Reviewer 2

We thank the reviewer for their careful and thoughtful comments. Their feedback has helped us substantially improve the manuscript. Due to the very extensive and detailed revisions made throughout the manuscript, we have not reproduced every change here; the track-changes version provides a full record of all modifications.

This study investigates projected changes in fire weather, focusing on the Forest Fire Danger Index (FFDI) across three distinct regions: Australia, Brazil, and the USA. While the authors conduct several types of analyses, the overall novelty of the work is somewhat limited. Nevertheless, I am not necessarily opposed to this; the methods and analyses are sound, data sets are public, which I appreciate. However, the study needs to present more specific insights. As the title suggests, the main focus lies in understanding future fire weather changes and potential mitigation strategies. In my opinion, there is potential to deepen this focus. Below are some of the main issues and suggestions on how to address them.

We thank the reviewer for their suggestion to deepen the focus of some of our analysis. We have made extensive changes to clarify how our work extends beyond existing global and regional fire-weather projections. While many previous studies quantify changes in fire-weather indices under future climate scenarios, they generally focus on overall increases in index values or extremes. In contrast, our study is the first to examine projected changes in fire danger across the full fire season, explicitly separating the main fire season, shoulder/transition seasons, and the off-season. This approach allows us to assess not only how much fire weather will change, but also when and under which conditions fire management actions, such as controlled burns, preparedness activities, and recovery, can be carried out.

This framing of fire-weather changes from a fire management perspective represents a novel contribution. It moves the discussion from purely documenting increases in fire risk toward providing actionable insights for adaptation and mitigation strategies. By quantifying changes in both **seasonal timing and extent**, we highlight shifts in management windows that have not previously been systematically explored at global or regional scales.

In addition, the methodological novelty further strengthens the study. We combine:

1. A Perturbed Physics Ensemble to capture parametric uncertainty,
2. Analysis across three Global Warming Levels (1.5°C, 2°C, 4°C), and
3. Multiple emissions scenarios for each GWL,

to provide a comprehensive assessment of uncertainty. These elements, together with our full-season FM lens, ensure that the study provides more than a replication of prior work: it offers the next step towards policy-relevant, practically useful perspective on how future fire-weather changes intersect with fire management planning.

Though we also agree with the reviewer that replication and independent confirmation of fire-weather projections is important in climate science. Even where our results align with previous studies, the added value lies in the **management-oriented framing and comprehensive uncertainty quantification**, which are essential for informing both mitigation benefits and adaptation strategies.

Introduction:

As the first reviewer already pointed out, the study lacks a clearly defined research gap. Given that it compares three climatically and geographically diverse regions, there is an inherent strength in highlighting region-specific mitigation strategies and identifying similarities and differences based on local conditions. However, the current text remains too broad and reads more like a general overview. I recommend restructuring the introduction to clearly define the research gap and then justify the choice of focusing on Australia, Brazil, and the USA.

Thank you for the comment. We have now restructured the Introduction according to the Reviewer's suggestion, with the research gap near the beginning, followed by region-specific details, and finishing with how the PPE is used here for the first time with the FFDI to give new insights into future fire weather projections for management.

In addition, existing other FFDI products and the state of the art should be summarized, with a clear explanation of how the Perturbed Physics Ensemble approach can yield new insights.

We have added the following to the discussion:

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. Beyond these established measures, there is also growing interest in machine learning and AI-based indices (e.g. McNorton 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.

Methods:

There is considerable repetition between the justification provided in the introduction and the methods section. This could be streamlined. The methods section should focus on technical clarity. Important technical details—such as the spatial resolution of the datasets, software used to estimate the FFDI, and other relevant aspects should be added.

We have streamlined the Methods section to reduce repetition with the Introduction and improved the description and flow of key technical details, including spatial resolution, FFDI calculation procedures, software used, and ensemble design. These revisions clarify the methodological approach while keeping the focus on reproducibility and technical clarity See response to a similar point made by reviewer 1.

Results and Figures:

While the study claims to focus on three specific regions, only global-scale maps are shown. This is a missed opportunity. To align with the paper's stated goals, I strongly recommend including detailed regional breakdowns, for instance zoom-ins on Australia, Brazil, and the USA, particularly where changes in FFDI are most significant. Instead of clipping results only to non-burnable land, including hotspots of burnable land (e.g., using a proxy for fuel loads) could make the recommendations more specific.

We thank the reviewer for this suggestion. In response, we have added detailed regional maps for Australia, Brazil, and the USA in the Appendix (Figures B1–B6), showing the spatial distribution of annual FFDI days across all categories for baseline, historical, and future Global Warming Levels, along with ensemble uncertainty (5th–95th percentiles). These figures are now extensively referenced throughout the Results, providing regional context, highlighting burnable land hotspots, and allowing readers to examine patterns at the scale of the study regions.

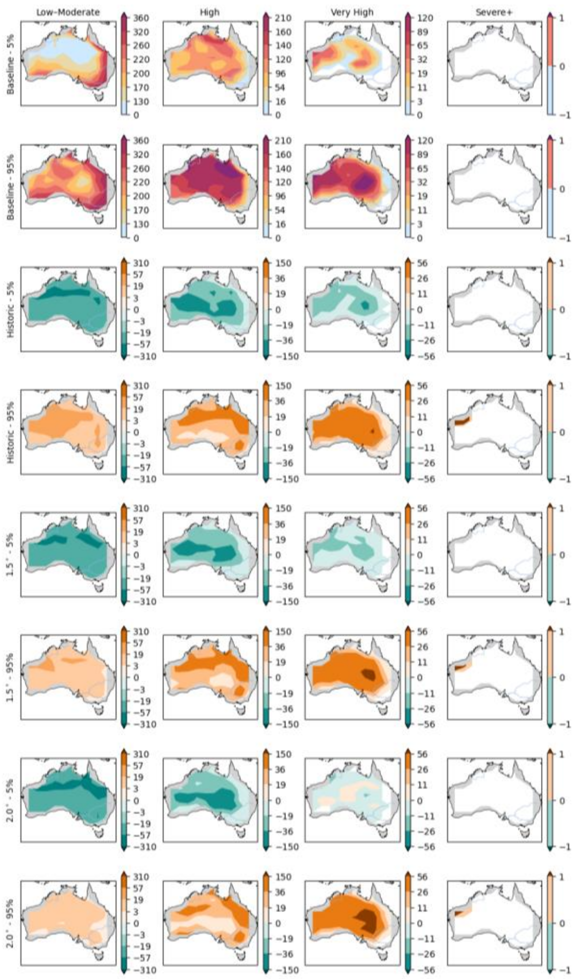

Figure B1: Spatial distribution of the annual number of days in each McArthur Forest Fire Danger Index (FFDI) category across Australia. Rows show (from top to bottom): the baseline period (1986–2005), the recent historical

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.

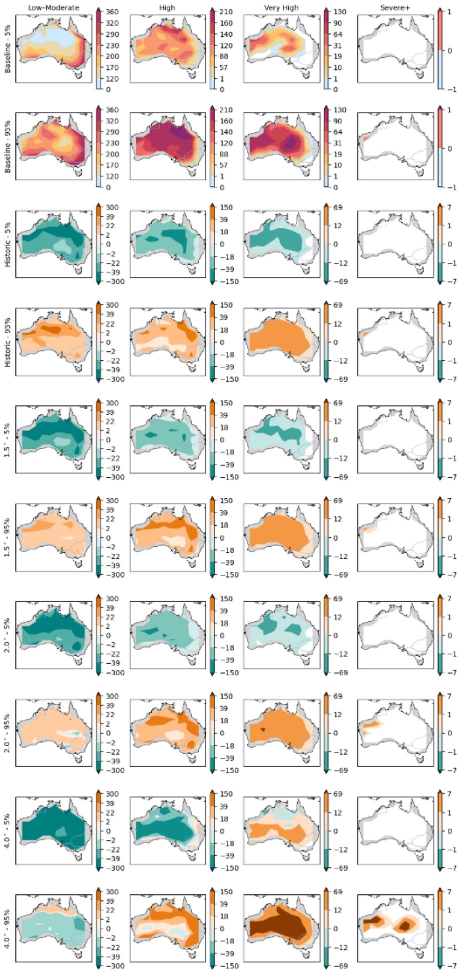

Figure B2: same as figure B1 but for RCP8.5 and including GWL of 4.0 °C

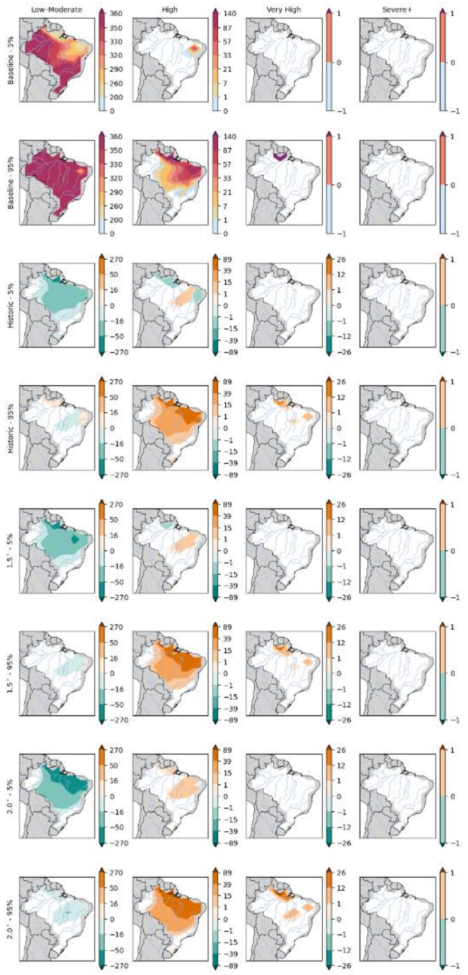

Figure B3: same as figure B1 but for Brazil

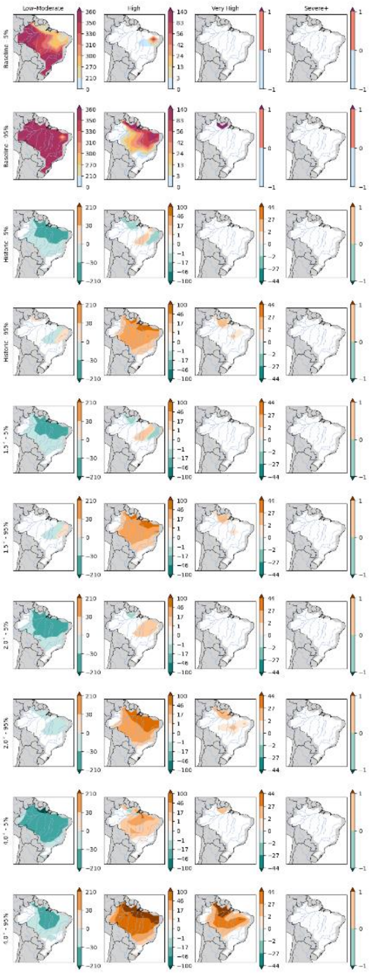

Figure B4: same as figure B2 but for Brazil

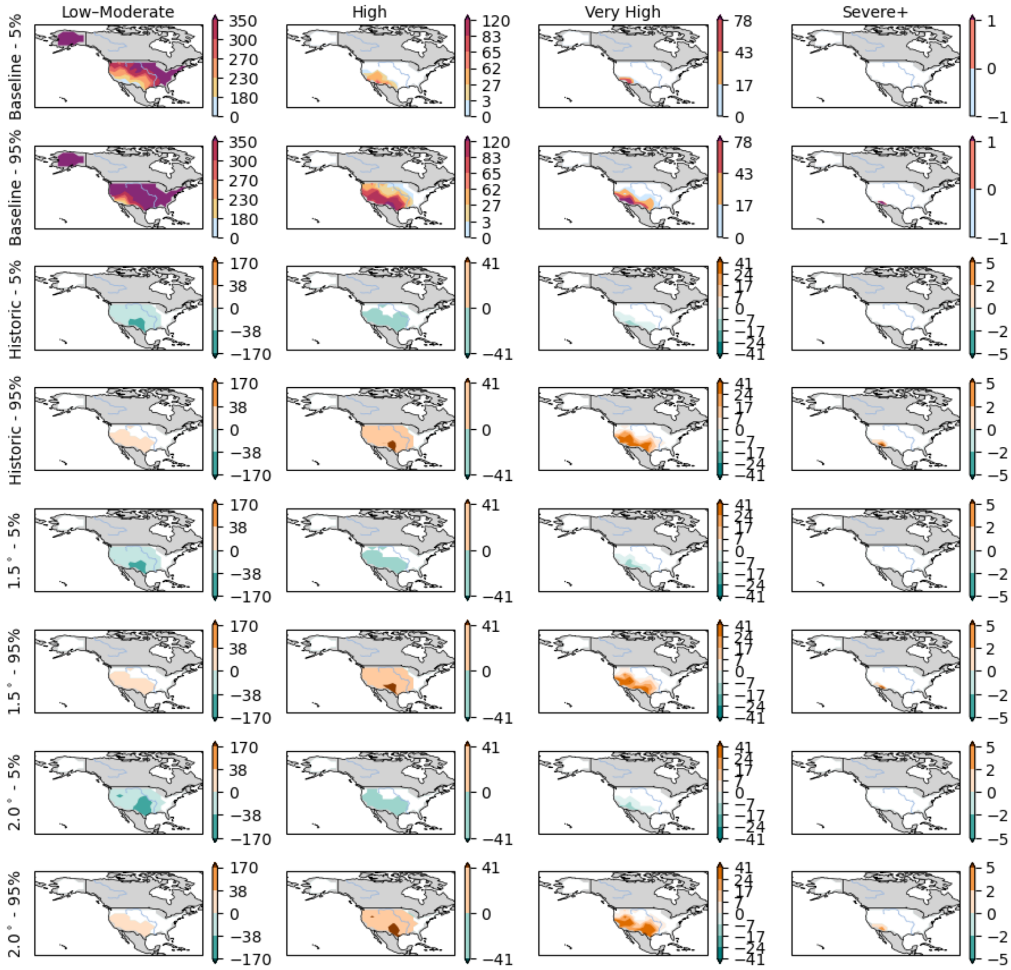

Figure B5: same as figure B1 but for USA

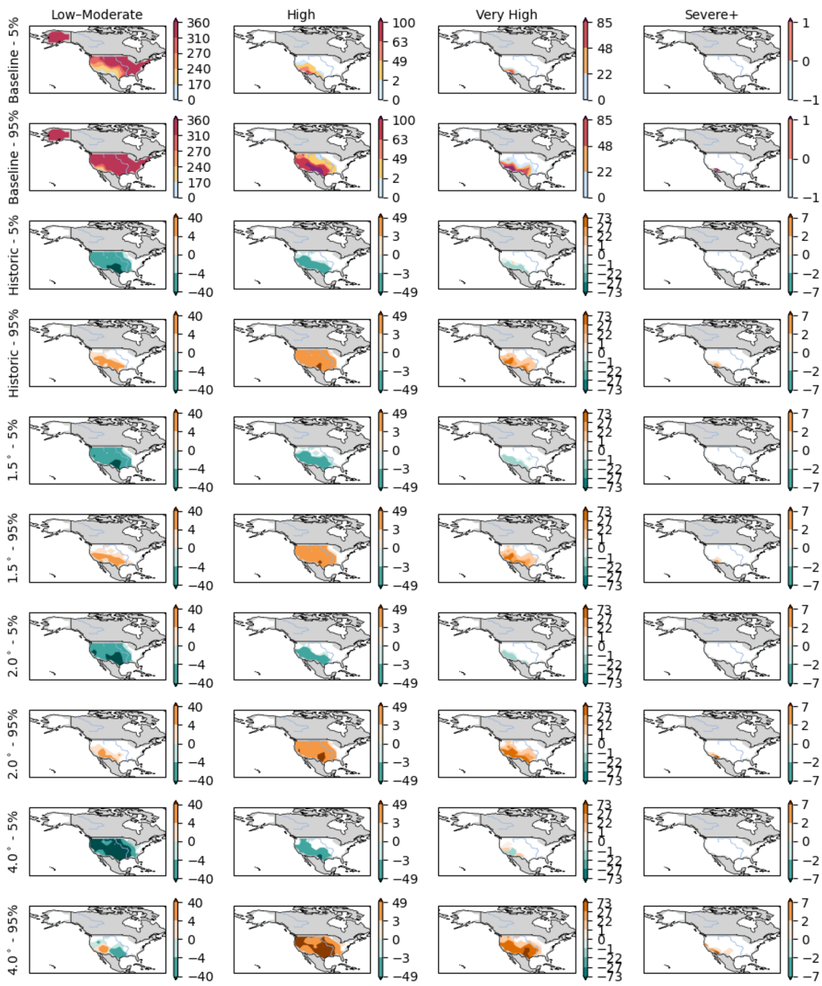

Figure B6: same as figure B2 but for USA

These are now discussed extensively in the results:

We also evaluate projected changes in the spatial distribution of time spent in different FFDI categories across Australia, Brazil, and the USA (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.*

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.

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.

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.

In the USA, 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.

Figure 5 stands out as the most promising in terms of offering new insight into mitigation potentials. It would be valuable to expand this part of the discussion.

We thank the reviewer for highlighting the potential of Figure 5. In the revised manuscript, we have redone Figure 5 with the Random Forest (RF) analysis, which provides a more robust and interpretable assessment of the meteorological drivers of FFDI under future warming. This approach allows us to link changes in fire-weather risk directly to underlying variables, thereby strengthening the discussion of mitigation potentials. As noted in our response to Reviewer 1, the RF analysis emphasizes how and why fire-weather risk changes with warming, providing a clearer basis for management-relevant insights and the implications of mitigation.

Figure 5 shows the relative importance of meteorological drivers contributing to FFDI variability for Australia, Brazil, and the USA, estimated using RF models for baseline conditions and for a GWL of 4 °C. Across all regions, relative humidity, 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 GWL4, all regions exhibit a consistent reduction in the relative importance of 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 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 relative humidity, temperature, and wind importance declining substantially (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 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 significant (t-test <0.001) for all regions and for baseline and 4°C warming.

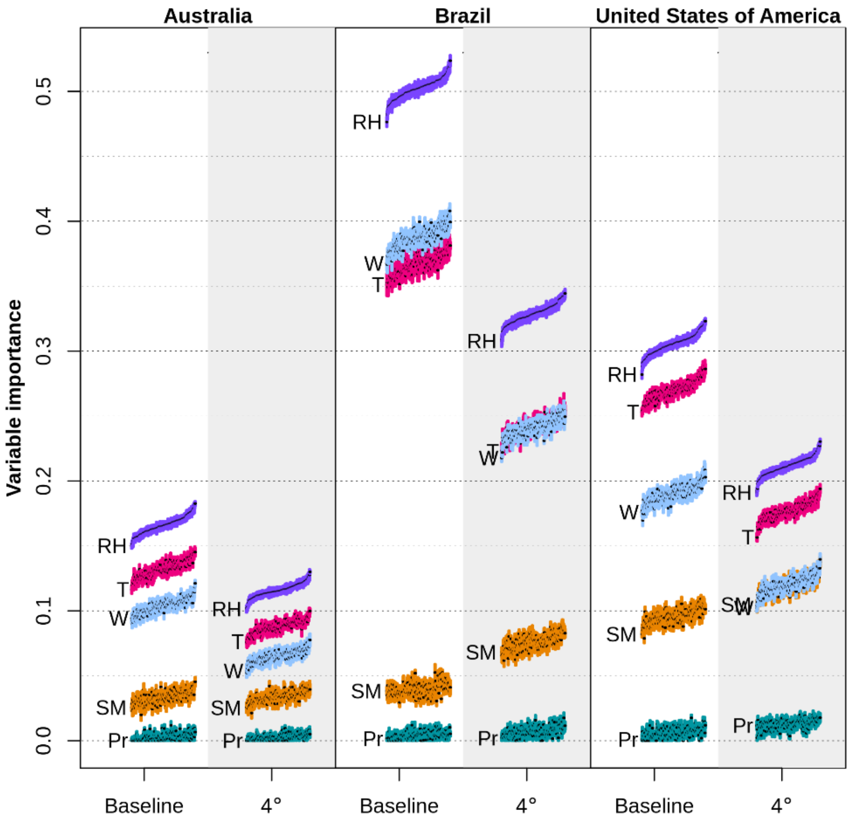

Figure 5: *Relative variable importance of meteorological drivers contributing to the Fire Forest Danger Index (FFDI), derived from random forest models, shown for (left to right) Australia, Brazil, and the USA. For each region, results are presented for baseline conditions (1986–2005; left column within each panel) and for a Global Warming Level (GWL) of 4 °C (right column). The variables are Relative Humidity (RH), 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 the estimated means and their spread.*

Figure 6 shows that several extreme years are expected in the future. This deserves a closer look: what do these extremes look like regionally? Which areas are most at risk? It would be useful to analyze a few “what-if” scenarios more deeply—especially if the PPE approach allows a better understanding of tail risks than traditional GCM ensembles.

Figure 6 does highlights the emergence of years with exceptionally high fire weather conditions under future warming, and we agree that understanding the nature of these extremes is important. In response to this comment, we have strengthened the manuscript in two ways.

First, throughout the Results section we now describe how the distribution of peak-season FFDI shifts with warming, focusing on changes in the range and upper bounds of the likely (90% confidence range) fire weather conditions during the core fire season at both global and regional scales.

Second, we have added discussion text explicitly addressing the interpretation of extremes in the context of a Perturbed Physics Ensemble (PPE).

However, while the PPE samples a wide range of plausible climate model parameterisations, it is not designed to represent stochastic variability or event probabilities in the same way as impact-focused or Bayesian inference frameworks. As such, PPE members should not be interpreted as probabilistic "tail risks" of extreme wildfire events, but rather as bounding the sensitivity of fire weather outcomes to structural and parametric uncertainty in the climate system.

Formal assessment of tail risks and "what-if" scenarios for extreme wildfire impacts typically requires frameworks that explicitly link parameter perturbations to fire outcomes using observational constraints, and often stochastic representations of residual uncertainty (e.g. Kelley et al., 2021; Burton & Lampe et al., 2024). These approaches are powerful but involve additional assumptions, data, and modelling complexity that are beyond the scope of a single study.

We therefore frame the PPE results as identifying regions and seasons where plausible climate states lead to substantially elevated fire weather conditions, highlighting areas of heightened concern rather than predicting the likelihood or precise manifestation of individual extreme wildfire events.

Discussion:

The discussion begins to touch on relevant points but currently lacks depth. The section on the different regions holds the most promise in my opinion, but the latter part feels somewhat half-hearted, especially where it lists potential future research questions without any explaining how this study contributes to solving them.

We thank the reviewer for this feedback. In response, we have strengthened the discussion around Integrated Fire Management (IFM), highlighting how our findings—particularly the full annual-cycle projections of fire danger—can inform seasonally adaptive strategies in different regions:

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 (Pandey et al., 2023). Despite this variability, a consistent pattern emerges across all regions. Under strong warming, the relative influence of individual meteorological drivers on fire weather declines, reflecting an increasing role for compound fire-weather conditions rather than the dominance of any single variable.

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 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 (Barbosa et al., 2022b), and preventing fragmentation of riparian zones (Ferreira et al., 2023)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 increases by 4 ºC.*

Large, destructive fires play a critical role in shaping fire regimes in fire-sensitive regions of Brazil, often accounting for a substantial portion of seasonal burned area (Flannigan et al., 2016). Our projected increase in fire weather days in these regions 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 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).

Evidence also shows that controlled burns reduce 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 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 nearly a month at 4°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, 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), and strengthening early warning systems that monitor key meteorological variables (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 5). At 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 services (Russell-Smith et al., 2020). Shifting the timing of policies aimed 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°C warming, potentially increasing firefighter fatigue and reducing public compliance over time (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).

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, 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 5). 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 wellbeing (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 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 in winter remain. 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 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 that will require enhanced firefighting and emergency response capacities – though simulation evaluation of time in the severe+ 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 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.

At the same time, we have clarified the scope of our study: while providing a coarse, globally consistent assessment of fire danger across three regions, our results are not intended to provide highly detailed local management prescriptions. We have added in the discussion an explicit acknowledgement of this trade-off, and to frame the suggested future research questions as opportunities to build on our findings rather than as gaps left unaddressed by this study (under discussion section 4.3, recommenations):

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 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 policies are most effective for the projected 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.

General:

All in all, I share many of the concerns raised by reviewer 1, particularly regarding consistency in terminology and the lack of depth in the analysis. However, I still believe the study could make a valuable contribution once the text is improved and the novel aspects are clarified.