducive conditions become increasingly driven by compound interactions with temperature, wind, and fuel dryness. Approaches that have been proposed or implemented, such as conserving forests, protecting wetlands, especially in the Brazilian Pantanal (Ferreira Barbosa et al., 2022), ~~(Barbosa et al., 2022b),~~ and preventing fragmentation of riparian zones (Ferreira et al., 2023) ~~(Ferreira et al., 2023) , may help maintain local humidity levels,~~may help maintain local humidity levels and act as natural firebreaks. Nonetheless, our results imply that these will be more likely to remain effective if they also affect soil moisture and precipitation, whose contribution also increases by 4.0ºC in comparison to the baseline period of 1986 - 2005.

Large, destructive fires play a critical role in shaping fire regimes in ~~fire sensitive~~fire-sensitive regions of Brazil, often accounting for a substantial portion of seasonal burned area (Flannigan et al., 2016). ~~(Flannigan et al., 2016).~~ Our projected increase in fire weather days in these regions ~~elevate the potential for ignition and precondition~~elevates the potential for ignition and preconditions the environment for large, impactful events. In the Brazilian Cerrado, where FFDI is generally higher and fire danger ~~more temperature-driven, forecasting periods of elevated fire danger (Anderson et al., 2022),~~is more temperature-driven, forecasting periods of elevated fire danger (Anderson et al., 2022) ~~-~~and reducing human ignitions, such as restricting agricultural burning during peak fire weather, have been identified as strategies to reduce fire occurrence (Pivello, 2011). ~~(Pivello, 2011).~~

Evidence also shows that controlled burns reduce late dry-season fires in areas surrounding the Cerrado (Moura da Veiga et al., 2025; Santos et al., 2021; da Veiga and Nikolakis, 2022) ~~(Santos et al., 2021; da Veiga et al., 2024; da Veiga and Nikolakis, 2022)~~. Our findings indicate that the window for applying controlled burns may expand by 9–13 days at 1.5°C under RCP2.6 and up to 16 days at 2.0°C (Figure 7; Brazil, High FFDI category). However, this

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expansion in high FFDI time, reaching up to a week at 1.5°C and nearly a month at 4.0°C, is likely to coincide with a contraction of Low–Moderate periods, increasing the duration over which seasonal firefighting capacity is required.

In Australia, fire danger is strongly influenced by the co-occurrence of low relative humidity, high temperatures, and high winds (Figure 5), which exacerbate fire spread and intensity. Our findings imply that fire management effort might be most effective when they focus on reducing fuel loads, commonly through controlled burns during milder weather conditions (Morgan et al., 2020; Russell-Smith et al., 2020)~~ (Morgan et al., 2020; Russell-Smith et al., 2020)~~, and strengthening early warning systems that monitor key meteorological variables (de Groot et al., 2015)~~ (de Groot et al., 2015)~~. Under stronger warming, however, reliance on individual meteorological indicators becomes less effective, reinforcing the need for integrated early warning systems that explicitly account for compound fire weather conditions. We find that the end of the controlled burn season in Australia shifts earlier, approximately 5–12 days at 1.5°C under RCP2.6 and up to 22 days at 2.0°C (Table 54). At 4.0°C, this contraction is partly offset by a modest extension of the High FFDI period, by almost one week, during which controlled burning may still be feasible. These largely agree with the earlier and longer control burn season by mid-century found by Clarke et al. (2019)~~(Clarke et al., 2019)~~. At the same time, the Low to Moderate fire weather~~danger~~ off-season shortens substantially, by up to one month at 4.0°C, which may affect the recruitment, training, and availability of Australia's largely volunteer-based rural fire services (Russell-Smith et al., 2020)~~ (Russell-Smith et al., 2020)~~. Shifting the timing of policies aimed ~~to reduce~~at reducing human ignitions, such as closing national parks and restricting campfires during high-risk periods, could complement fuel management measures. However, our results indicate that such restrictive and suppression measures are likely to be required for longer, even at 2.0°C warming, potentially increasing firefighter fatigue and reducing public compliance over time (Doley et al., 2016)~~ (Doley et al., 2016)~~. In this context, additional measures such as fire-resistant vegetation and buffer zones around vulnerable areas could help mitigate risks associated with wind-driven fires (Pandey et al., 2023)~~ (Pandey et al., 2023)~~.

In the USA, High fire weather is primarily linked to the combined influence of temperature and wind, with temperature showing almost as high importance as relative humidity (Figure 5), particularly in the western regions where strong, dry winds are common. These results suggest that targeted controlled burns during periods of lower wind activity, alongside mechanical thinning to reduce fuel loads, could be important strategies. The end of the controlled burn season advances by approximately 17 to 24 days under RCP2.6 at 1.5°C and by up to 24 days under RCP8.5 (Table 54). While these shifts are smaller than those projected for Australia, they still represent a meaningful change that is likely to affect spring and early summer management. Concurrently, a lengthening fire season and a contraction of the Low to Moderate fire weather~~danger~~ period may increase pressures on firefighting capacity, recruitment, and workforce wellbeing (O'Brien and Campbell, 2021)~~ (O'Brien and Campbell, 2021)~~. Efforts to reduce human ignitions, particularly in the wildland- urban interface, could further alleviate fire risks. As in Australia and Brazil, the reduced dominance of individual meteorological drivers under warming suggests that

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fire management strategies based on single thresholds may become less effective, increasing the importance of integrated, season-scale planning.

~~Crucially, our analysis goes beyond quantifying increases by identifying earlier season onsets, longer high -danger periods, and reduced low -fire windows. These features directly determine the opportunities and constraints for management actions such as pre-season preparation, controlled burns, and firefighter mobilisation, — an aspect not systematically explored in global fire weather studies.~~

~~RCP2.6 (the mitigation scenario) limits global warming to much lower temperatures than RCP8.5. However, at the lower warming thresholds, fire weather changes are primarily driven by GWLs, with relatively little variation between emissions scenarios – evidence of the critical role of achieving and maintaining Paris Agreement targets. Mitigation to limit warming to well below 2.0°C presents a substantial opportunity to reduce the area affected by worsening FWfire weather, but even at 1.5°C, our results suggest that increases in Very High fire danger days are unavoidable. Any policy response to this projected increase in future fire weather ideally needs to address these two elements that should complement and support each other. Firstly, an effective global mitigation policy is needed to limit future climate change and hence limit the increase in future fire weather days. Secondly, enhanced fire management policies are needed to respond to the unavoidable increases in fire weather days that are projected for all global warming levels.~~

~~The magnitude ofextent of FFDI increases varyies across our study regions, alongside with shifts in fire season the timing and duration of fire seasons and differences in regional sensitivityies to key climate drivers. This indicatesese findings suggest that each region's fire season respondss differently to climate change, requiring and therefore need tailored adaptation strategies (Barbosa et al., 2022; Pandey et al., 2023). However, our results do show one common trend across all regions: under strong warming, the relative importance of individual meteorological drivers of fire weather decreases, indicating an increasing role for compound fire-weather conditions rather than dominance by any single variable. Despite this variability, a consistent pattern emerges across all regions. Under strong warming, the relative influence of individual meteorological drivers on fFire wWeather declines, reflecting an increasing role for compound fire weatherFW conditions rather than dominance by any single variable. Brazil, for example, generally experiences lower FFDI values compared to Australia and the USA, and we find our results suggest that relative humidity is a dominant contributor to fire danger variability under baseline conditions but that its relative importance declines under strong warming as fire-conducive conditions become increasingly driven by compound interactions with temperature, wind, and fuel dryness.our results suggest that relative humidity plays a more critical role than temperature in shaping fire danger, particularly at lower FFDI levels (Figure 5) associated with many of Brazil's forests and wetland areas. This suggests that maintaining higher humidity levels, such as above 20%, could play an important role in mitigating fire risk in Brazil's humid, fire-sensitive biomes(Ferreira Barbosa et al., 2024). Approaches that have been proposed or implemented, such as conserving forests, protecting wetlands, especially in the Brazilian Pantanal (Ferreira Barbosa et al., 2022b), and preventing fragmentation of riparian zones (Ferreira Barbosa et al., 2024; Ferreira et al., 2023), may help sustain soil moisture, maintain local~~

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~~humidity levels, and act as natural firebreaks. These strategies could also integrate water conservation with fire risk mitigation. In regions with significant human influence, such as the Amazon and Pantanal (Ferreira Barbosa et al., 2022; Kelley et al., 2021), addressing both climatic and human factors is essential for understanding and mitigating fire weather-related risks. NonethelessThough, our results suggest that these will be more likely to remain effective in the future if they also affect soil moisture and precipitation, whose contribution increases by 4 ºCdegrees.~~

~~Large, destructive fires play a critical role in shaping fire regimes in fire sensitive regionsin these areas, often accounting for a substantial portion of seasonalthe burned area during fire seasons (Flannigan et al., 2016). Our projected increase in fire weatherFWfindings indicate that increased fire weather days in these regions elevate the potential for ignition and precondition the environment for large, impactful events. In the Brazilian Cerrado, where FFDI is generally higher and fire danger more temperature-driven, forecasting periods of elevated fire danger (Anderson et al., 2022; Barbosa et al., 2022), and reducing human-sourced ignitions, such as restricting agricultural burning during peak fire weather, have been identified as strategies to reduce fire occurrence (Pivello, 2011), particularly in agricultural and transitional zones(Ferreira Barbosa et al., 2021, 2022). Evidence suggestsalso shows that controlled burns are effective in reducinreduceg late dry-season fires in areas surrounding the Cerrado (Santos et al., 2021; da Veiga et al., 2024; da Veiga and Nikolakis, 2022) Our findings indicate that the window for applying controlled burns may expand in the future, potentially by 9–13 days at 1.5°C under RCP2.6 and up to 16 days at 2°C (Figure 7). However, this expansion in high FFDI time, reaching — up to a week at 1.5°C and nearlyas much as a month at 4°C, is (Figure 7) — will likely to coincide with a contraction of time ofin the Low–Moderate periodscategory, potentially increasing the windowduration overin which seasonal firefighting capacity is required.~~

~~In Australia, fire danger is strongly influenced by the co-occurrence of low relative humidity, high temperatures, and high windsfire danger is strongly influenced by low relative humidity, high temperatures, and high winds, which exacerbate fire spread and intensity. Our findings imply that fire management efforts in these areas might be most effective whenif they focus on reducing fuel loads, which today is often achievedcommonlycommo through controlled burns during milder weather conditions (Morgan et al., 2020; Russell-Smith et al., 2020), and strengthening effective early warning systems that monitor key RH, temperature, and wind speedsmeteorological variables (de Groot et al., 2015). Under stronger warming, hHowever, our results suggest that under stronger warming, reliance on individual meteorological indicators becomes less effective, reinforcing the need for integrated early -warning systems that explicitly account for compound fire-weather fire weatherFW conditions. We find that tThe end of the controlled burn season in Australia shifts significantly earlier, occurring approximately 5–12 days at 1.5°C earlier under RCP2.6 at 1.5°C and up to 22 days earlier atunder 2.0°C (Table 4). , though notably with a slightly longer period of High FFDI of almost a week by 4°C, during which time controlled burns may occurAt 4°C, this contraction is partly offset by a modest extension of the High FFDI period, by almost one week, during which controlled burning may still be feasible.. These largely agree with the earlier and longer control burn season by mid-century found by (Clarke et al., 2019). At the same time, the Low to Moderate fire danger off-season shortens substantially, by up to one month at 4°C, which may affect the recruitment, training, and availability of Australia's largely volunteer-based rural fire servicesHowever, like Brazil, the Low-Moderate off-season will also~~

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~~reduce, possibly by almost a month, at 4°C, which could substantially impact the way many of the heavily seasonal volunteer rural fire services recruit (Russell-Smith et al., 2020). Shifting thes in the timing of policies aimed to reduce human ignitions, such as closing national parks and restricting campfires during high-risk periods, could complement these measuresfuel management measures by preventing fires from starting in the first place. However, our results indicate that such restrictive and suppression measures are likely to besome of these firefighting and restrictive measures would very likely be required for longer, even atby 2°C warming, which could have associated firefighter and general compliance fatigue potentially increasing firefighter fatigue and reducing public compliance over time (Doley et al., 2016). AdditionallyIn this context, additional measures such as integrating fire-resistant vegetation and buffer zones around vulnerable areas could help mitigate risks associated with wind-driven fires (Pandey et al., 2023).~~

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~~In the USA, High fire weatherfire weatherFW is primarily linked to the combined influence of temperature and wind, with temperature showing almost as high importance as relative humidityIn the USA, High fire weather is primarily linked to temperature and wind, particularly in the western regions where strong, dry winds are common. These results suggest that targeted controlled burns during periods of lower wind activity, alongside mechanical thinning to reduce fuel loads, could be important strategies. The end of the controlled burn season advances by approximately 17 to 24 days under RCP2.6 at 1.5°C and by up to 24 days under RCP8.5 (Table 4). While these shifts are smaller than those projected for Australia, they still represent a meaningful change that is likely to affect spring and early summer management. Concurrently, a lengthening fire season and a contraction of the Low to Moderate fire danger period may increase pressures on firefighting capacity, recruitment, and workforce wellbeingThe USA also sees advancement in the end-of-controlled burn season by approximately 17–24 days under RCP2.6 at 1.5°C and up to 24 days earlier under RCP8.5 (Table 4). These changes, while less dramatic than in Australia, mark a significant adjustment likely to impact spring/summer management practices. Increased length of the fire season and decreased length of the Low-Moderate season may also, like Australia, need to be factored into firefighting recruitment and wellbeing (O'Brien and Campbell, 2021). Efforts to reduce human ignitions, particularly in the wildland–urban interface, could further alleviate fire risks, given that many large fires originate from human activities. As in Australia and Brazil, the reduced dominance of individual meteorological drivers under warming suggests that fire management strategies based on single thresholds may become less effective, increasing the importance of integrated, season-scale planning.~~

Across all three regions, even at the highest warming levels, distinct periods of low ~~-fire weather~~~~FW~~fire weather in winter remain (Figure 1 and Figure 7). These retained low-fire periods provide strategic windows for resource planning, but the consistent advancement of season-start dates demonstrates an increasing need for earlier shifts for pre-season preparation within fire season firefighting and management as global temperatures rise. Projections indicate consistent increases in both High and Very High fire weather~~danger~~ days with each level of warming, with the most substantial shifts seen in Australia and Brazil. The slight but significant projected increases in the Severe and Extreme categories, particularly in Australia, reflect a growing likelihood of extreme fire events ~~requiring~~ that will require enhanced firefighting and emergency response capacities – though simulation evaluation of time in the S~~s~~evere+ categories suggests more work is needed before we can be confident in these increases. By focusing on region-specific dynamics, preparing for extended fire seasons, and adapting controlled burn strategies to account for earlier season dates and potentially longer ~~periods of control burn season length~~control burn seasons, fire management practices may be optimised to minimise the impacts of intensifying fire risks.

Globally, longer-term strategies, such as sustainable forest and land management practices that prevent deforestation or conserve wetland areas should align with mitigation goals and contribute to building resilience to rising fire weather risks. Building wildfire-adapted communities, particularly in regions where fire intersects with human infrastructure, can reduce fires' social and economic impacts when they do occur. Fire management focused on strategic planning and prevention will be critical in managing fire risks across diverse fire-prone regions (UNEP et al., 2022) for example, improving fire detection systems, supporting research into fire-resistant landscapes, pre-season preparation and fuel management, and enhancing rapid-response capabilities. This will require dedicated, long-term investment.

~~Here, we take a novel approach by also quantifying uncertainty in future projections using a Perturbed Physics Ensemble (PPE) of HadCM3C. Although the Perturbed Physics Ensemble (PPE)PPE of HadCM3C captures considerablesome uncertainty in future fire weather projections by systematically perturbing key model parameters, it does not encompass the full range of plausible or possible outcomes across structurally different climate models. However, the structured nature of the PPE provides key advantages: it allows for a more systematic exploration of parameter-driven uncertainties and offers a more straightforward coupling between model outputs and fire weather indices like the FFDI. Unlike the CMIP multi-model ensemble, which relies on a smaller selection of available models with varying levels of evaluation for fire weather projections, the PPE is based on a single, extensively evaluated climate model. This structured approach helps isolate climate sensitivities relevant to weatherfire risk, which would be harder to disentangle in the more heterogeneous CMIP ensemble.~~

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4.3 Recommendations

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Future studies that incorporate~~ing~~ a broader range of climate models could improve confidence in projections by sampling a wider range of plausible uncertainties and offer ~~, offering~~ more ~~realistic~~ refined estimates of the likelihood of fire-related impacts. ~~In particular, expanding beyond a single-model PPE could help refine fire weatherrisk estimates in regions where fire dynamics are less well understood~~In particular, expanding beyond a single-model PPE could help refine fire weather estimates in regions where fire dynamics are less well understood, although our evaluation, which shows observed time in FFDI categories falling within the ensemble, suggests the PPE is already broad enough in itself.

While the FFDI provides strong sensitivity to temperature and humidity in fuel-abundant ecosystems and has proven very useful for our temperate and tropical focus regions, using multiple fire danger indices in parallel could improve understanding and applicability across biomes. For example, boreal forests may benefit from indices better suited to high-latitude ecosystems, such as the Canadian Fire Weather Index (FWI), while other metrics like the Keetch–Byram Drought Index (KBDI) or the US Energy Release Component (ERC) capture additional aspects of fire danger relevant in specific regions. Applying a suite of indices would help build a more complete picture of future fire risk and reduce reliance on any single metric, representing an important avenue for future research, particularly for studies seeking global coverage~~Using multiple fire weatherdanger indices would help as well. For example, boreal forests would benefit from research that incorporates fire indices better suited to high-latitude ecosystems, such as the Canadian Fire Weather Index (FWI), where the FFDI may be less effective. However,~~ we have shown ~~FFDI~~ to be ~~is a very useful metric for our temperate and tropical focus regions in this study. Comparative, multi-index approaches therefore represent an important avenue for future work, particularly for studies seeking global applicability.recommendation~~. Beyond these established measures, there is also growing interest in machine learning (ML) and AI-based indices (Di Giuseppe et al., 2025), which can integrate diverse meteorological and ecological variables and may improve predictive skill in data-rich regions. Future assessments that benchmark traditional and ML-derived indices across regions could offer valuable insights into the strengths and limitations of each approach, and guide the development of hybrid frameworks that combine physical process understanding with data-driven methods.

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As climate models continue to improve in resolution, future assessments could further refine these projections, linking fire management needs to more specific changes in fire weather across multiple GWLs. Additionally, improving our understanding of meteorological drivers behind regionally tailored fire indices could support more targeted fire management strategies, such as early warning systems. Further research could ~~continue to expand~~expand on our findings and provide useful information for fire managers and responders. In particular, the following areas would benefit from future studies:~~;~~

1. Exploring if and when fire weather might reach a point where fire suppression efforts are no longer effective once there is an ignition i.e. what are the limits of fire suppression capabilities?
2. Which adaptation ~~policies~~ strategies are most effective at reducing risks related to ~~for the~~ projected future fire weather ~~future~~?
3. Developing a deeper and more nuanced understanding of ignition sources and representation of them in fire and climate models
4. Integration of socio-economic factors: Investigating how socio-economic changes, such as population growth, land-use changes, and resource availability, interact with projected fire weather to influence fire risks and management outcomes.
5. Adapting fuel load management strategies: Understanding how changes in controlled burn seasons, influenced by fire weather projections, can be optimised for fuel management while minimising unintended consequences.

~~5.~~6. Co-development of adapted fire management strategies between fire managers, emergency responders and fire scientists

5 Conclusions

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This study demonstrates the profound impact of future climate change on fire weather and emphasizes the importance of both mitigation and adaptation strategies. As global temperatures rise, regions such as Australia, Brazil, and the USA are projected to face longer, earlier, and more intense fire seasons, with Very High fire weather days increasing in frequency and duration. Limiting global warming to 1.5°C could slow the rate of these changes, but even under strong mitigation scenarios, fire weather is expected to intensify, ~~underscoring~~ requiring some level of adaptation~~the need for adaptive measures~~. Fire management strategies should ~~must~~ evolve to address shifts in fire season timing and severity, requiring expanded controlled burn windows, enhanced pre-fire preparations, and landscape management tailored to regional conditions. Ecosystem restoration through reforestation and sustainable land use can help maintain a higher soil moisture, which can reduce an ecosystems susceptibility to fire and have a favourable impact on biodiversity. ~~An increased resilience to fire impacts for the most affected regions could be gained by considering these ecosystem services and considering fire management alongside~~Increased resilience to fire impacts in the most affected regions could be achieved by integrating ecosystem services and fire management with the needs of local communities. Proactive adaptation, coupled with the development of fire weather indices suited to diverse ecosystems, will be essential for managing escalating risks. Ultimately, balancing mitigation to limit long-term impacts with adaptive measures, including ecosystem restoration, offers the greatest potential for protecting biodiversity, infrastructure, and communities in a warming world. Our study is the first to explicitly frame global fire weather projections through the lens of seasonal management timing, highlighting how retained low-fire windows and advancing season starts to reshape opportunities for preparation. This inversion from documenting increases to identifying adaptation pathways provides a new perspective for research and policy.

We argue for dynamic fire management, —an approach that embeds shifting fire seasons, real-time fire weather information and flexible operational windows directly into Integrated Fire Management frameworks. As climate change reshapes when and where fire becomes hazardous, static calendars can no longer keep pace. A dynamic approach ensures that mitigation, preparedness and fuel treatments adapt alongside the changing risk, supporting more effective and climate-aware fire stewardship.

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Appendix

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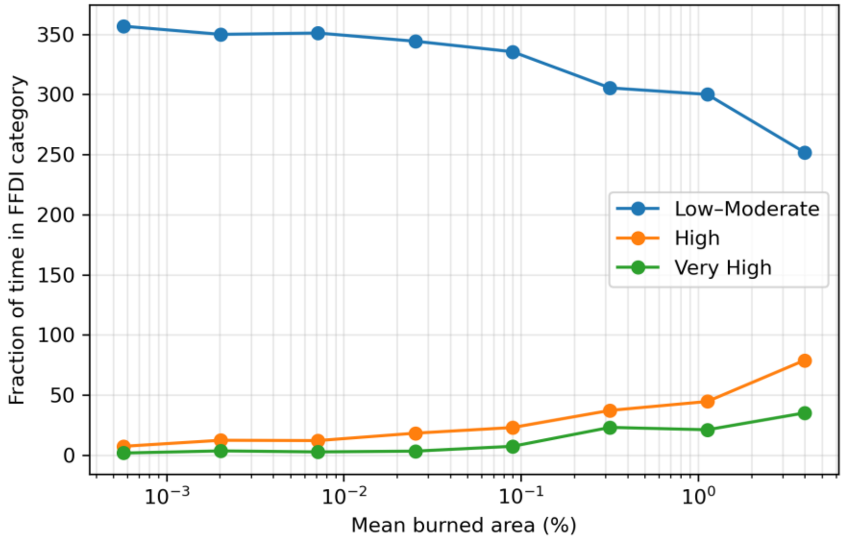

~~Figure~~

Figure A1: Relationship between burned area and time spent in fire weather danger categories. Mean fraction of time spent in each McArthur Forest Fire Danger Index (FFDI) category is shown as a function of mean burned area across grid cells. Burned area is taken from the ESA Fire CCI burned area product (version 5.1), expressed as percentage of area burned. Time spent in each FFDI category is calculated using Copernicus reanalysis meteorology. Burned area values are grouped into logarithmically spaced bins, and lines show the mean fraction of time in each category within each bin.

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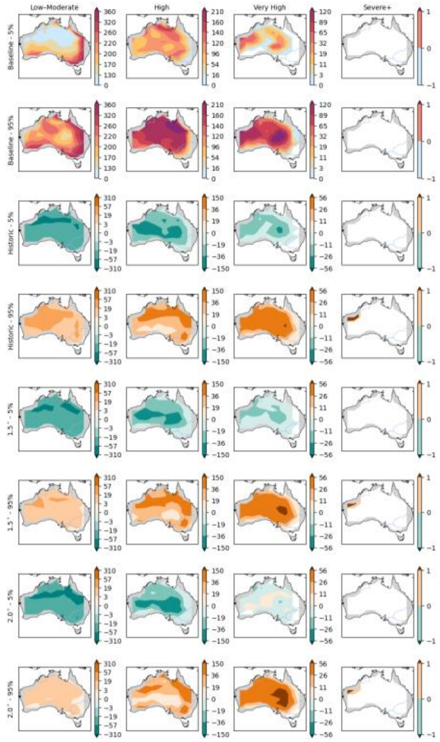

Figure B1: Spatial distribution of the annual number of days in each McArthur Forest Fire Danger Index (FFDI) category across Australia. Rows show (from top to bottom): the baseline period (1986–2005), the recent historical period (2004–2023), and projections at the 1.5 °C and 2.0 °C Global Warming Levels (GWLs) under RCP2.6. For each GWL, uncertainty across the perturbed physics ensemble is represented by paired maps showing the 5th percentile (upper map) and 95th percentile (lower map) of ensemble members. Columns show (from left to right) the number of days in the Low–Moderate, High, Very High, and Severe-or-higher FFDI categories. The baseline period is shown as absolute annual days, while all other panels show changes in the annual number of days relative to the baseline, calculated using paired differences for each ensemble member.

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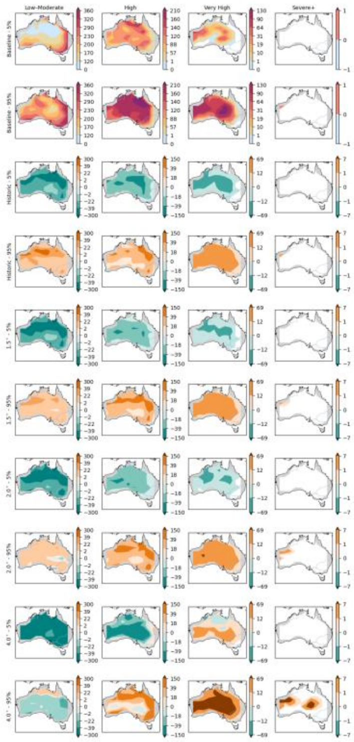

Figure B2: same as figure B1 but for RCP8.5 and including GWL of 4.0 °C

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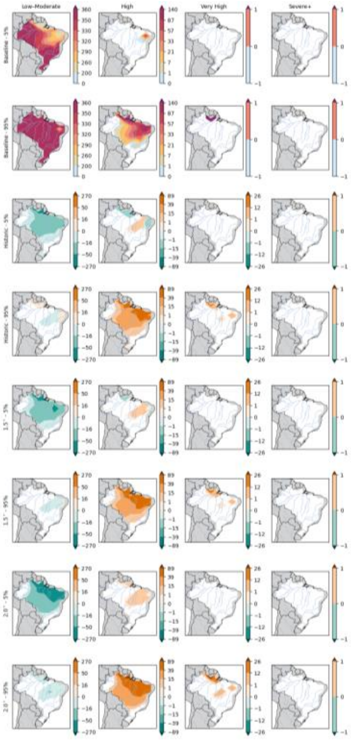

Figure B3: same as figure B1 but for Brazil

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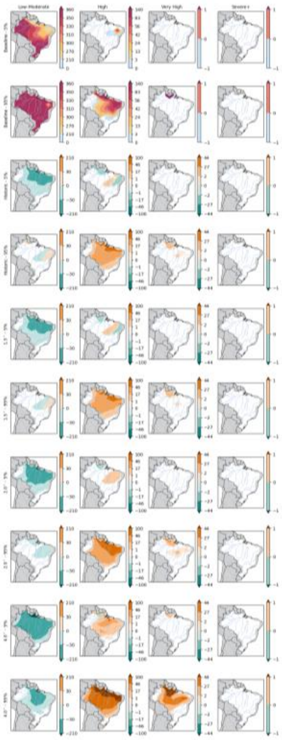

Figure B4: same as figure B2 but for Brazil

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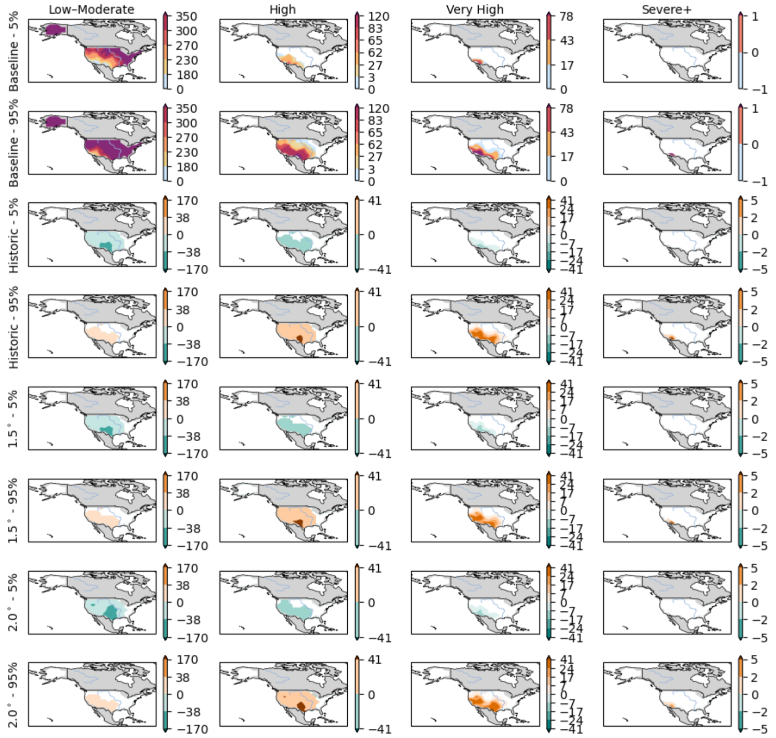

Figure B5: same as figure B1 but for USA

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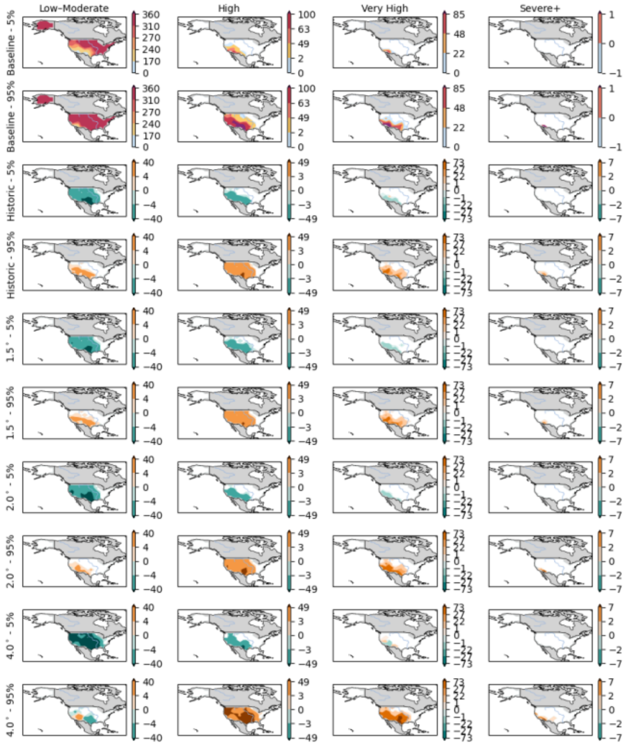

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Figure B6: same as figure B2 but for USA

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Code availability

The code to produce FFDI variables from HadCM3 is available at https://code.metoffice.gov.uk/trac/utils/wiki/fire, with access to Met Office Science Repository Service freely available by registering at http://jules-lsm.github.io/access_req/JULES_access.html.

The code for performing analysis and producing figures and tables is available at doi:10.5281/zenodo.14871362 (Taylor et al., 2025a)~~doi:10.5281/zenodo.14871362 (Taylor et al., 2025a)~~

Data availability

HadCM3 PPE FFDI outputs are available at doi:10.5281/zenodo.14860331 (Taylor et al., 2025b) ~~(Taylor et al., 2025b)~~ for RCP2.6~~-~~ and doi:10.5281/zenodo.14859064 (Taylor et al., 2025c) ~~(Taylor et al., 2025c)~~ for RCP8.5.

Author Contributions

Inika Taylor planned and led the research, analysis and visualisation of results, with input to the experimental design and GWLs analysis framework by Douglas Kelley, Richard Betts and Chantelle Burton. Inika Taylor, Douglas Kelley and Camilla Mathison conducted the analysis and visualisation of results. Andrew J. Hartley analysed and visualised the assessment of the FFDI variables. Karina Williams developed the original model code for calculating the FFDI. Inika Taylor and Douglas Kelley prepared the manuscript with contributions from Camilla Mathison, Karina Williams, Andy Hartley, Richard Betts, ~~and~~ Chantelle Burton and Maria LF Barbosa. Camilla Mathison and Maria LF Barbosa reviewed and edited the draft and final manuscripts.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We extend our sincere gratitude to Camilla Mathison for her exceptional dedication in coordinating co-authors and driving the manuscript forward. Her proactive efforts and commitment were instrumental in preparing this paper for submission.

We acknowledge the use of GrammarlyGO (www.grammarly.com) and ChatGPT-4 (https://chatgpt.com/) to identify improvements in language use and writing style only.

Financial support

This work and its contributors (Inika Taylor, Andy Hartley, Richard Betts, Chantelle Burton, Camilla Mathison and Karina Williams) were funded by the Met Office Hadley Centre Climate Programme (MOHCCP) and the Climate

Science for Service Partnership (CSSP) Brazil project, both of which are supported by the Department for Science, Innovation & Technology (DSIT).

Douglas I. Kelley and Maria L. F. Barbosa were~~as~~ supported by the Natural Environment Research Council as part of the LTSM2 TerraFIRMA project.

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