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Changes in fire weather climatology under 1.5 °C and 2.0 °C warming

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Abstract

The 2015 Paris Agreement led to a number of studies that assessed the impact of the 1.5 °C and 2.0 °C increases in global temperature over preindustrial levels. However, those assessments have not actively investigated the impact of these levels of warming on fire weather. In view of a recent series of high-profile wildfire events worldwide, we access fire weather sensitivity based on a set of multi-model large ensemble climate simulations for these low-emission scenarios. The results indicate that the half degree difference between these two thresholds may lead to a significantly increased hazard of wildfire in certain parts of the world, particularly the Amazon, African savanna and Mediterranean. Although further experiments focused on human land use are needed to depict future fire activity, considering that rising temperatures are the most influential factor in augmenting the danger of fire weather, limiting global warming to 1.5 °C would alleviate some risk in these parts of the world.

1. Introduction

While climate-driven wildfire hazard varies under different global warming scenarios, the increase of climate extremes conducive to wildfires, such as heatwaves and droughts, is a universal and inevitable outcome of anthropogenic climate change. Globally, widespread wildfires have intensified and are occurring more frequently than before (Moritz *et al* 2012, Seidl *et al* 2017), with climate overtaking human activity as the dominant influence on fire in some regions (Vachula *et al* 2019). Modeling results show that anthropogenic climate change is already causing fire weather conditions in excess of natural variability in certain areas (Abatzoglou *et al* 2019). This trend is driven primarily by rising temperatures (Pechony and Shindell 2010) and has had a particularly profound impact on western North America and Australia (Jolly *et al* 2015, Yoon *et al* 2015). Previous modeling studies have also warned that fire weather conditions would become more extreme under climate change (Liu *et al* 2010, Eliseev *et al* 2014, Bedia *et al* 2015, Abatzoglou *et al* 2019). However, fire activity is not driven by fire weather alone, but also by the influenced of anthropogenic factors, such as demographic and socio-economic changes (Andela and Van Der Werf 2014, Bistinas *et al* 2014). For instance, the expansion of agricultural land in forest regions can increase fire activity, while decreasing such activity in semi-arid savannah regions. It is also important to note that fire model projections which do not properly reflect the human influences may overestimate future fire activity (Andela *et al* 2017). Nevertheless, the long-term trend of increasing fire activity under global warming may not be reversed, but rather accelerated, as a result of the reversal of land conversion and declining populations (Pechony and Shindell 2010).

Under the Paris Agreement, the United Nations Framework Convention on Climate Change agreed to pursue efforts to limit the temperature increase to 2.0 °C and, ideally, to 1.5 °C, over preindustrial levels. Most of previous studies, however, were designed to look at the impact of extreme emission scenarios, rather than the specific and relatively moderate warming levels that global societies are attempting to achieve. It is difficult to distinguish between model uncertainty and internal variability under representative concentration pathway (RCP) scenarios (Mitchell *et al* 2016), so the Intergovernmental Panel on Climate Change (IPCC) compiled a special report examining the potential effects under these moderate targets (Pörtner *et al* 2019), which led to the half a degree additional warming, prognosis and projected impacts (HAPPI) project, a focused modeling database intended to facilitate the study of extreme weather events under moderate warming (Mitchell *et al* 2017). Subsequent studies using HAPPI have delineated potential changes in climate extremes including drought (Lehner *et al* 2017), heatwaves (Wehner *et al* 2018), and hydrological cycles (Madakumbura *et al* 2019) for the respective 1.5 °C and 2.0 °C thresholds. All of these factors are known to affect wildfire occurrence and intensity, but fire weather conditions have not been specifically and comprehensively explored with the HAPPI experiments. Although a similar assessment of fire weather with RCP8.5 has been discussed (Sun *et al* 2019), the documented difference in climate responses among different RCP scenarios limits the assessment of warming impacts (Mitchell *et al* 2016). Thus, this study was conducted to examine potential changes in fire weather conditions under 1.5 °C and 2.0 °C warming levels using the HAPPI database, and to evaluate the change in wildfire hazard associated with a half a degree of additional warming (HADAW).

2. Data and methods

2.1. Model simulation data

We analysed the simulations from five HAPPI models, each with 100 ensemble members: CAM4 (Neale *et al* 2013), CanAM4 (Von Salzen *et al* 2013), ECHAM6 (Stevens *et al* 2013), MIROC5 (Watanabe *et al* 2010) and NorESM1 (Debernard *et al* 2013). The model outputs include three sets of experiments of a 10 year period: present (observed, 2006–2015), 1.5 °C warmer (RCP2.6, 2106–2115) and 2.0 °C warmer (weighted combination of RCP2.6 and RCP4.5, 2106–2115).

2.2. Fire Weather Index

The Fire Weather Index (FWI), was originally derived from the Canadian forest fire danger rating system (Stocks *et al* 1989), to estimate fire weather conditions. A popular indication for fire weather, FWI involves five different indices related to fire ignition and intensity and it considers four near-surface meteorological variables: temperature, relative humidity, wind speed and last 24 h accumulated precipitation. Fuel Moisture Codes, such as Fine Fuel Moisture Code, Duff Moisture Code and Drought Code, track moisture changes in different layers of the forest floor alongside changes in weather. These variables are used to calculate the Initial Spread Index (ISI), which represents the potential rate of spread, and the Build-Up Index (BUI), which estimates the total fuel available for consumption. Finally, FWI is derived from a weighted combination of ISI and BUI to describe potential fire occurrence and intensity. FWI has been widely employed to measure wildfire hazard across the globe and it has been shown to have a close relationship with burned area and fire frequency (Bedia *et al* 2015, Abatzoglou *et al* 2018, Fox *et al* 2018). Although there is not a unified FWI threshold to explain extreme wildfire conditions worldwide, previous studies have highlighted the association between high values of FWI and extreme fire activities (Urbieta *et al* 2015, Bowman *et al* 2017, Goss *et al* 2020). Following those studies, we use the 90th percentile of FWI on each model grid to demarcate extreme fire weather conditions.

2.3. Bias correction

Before one can estimate extreme fire weather conditions using FWI, biases of each model need to be corrected. Here, we adopted the Japanese 55 year Reanalysis (JRA55) (Kobayashi *et al* 2015) and followed a published bias correction method (Maraun 2016). The daily climatology of the model outputs is replaced with the JRA55's for temperature and humidity using equation (1). For precipitation and wind speed showing only positive values with distribution skewed to zero, a log transformation is executed before applying equation (1), hence simplifying the computation in equation (2),

$$\mathrm{Model_{correct}} = \mathrm{Model} - \mathrm{Model\_Hist_{clim}} + \mathrm{JRA_{clim}}. \tag{1}$$

$$\mathrm{Model_{correct}} = \mathrm{Model} \div \mathrm{Model\_Hist_{clim}} \times \mathrm{JRA_{clim}}. \tag{2}$$

In these equations, Model (Model_Hist) represents the historical simulations from the HAPPI models, which is applied separately for each model. The subscript clim and correct mean 'climatology' and 'corrected results,' respectively. Next, to avoid inconsistencies between different warming scenarios, which may potentially induce underestimated FWI, we further applied the delta change approach correction (Maraun 2016) for the sensitivity analysis. This step is similar to the previous formulations, but the anomaly of present climate is added or multiplied on the climatology of each warming condition; these are summarized by equations (3) and (4).

$$\text{Sensitive} = \text{Future}_{\text{clim}} + (\text{Present} - \text{Present}_{\text{clim}}). \quad (3)$$

$$\text{Sensitive} = \text{Future}_{\text{clim}} \times (\text{Present} \div \text{Present}_{\text{clim}}). \quad (4)$$

Here, Sensitive represents sensitive components in the sensitivity analysis ($\Delta \neq 0$), Future is for the 1.5 °C warmer and the 2.0 °C warmer scenarios (2106–2115) and Present represents all simulated results from the present scenario (2006–2015). This is applied separately for each scenario of each model. For wind speed, we modified equation (4) for conditions that demonstrate too high of a correction rate for low values in the denominator of equation (5):

$$\begin{aligned}
&\text{if } \text{Present}_{\text{clim}} < 1,\\
&\quad \text{Sensitive} = (\text{Future}_{\text{clim}} + 1) \times (\text{Present} + 1)\\
&\qquad\qquad \div (\text{Present}_{\text{clim}} + 1) - 1\\
&\text{else},\\
&\quad \text{Sensitive} = \text{Future}_{\text{clim}} \times (\text{Present} \div \text{Present}_{\text{clim}}).
\end{aligned} \quad (5)$$

2.4. The masking of arid areas

Arid areas and polar regions have few plants and are classified as 'Barren or Sparsely Vegetated', 'Open Shrublands' and 'Permanent Snow and Ice' (Friedl *et al* 2010) (figure S1(a) (available online at stacks.iop.org/ERL/16/034058/mmedia)). Even when fire-prone climate appears in such areas, the probability of fire occurrence is low due to the lack of fuel. However, the changes of the fire weather conditions in these barely vegetated areas, such as those in the Sahara Desert and Australian deserts, are not negligible. Therefore, we use the enhanced vegetation index (EVI) from the Moderate Resolution Imaging Spectroradiometer Land Discipline Group (Huete *et al* 1999) and define the approximated masking areas as those with a mean value of EVI that is less than 0.12 (figure S1(c)). This definition leads to a coverage that is in good agreement with figure S1(a). We note that such approximation may oversimplify the precipitation effect by climate change and ignore the changes in some arid areas. However, our study is mainly focused on general fire weather changes based on the IPCC AR5 regions (figure 1(f)), and the change in boundary zones is omitted. (All results in our study are derived on land.)

2.5. The fraction of attributable risk

To investigate the distribution of regional extreme wildfire danger, we spatially average FWI for the regions shown in figure 1(f). The regional FWI is compared among the warming scenarios for the top 0.1 quantile. We then use the fraction of attributable risk (FAR) to quantitatively compare the changes in the distribution of wildfire hazard (Stone and Allen 2005). The FAR is calculated by equation (6) with the probability of exceedance (P) of 0.9 quantile obtained from the present condition.

$$1 - P_{\text{present}} \div P_{\text{future}}. \quad (6)$$

This explains the changes in the probability of extreme fire weather that is attributable to the external forcing from the current state. For instance, if FAR is 0.2, then it indicates that the warming-induced event probability has increased 25% over natural causes. Thus, the higher value of FAR the higher probability of a fire hazard.

2.6. Sensitivity analysis

For each of the factors leading to fire weather, such as the maximum temperature, relative humidity, precipitation and wind speed, the changes in FWI are individually compared according to the future warming scenarios (figures 3 and S6–S9). For instance, when the sensitivity of the fire weather is examined with respect to the maximum temperature, only the maximum temperature is changed according to the warming levels, while the other variables are preserved as the present conditions. Here, we introduce an additional correction to remove any complication due to mismatching of meteorological parameters. For example, simply using a precipitation time-series from the future and others from the present could produce peculiar values. This additional bias correction is important for rainy and humid days, as the potential inconsistency between present and future variables may result in an underestimation of FWI. We then compared the relative contribution of each component. However, the globally averaged difference in FWI for the additional correction is less than 2.5% and the regions with greater difference mostly show high sensitivity on humidity and precipitation (figure S15).

3. Results

3.1. Annual mean changes

The annual mean of FWI, as shown in figures 1(a) and (b), reveals that the higher the temperature becomes in a particular region, the greater the fire weather in that region. By comparing the present day FWI with the 1.5 °C and 2.0 °C warming levels (figure 1(c)), it can be seen that the increased wildfire hazard associated with a HADAW is nearly equivalent to the increased FWI between present warming and the 1.5 °C threshold worldwide (figure 1(a)), with the exception of Oceania (which includes Australasia, Melanesia, Micronesia and Polynesia; discussed later).

By calculating the FAR for extreme fire events (those in the top 0.1 quantile of FWI values), we found that the global-mean of FAR for extreme events reaches 0.32 in the 1.5 °C scenario and 0.47 in the 2.0 °C scenario (figure 1(d)), with the most striking

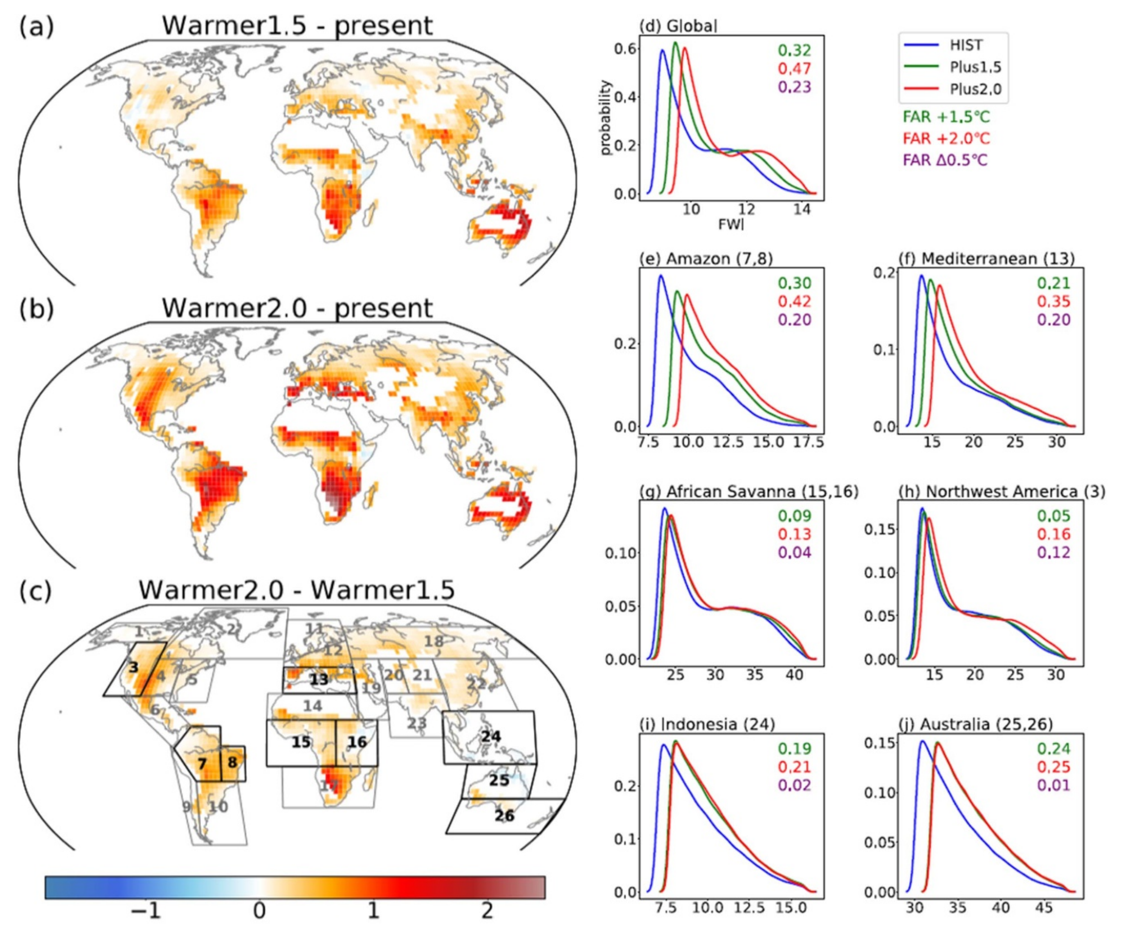

Figure 1. (a)–(c) Annual mean difference of FWI: (a) from 1.5 °C warmer scenario to present (2006–2015), (b) from the 2.0 °C to the present and (c) from the 2.0 °C to the 1.5 °C. Arid areas (shown in the figure S1(c)) and insignificant results ($p > 0.01$) are masked. (d)–(j) Kernel density estimations of annual mean FWI, spatially averaged based on the IPCC AR5 reference regions (shown in (c), www.ipcc-data.org/guidelines/pages/ar5_regions.html). (d) Global, (e) Amazon, (f) Mediterranean, (g) African savanna, (h) Northwest America, (i) Indonesia and (j) Australia. FAR indicates the fraction of attributable risk for each 1.5 °C (green) and 2.0 °C (red) to P90 (0.9 quantile) in the present and between 1.5 °C and 2.0 °C (purple), respectively. The *y*-axis explains the probability of FWI (*x*-axis).

regional increases in the Amazon basin and Europe, especially the Mediterranean. The spatially averaged FWI over these individual regions (figure 1(c)) shows that the FAR for extreme events under HADAW could rise in increments that could double the difference between the present and the 1.5 °C warming scenario (figures 1(e) and (f)). This is consistent with earlier studies that indicated the potential for increased wildfires in these regions (Engelbrecht *et al* 2015, Ciscar; *et al* 2018, Fonseca *et al* 2019). In western North America and the African savanna, the changes in the top 0.1 quantile range are not discernible and FAR is relatively low at each warming level (figures 1(g) and (h)). However, the FAR in western North America abruptly rises from 0.05 in the 1.5 °C warming scenario to 0.16 in the 2.0 °C scenario, an increase of 0.12 under HADAW. These non-linear relationships suggest that the effect of global warming on wildfire may seem insignificant at first in some regions, but can quickly increase with relatively small rises in temperature. Australia and Indonesia show a comparably small change (less than 0.02) in FWI under HADAW, despite a large rise at 1.5 °C (figures 1(i) and (j)). This 'levelling off' of HADAW, however, may be only temporary and, if warming is not limited to 2.0 °C, the fire danger may become even more extreme in those regions (Liu *et al* 2010).

3.2. Changes in seasonal mean

Regional wildfire activity has a distinct seasonality (Aldersley *et al* 2011) (figures S2–S5). Figure 2 summarizes the most significant changes of FWI under HADAW by season based on the IPCC AR5 reference regions. The results generally show similar patterns and tendencies to those identified under the analysis of annual means, but with remarkable intensification in different seasons. Most regions in the northern hemisphere, including Europe and Siberia, show the most increase during the boreal summer (June–August, pink box in figure 2). East Asia, however, shows a pronounced increase during the boreal winter (December–February, purple box in figure 2), a season earlier than the observed climatological period with the most frequent fires (Aldersley *et al*

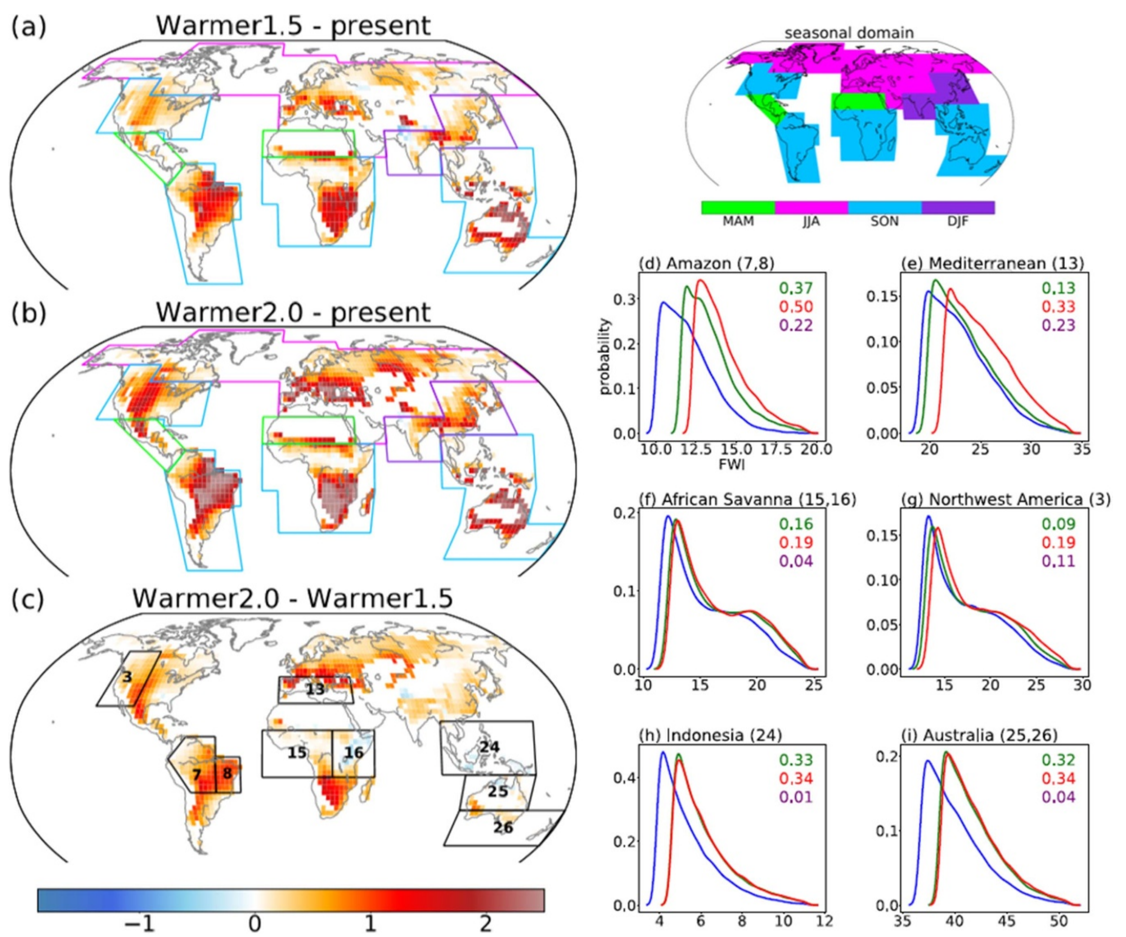

Figure 2. (a)–(c) Seasonal mean difference of FWI during the largest change (separated by four seasons: spring (March - April - May (MAM), green), summer (June - July - August (JJA), pink), autumn (September - October - November (SON), blue), winter (December - January - February (DJF), purple)): (a) 1.5 °C to present (2006–2015), (b) 2.0 °C to present and (c) 2.0 °C to 1.5 °C. Arid areas (shown in the figure S1(c)) and insignificant results ($p > 0.01$) are masked. (d)–(j) Kernel density estimations of seasonal mean FWI, spatially averaged based on the IPCC AR5 reference regions (shown in (c)). (d) Amazon, (e) Mediterranean, (f) African savanna, (g) Northwest America, (h) Indonesia, and (i) Australia. FAR indicates the fraction of attributable risk for each 1.5 °C (green) and 2.0 °C (red) to P90 (0.9 quantile) in the present, and between 1.5 °C and 2.0 °C (purple), respectively. The y-axis explains the probability of FWI (x-axis).

2011). In North America, the biggest increase is in the fall season (as opposed to summer when wildfires have traditionally peaked), suggesting a lengthening of the fire season. In addition, most of the Southern Hemispheric regions, where active wildfire occurs in the boreal summer, show the most outstanding changes during the boreal autumn (September–November, blue box in figure 2), echoing the finding of an extended fire season worldwide (Flannigan *et al* 2013). These HADAW results paint a worrisome picture of increased fire weather conditions associated with relatively small increases in global temperature.

3.3. Fire hazard sensitivity to climate factors

Multiple climate factors play a role in wildfire hazard (figures 3 and S6–S9) and these roles vary in significance from region to region and at different warming projections. In the tropics, changes in humidity and precipitation exhibit a considerable effect on the increase of FWI under HADAW. In the Mediterranean and western North America, changes in wind appear to be negligible, while in the Amazon and Indonesia, the influence of wind is greater than some other factors (table 1). In the subtropics, the increase in temperature dominates the change of FWI more than other factors (table 1 and figures S1–S4), echoing the argument that the rise of temperature is the most influential factor for climate-driven wildfire hazard (Pechony and Shindell 2010). It is worth noting that humidity and precipitation may play different roles in the mid-latitudes. In western North America increases of humidity and precipitation may slightly offset temperature increases (table 1). This finding is not in accordance with historical observations (Abatzoglou and Williams 2016, Holden *et al* 2018), though some analyses did find similar results by accounting for increases in the amount and frequency of precipitation (Flannigan *et al* 2000) and decreases in the number of dry days (Brown *et al* 2004). In the Southern Hemisphere, warmer temperatures and less humidity liaise to increase the danger of wildfire. In the near-term future, humidity may play a role in modulating the wildfire hazard, but this effect appears to be negated by temperature in the

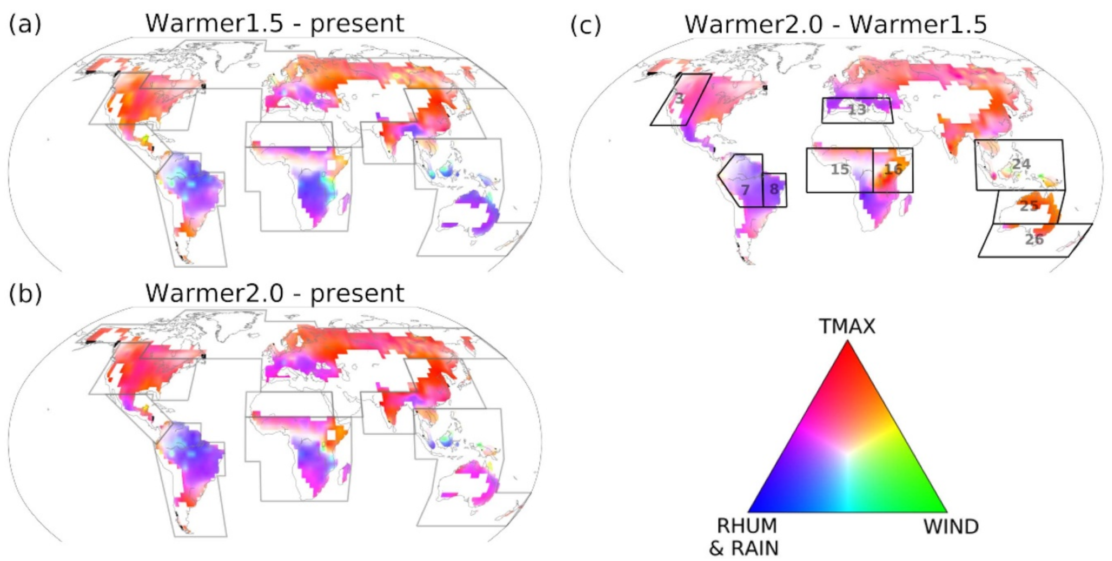

Figure 3. Sensitivity comparison between climate components (maximum temperature (red), relative humidity and precipitation combined (blue) and wind speed (green)) during regionally separated season (same with figure 2, gray boxes): (a) 1.5 °C to present (2006–2015), (b) 2.0 °C to present and (c) 2.0 °C to 1.5 °C. Each component is scaled in range (−0.2 to 1.0). Arid areas (shown in the figure S1(c)) and insignificant results ($p > 0.01$) are masked. FAR of the major AR5 reference regions (shown in (c)) are summarized in table 1.

Table 1. FAR for the individual sensitivity comparison results during regionally separated season (shown figure 3). From present to 1.5 °C (Plus 1.5), to 2.0 °C (Plus 2.0) and from 1.5 °C to 2.0 °C (Additional 0.5) °C are compared in P90 (0.9 quantile, same method with figures 2(d)–(j)). The threshold of the 99% significant level is ±0.012.

Amazon (7, 8)	TMAX	RHUM	Rain	Wind
Plus 1.5	0.07	0.11	0.05	0.11
Plus 2.0	0.12	0.16	0.08	0.11
Additional 0.5	0.05	0.06	0.02	0.00
Mediterranean (13)				
Plus 1.5	0.06	0.04	0.00	0.01
Plus 2.0	0.12	0.11	0.01	0.00
Additional 0.5	0.06	0.08	0.01	0.00
African Savanna (15, 16)				
Plus 1.5	0.07	0.05	0.00	0.01
Plus 2.0	0.12	0.06	−0.01	0.02
Additional 0.5	0.05	0.00	−0.01	0.00
Northwest America (3)				
Plus 1.5	0.08	−0.02	−0.03	0.01
Plus 2.0	0.16	0.02	−0.03	0.01
Additional 0.5	0.08	0.04	0.00	0.00
Indonesia (24)				
Plus 1.5	0.08	0.09	−0.01	0.08
Plus 2.0	0.12	0.10	−0.03	0.08
Additional 0.5	0.04	0.01	−0.02	0.00
Australia (25, 26)				
Plus 1.5	0.09	0.15	0.04	0.05
Plus 2.0	0.16	0.13	0.03	0.04
Additional 0.5	0.07	−0.03	−0.01	0.00

long term. This is the case for Australia and other neighbouring countries impacted by the complexity of the future changes in the Australian monsoon (Chevuturi *et al* 2018).

Given that relative humidity is a function of temperature, we also compare FWI in consideration of both the maximum temperature and relative humidity (figure S10), and the results are similar with the sum of the individual climate factors. Some regions, such as Siberia, China and the Amazon, show higher increases of temperature than each warming level, reaching 3.5 °C in the 2.0 °C warming scenario (figure S11). In the case of humidity and precipitation, changes in the Amazon are more evident than in other regions (figures S12 and S13). In sum, it would appear that none of the evaluated areas can avoid an increased hazard of wildfire, even under the targeted rising temperature goals of the Paris Agreement, HADAW confers considerable additional extreme fire weather risk.

4. Discussion and conclusions

The HAPPI simulations, which target specific warming levels of 1.5 °C and 2.0 °C following the Paris Agreement, project that fire weather conditions will be more extreme worldwide regardless of the warming level. However, suppressing the 0.5 °C additional warming could reduce climate-driven extreme fire activities globally, except for a few areas that seem to reach their peak risk level at an earlier warming state (before 1.5 °C). These areas of accelerated fire hazard include Australia and Indonesia. Given that temperature is the principal factor for fire risk, the inhibition of a half-degree of warming would provide measurable benefits toward a reduction in wildfire likelihood. However, in areas where the risks may already peak, an even stricter target to reduce climate warming would be required.

Although the HAPPI experiments include a large number of ensembles for statistical significance, caution should be exercised when interpreting the results presented, given that the models are atmosphere-only and not fully coupled. Internal ocean-atmosphere variability can only be simulated using coupled models, and the lack of that information in the HAPPI experiments could distort trends in places such as western North America (Coats *et al* 2016). Although climate increasingly may be reassuming a role as the dominant influence on fire, wildfires are not merely driven by fire weather but also vegetation changes, fuel loads and ignition sources (e.g. lightning activity). Fuel loading is a major factor in determining fire intensity (Deeming and Brown 1975) and soil moisture is crucially associated with the fuel system (Krueger *et al* 2016). Furthermore, human activities, such as population growth and land-use, also need to be considered (Rego *et al* n.d., Thompson *et al* 2018), otherwise estimated fire activity can be significantly misleading in comparison to real-world (Andela *et al* 2017). Thus, while our study is solely focused on climate-related stressors in the global scale, mitigation of warming alone would not be sufficient to negate wildfire hazard.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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