The April 2021 Cape Town wildfire: has anthropogenic climate change altered the likelihood of extreme fire weather?

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30-word capsule: CMIP6 models suggest that extreme fire weather associated with the April 2021 Cape Town wildfire has become 90% more likely in a warmer world.

Introduction

In April 2021, a devastating wildfire tore through the iconic Table Mountain area of Cape Town, South Africa[1]. Following a human-induced ignition on the morning of 18 April, worsening weather conditions led to increased fire spread that lasted until the afternoon of 20 April when the fire was eventually extinguished. The fire burned across more than 600 hectares of wildland[2], with its incursion into urban areas resulting in widespread evacuations and several hospitalisations[3]. Up to 1 billion ZAR (approximately 60 million USD) worth of damage to buildings and infrastructure was incurred by the University of Cape Town campus alone[3], and irreplaceable collections in its Jagger Library were destroyed. While summer wildfires are common in the Cape Town area, the rapid spread, spotting behaviour and unprecedented impacts of this fire so late in the fire season, which is usually considered to run from mid-

[1] https://www.sanparks.org/assets/docs/parks_table_mountain/tmnp-fire-investigation-report.pdf
[2] https://ewn.co.za/2022/04/18/a-year-after-devastating-table-mountain-fire-rehabilitation-expected-to-take-years
[3] https://www.dailymaverick.co.za/article/2021-04-20-calculating-the-losses-of-cape-towns-three-days-of-hell/

November to mid-April (Forsyth and Bridgett, 2004; Christ et al., 2022), raise important questions about the challenges in responding to changing fire regimes at the wildland-urban interface.

The first three weeks of April 2021 were abnormally warm and dry along South Africa's west coast, at the southern tip of which Cape Town is situated. These conditions were highly conducive to wildfire ignition and spread. Previous work has demonstrated a link between extreme hydroclimatic events in the surroundings of Cape Town and anthropogenic climate change, most notably in an attribution study of the 2015-2017 drought (Otto et al., 2018a). While such droughts are likely to enhance fire risks, a quantification of how climate change has altered the likelihood of extreme weather conducive to late-season fires is worthy of dedicated analysis. Here, we analyse the exceptional nature of the meteorological conditions that coincided with the April 2021 event. Using an established probabilistic methodology applied to fire weather extremes simulated by multiple large ensembles from the latest generation of climate models, we quantify the influence of rising global temperatures on the likelihood of such conditions.

Data and methods

Firstly, to place the April 2021 event in the context of the regional fire regime, location and intensity data on historical fires (2001-2021) are taken from the Moderate Resolution Imaging Spectroradiometer (MODIS; Giglio et al., 2016) via the Fire Information for Resource Management System (FIRMS). Our analysis of fire-conducive meteorology is based on the Canadian Fire Weather Index (FWI; Van Wagner, 1987), which combines temperature, surface wind speed, relative humidity and precipitation. FWI has been widely used in related fire analysis across the world (e.g., Krikken et al., 2021; Liu et al., 2022a; 2022b) and forms the basis of GEFF-ERA5, the fire danger reanalysis based on the Global ECMWF Fire Forecast model and the ERA5 reanalysis (Vitolo et al., 2020), from which we derive historical FWI data for the period 1979-2021. The FWI value of 67.77 on 18 April 2021 is the highest recorded during autumn (March to May) in GEFF-ERA5. Our attribution analysis questions to what extent rising global temperature associated with anthropogenic climate change has altered the likelihood of a "2021-type event", defined by the exceedance of the 18 April 2021 threshold by yearly maxima in autumn FWI. It is widely accepted that global mean temperature change since the late 19th century has been predominantly driven by anthropogenic forcings, with the influence of natural forcings very small by comparison (Hegerl et al., 2010; Bindoff et al., 2013; Philip et al., 2020; Ara Begum et al., 2022). Recent work has revealed positive trends in observed fire weather extremes (Jain et al., 2022) and fire weather maxima (Liu et al., 2022a) across much of southern Africa, although the extent of the observational record limits each analysis to just a few decades. Here, simulations of historical FWI are derived from six large ensembles (at least 10 members) from the 6th phase of the Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016) for the period 1850-2014 (see supplemental material for details). As the extent of the April 2021 fire was relatively small, model output is taken for a single grid point closest to the fire's approximate origin (33.92° S, 18.42° E). The meteorological and climatic diversity of the wider region (Conradie et al., 2022) means that including model output across a larger area is very likely to conflate spatially heterogeneous change signals not relevant to the event in question.

We apply a probabilistic statistical methodology based on a time-dependent generalized extreme value (GEV) distribution to each of the six CMIP6 model ensembles to quantify changes in the likelihood of extreme fire weather to rising global temperatures. This method has been widely used in the attribution of different extreme events (e.g., Schaller et al., 2014; Eden et al., 2016; van der Wiel et al., 2017; Eden et al. 2018; Otto et al., 2018b), including episodes of extreme fire weather (e.g. Krikken et al., 2021; Liu et al., 2022b). For each model, 165 yearly FWI maxima (1850-2014) across all corresponding ensemble members are fitted to a GEV distribution scaled with the 4-year smoothed global mean surface temperature (GMST), under the assumption that the location parameter μ and the scale parameter σ have the same exponential dependency on GMST, while the "dispersion ratio" σ/μ and the shape parameter ξ remain constant (Philip et al., 2020; van Oldenborgh et al., 2021a).

We evaluate the FWI threshold associated with the April 2021 event for each CMIP6 model following a bias correction based on the ratio between the μ parameters of the stationary GEV fit and that fitted with FWI maxima from GEFF-ERA5. We then estimate the probability of this threshold being exceeded, firstly, in a "past" climate of 1880 (p_0) and, secondly, in a "present" climate of 2021 (p_1), both of which are defined by observed GMST (GISTEMP Team, 2022; Lenssen et al., 2019). The probability ratio (PR) p_1/p_0 is used to express the overall change in likelihood. A 1,000-sample non-parametric bootstrap is used to estimate confidence intervals (CIs) for each model. Following a model evaluation and selection step based on the dispersion ratio of each model's GEV fit, a final PR result is obtained by a multi-model weighted average (e.g., Eden et al., 2016; Philip et al., 2018).

Results

Between 2001 and 2021, fires frequently occurred across the Cape Floristic Region along South Africa's southern and southwestern coastal margins. Fires during March-May occurred predominantly in the west of this region (Fig. 1a) and regularly exceeded a fire radiative power (FRP) of 900MW (Fig. 1b). The majority of fires observed within 50km of Cape Town occurred between December and March; far fewer fires are observed later than mid-March (Fig. 1c). Synoptic conditions during the week leading up to the 18 April 2021 were characterised by a quasi-stationary mid-tropospheric ridge over South Africa and dry, downslope easterly or northerly drainage winds along the west coast, known locally as *berg winds* (Fig. 1d), which contributed to the exceptional meteorological conditions. The approximate time of the fire's spread coincided with temperatures over 33°C and very low relative humidity (Fig. 1e-f), in addition to the emergence of strong northwesterly winds (Fig. 1g). While, during the 2020-21 summer months, the FWI was generally above average, the absence of prolonged periods of extreme conditions and isolated daily FWI values as anomalous as that recorded on 18 April 2021 further illustrates the exceptionality of the event (Fig. 1h). FWI anomalies from the MAM climatology on 18 April 2021 were very positive (> 40) along the west and south coasts, yielding FWI values around Cape Town usually seen in the arid western interior (Fig. 1i).

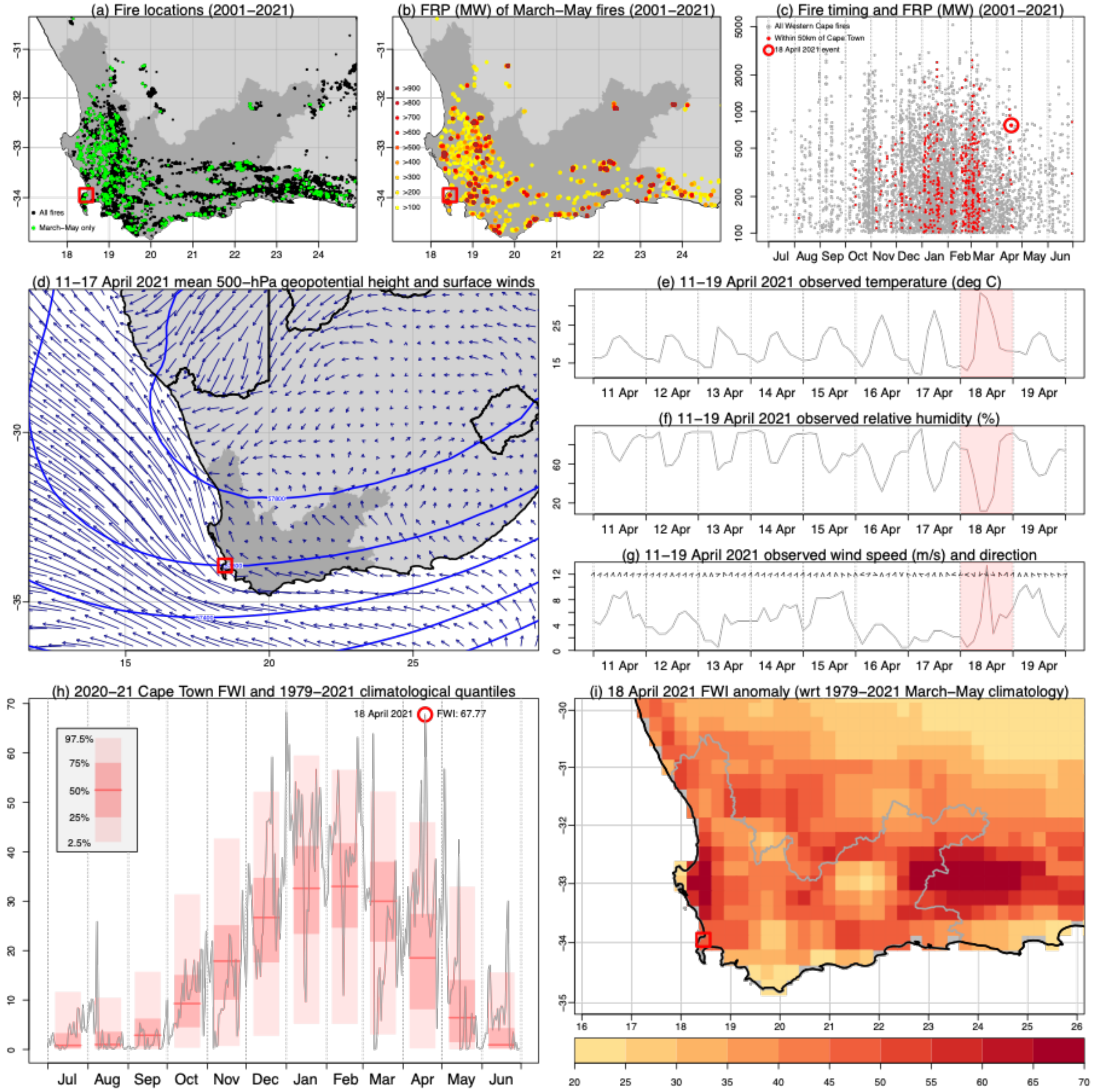

Fig. 1. (a) Location and (b) intensity (FRP) of FIRMS-detected fires (2001-2021). (c) Intra-annual timing and FRP of FIRMS-detected fires within the Western Cape Province. Fires within 50km of Cape Town are shown in red. (d) ERA5 mean 500-hPa geopotential height (contours) and surface winds (arrows) for 11-17 April 2021. (e) Temperature (°C), (f) relative humidity (%) and (g) wind speed (m/s) and direction observed between 11 and 19 April 2021 at Cape Town WO. (h) Cape Town FWI between July 2020 and June 2021 from GEFF-ERA5 (line) and 1979-2021 monthly climatological quantiles (bars). (i) GEFF-ERA5 FWI anomalies on 18 April 2021 with respect to the 1979-2021 March-May climatology. Western Cape province is shaded in (a), (b) and (d), and outlined in (h).

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An overall increase in the likelihood of a 2021-type event between 1880 to 2021 was found for all six CMIP6 models, with PR ranging from 1.2 (INM-CM5-0) to 4.1 (MPI-ESM1-2-HR) (Fig. 2a-f). The uncertainty ranges vary between models, and statistical significance is found only in CanESM5 (95% CI: 1.3-5.6; Fig. 2a) and MPI-ESM1-2-HR (95% CI: 1.6-29.5; Fig. 2f). These results complement the positive trends in observed extreme fire weather revealed in recent work (Jain et al., 2022; Liu et al., 2022a). In view of the inter-model differences, it is notable that the highest resolution model, MPI-ESM1-2-HR, is associated with the strongest trend but it is unclear whether results are sensitive to model resolution.

The small spatial extent of the April 2021 event, and the subsequent application of the method to a single model gridcell, results in a relatively large influence of internally driven natural variability on PR uncertainty (Kay et al., 2015). Combining results as part of a multi-model synthesis is a useful way to summarise and communicate overall findings when internal variability is large. Here, the synthesis is limited to those models that realistically represent FWI extremes, defined by the dispersion ratio of the GEV fit (see supplemental material). A weighted average is generated for the five models that meet the selection criteria, with weights for each model's PR given by the inverse of the squared uncertainty. The uncertainty of the weighted average is approximated by adding the errors for each PR estimate in quadrature (e.g., Phillip et al., 2018). The multi-model synthesis result suggests that the weighted average of the likelihood of the 2021-type event increased by a factor of 1.9 (95% CI: 1.2-3.1; Fig. 2h) between 1880 and 2021 as a result of rising global temperatures.

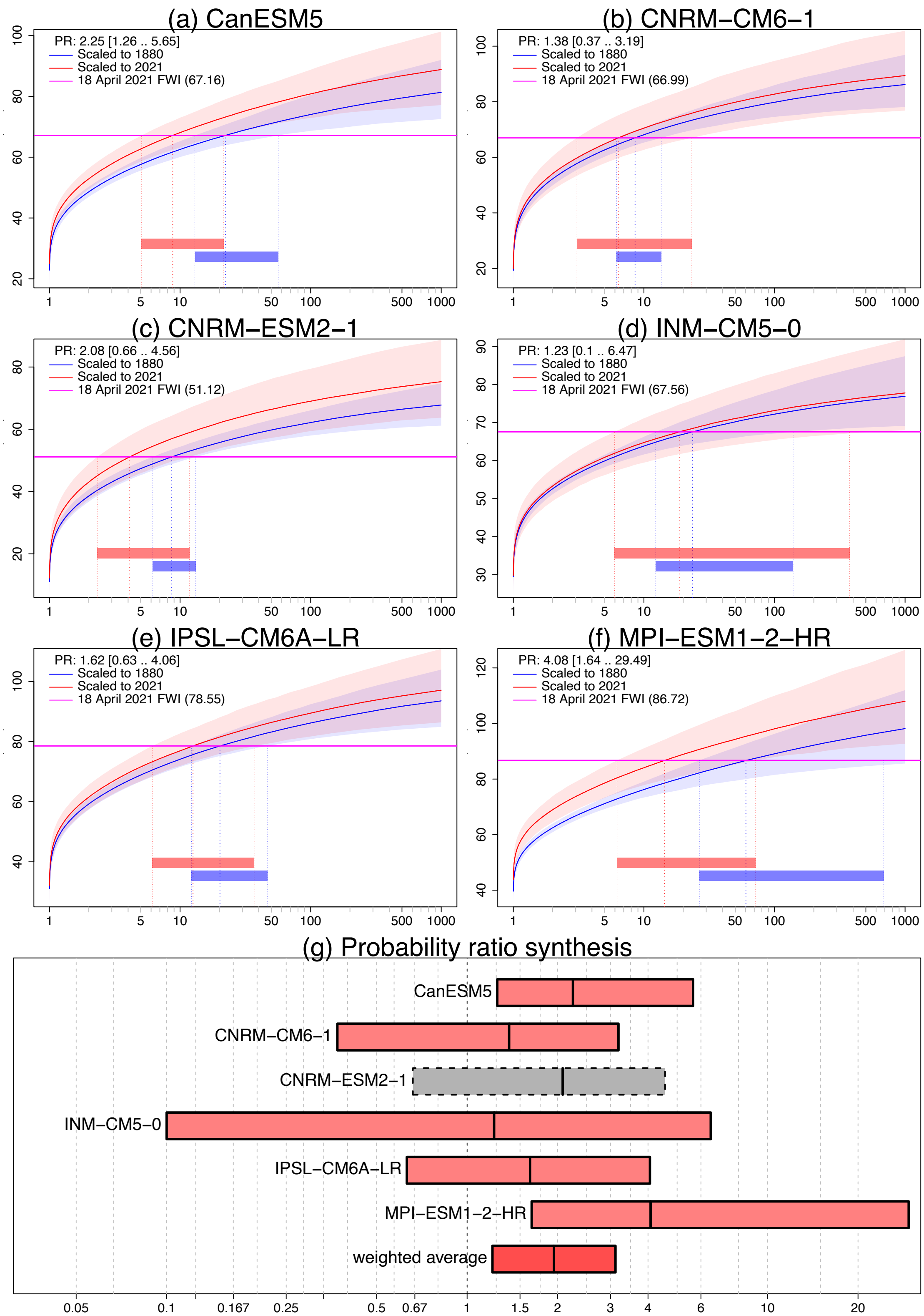

Fig. 2: (a)-(f) Gumbel plots for the six CMIP6 models, showing the GEV model fit scaled to the smoothed observed GMST (GISTEMP Team, 2022; Lenssen et al., 2019) of 1880 (blue) and 2021 (red). Shaded areas represent the 95% CIs following non-parametric bootstrapping. The

magenta lines represent the 2021-type event, scaled to the model distribution using bias correction. The blue (red) bars represent the 95% CIs for the return period of a 2021-type event in the climate of 1880 (2021). (g) PR estimates for the six CMIP6 models and the weighted average (for which CNRM-ESM2-1 is excluded). Bars show 95% CIs; central values are shown in bold.

Conclusions

Our analysis aimed to quantify the impact of a changing climate on the extreme fire weather that coincided with the Cape Town wildfire on 18 April 2021. We applied an established statistical method to the outputs of six large ensembles from CMIP6 to estimate how the likelihood of the 2021-type conditions has been altered by anthropogenic climate change, here expressed as the change in global mean temperature since the late 19^{th} century. Averaging the results from multiple models revealed a mean probability ratio of 1.9, i.e. an overall increase in likelihood of around 90%. Diagnosing discrepancies among different models of differing resolutions, particularly when the analysis is limited to a single model grid point, is challenging and a potential avenue for further study.

The results complement existing efforts to attribute hydroclimatological extremes around Cape Town, including droughts (e.g., Otto et al., 2018a; Zscheischler and Lehner, 2022), and add to the growing set of attribution studies on wildfires and extreme fire weather in different parts of the world (e.g., Krikken et al., 2021; van Oldenborgh et al., 2021b; Liu et al., 2022b). Our analysis also highlights the importance of drawing findings from multiple models in pursuit of the most robust statement possible for a singular wildfire episode.
The model-derived evidence of trends in fire weather extremes add to that drawn from observational analysis (Jain et al., 2022; Liu et al., 2022a), and the application of alternative modelling approaches and statistical methodologies is a potential pathway toward further building this evidence base (Otto et al., 2020).

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